SECTION 10

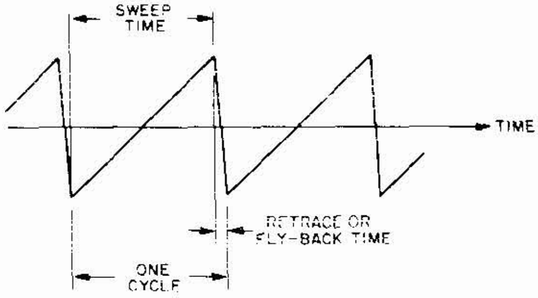
SWEEP-GENERATOR CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

SAWTOOTH-WAVE, GAS-TUBE SWEEP-GENERATOR CIRCUITS.

A **sawtooth wave** is defined as a periodic wave which varies in amplitude between two values to provide a waveform pattern resembling the teeth of a saw.

The sawtooth waveform has many applications in television, radar, and special test equipment. It is commonly used as the time base for cathode-ray tubes which employ electrostatic deflection of the electron beam. For this type of deflection, the horizontal deflection circuits require a linear time base, that is, a type of voltage waveform which is directly proportional to time. A sawtooth voltage waveform is illustrated below.



Typical Sawtooth Waveform

The useful portion of the sawtooth waveform is called the **sweep** time, and the remaining portion is called the **retrace**, or **fly-back**, time. The sweep voltage developed by the sweep-generator circuit is used to move (deflect) the spot across the fluorescent screen of the cathode-ray tube at a uniform rate. During the retrace, or fly-back, portion of the waveform, the spot is returned very rapidly to the initial starting point of the sweep, ready for another sweep trace to be generated. The waveshape of the retrace portion, during the period of time between the end of one sweep and the beginning of the next, is usually not very important insofar as the cathode-ray tube display is concerned. This is because the rate at which the spot returns across the fluorescent screen is usually too rapid to be visible or because a blanking pulse is applied to the cathode-ray tube to supress the spot during the retrace period. The sweep portion of the sawtooth waveform, however, must be very nearly a linear (straight-line) function of time.

The simplest forms of sawtooth sweep generator make use of the principle of charging and discharging a capacitor to obtain the desired output waveform. By using only the most linear portion of the exponential charging curve of a capacitor, the gas-tube sweep generator can produce a reasonably linear sawtooth waveform; however, perfect linearity of the sweep is difficult to obtain with this type of sweep generator.

NEON GAS-TUBE SWEEP GENERATOR.

APPLICATION.

The sawtooth-wave sweep-generator circuit using a neon gas tube is one form of relaxation oscillator. This type of circuit is occasionally used where a simple "free-running" sweep generator will provide a satisfactory sawtooth waveform for use in certain noncritical test-equipment circuits and in cathode-ray tube circuits employing electrostatic deflection.

CHARACTERISTICS.

Free-running, relaxation-oscillator type.

Output is sawtooth waveform.

Output sweep frequency is determined by R-C circuit, type of neon gas tube used, and voltage applied to circuit. Sweep frequencies up to 10 kilocycles can be produced.

Neon gas tube is used as switch to control charge and discharge of capacitor.

CIRCUIT ANALYSIS.

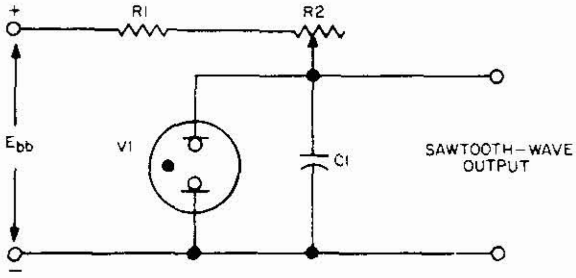
General. In the discussion of time constants given in Section 2, General Information on Electron Tube Circuits, the typical charging curve for an R-C circuit was illustrated. If a capacitor is charged through a resistance from a constant-voltage source, an exponential voltage curve is obtained across the terminals of the capacitor. Eventually the charge on the capacitor rises to a value equal to the applied voltage. The initial portion of the R-C charging curve is reasonably straight, with very little curvature, and if only a small part of the initial portion of the charging curve is utilized, the degree of linearity obtained is considered to be satisfactory for many sweep applications.

In order to develop a sawtooth voltage, it is necessary to charge the capacitor and then quickly discharge it to complete the charge-discharge cycle; the cycle is then repeated over and over to produce the desired sawtooth output waveform. A means must be provided to quickly discharge the capacitor once it has received a partial charge. At extremely low frequencies a mechanical switch can be used to short the capacitor terminals and discharge the capacitor; however, such a switching system becomes impractical at the higher frequencies.

The neon gas tube (or neon bulb) is a practical and simple device which can act as an electronic switch to discharge the capacitor. A neon gas tube has a negative resistance characteristic and, because of this characteristic, as soon as the tube is ionized, heavy current will flow through it. If the tube is connected directly across a source of voltage which is sufficiently high to ionize the gas, the current rises rapidly to a value which can damage the tube. However, in a typical sweep-generator circuit, the resistance in the circuit limits the current and prevents it from damaging the gas tube; furthermore, the tube conducts primarily to discharge the capacitor.

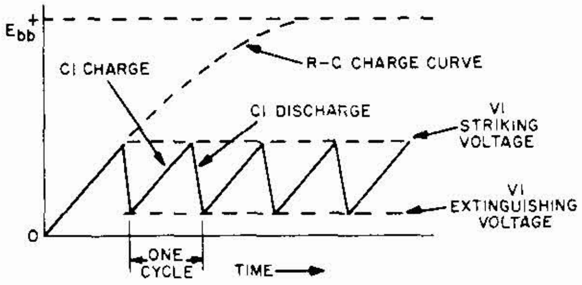
The value of the terminal voltage necessary to cause ionization of the gas tube is termed the **striking**, or **firing**, voltage. When the tube ionizes, its internal resistance becomes very low and will allow a heavy current flow as long as the voltage applied to the tube is sufficient to maintain ionization. However, when the voltage drops to a low value, conduction ceases. The value of voltage at which conduction ceases and the tube deionizes is termed the **extinguishing**, or **recovery**, voltage. Approximate values of striking and extinguishing voltages for several common types of neon gas tubes are 65 and 20 volts, dc, respectively.

Circuit Operation. In the accompanying illustration, a simple neon gas-tube sweep-generator circuit is shown. Resistor R1 is a series current-limiting resistor; resistor R2 is a variable resistor which permits the frequency of oscillation to be changed. Capacitor C1 is a charging capacitor and V1 is a neon gas tube.



Neon Gas-Tube Sweep-Generator Circuit

Initially, when voltage is applied to the circuit, capacitor C1 begins to charge through resistors R1 and R2, in series. The R-C time constant establishes the frequency of oscillation for a given value of applied voltage and depends upon the value of the capacitor and the combined resistance of the two resistors, R1 and R2. The tube is not ionized during this period of time and represents a high impedance in parallel with the charging capacitor. The voltage across capacitor C1 builds up gradually following the R-C charge curve, shown on the accompanying illustration of the output-voltage waveform, until the terminal voltage of the capacitor reaches the striking voltage of the neon gas tube, V1. When the striking voltage is reached, the tube ionizes and conducts to form a low-impedance path to discharge the capacitor. Capacitor C1 discharges through the tube, and the terminal voltage drops rapidly. As soon as the voltage drops to a value equal to the extinguishing voltage of the gas tube, the tube deionizes and current stops flowing. The tube again represents a high impedance in parallel with the charging capacitor, C1, and the voltage again starts to rise across the capacitor. As shown on the waveform illustration, capacitor C1 charges again until the striking voltage of the gas tube is reached. The tube then ionizes and discharges the capacitor; this operation repeats over and over as long as voltage (E_{bb}) is applied to the circuit.



Output Voltage Waveform

The linear sweep portion of the sawtooth waveform is produced when capacitor C1 is charged, and the retrace or flyback portion of the waveform is produced when the capacitor is discharged by conduction of the tube. The sweep time depends upon the values of resistance and capacitance in the circuit, upon the applied voltage, and upon the characteristics (striking and extinguishing voltages) of the neon gas tube. The characteristics of the tube are fixed and depend upon the particular type of tube used. Therefore the sweep time and frequency are controlled primarily by any of the first three factors previously mentioned: the resistance, the capacitance, or the applied voltage.

In order to obtain reasonable linearity of the sweep portion of the sawtooth wave, the applied voltage is maintained at a high constant potential so that operation of the neon gas tube and charging capacitor takes place on the lower, straight portion of the charging curve, as shown on the accompanying waveform illustration. Variations in operating frequency are usually accomplished by changing either the circuit resistance or capacitance, or both. In a practical sweep generator, the value of the capacitance (C1) is fixed, and the resistance (R2) is adjusted to change the R-C time constant of the circuit. The range of operating frequency is sometimes extended beyond that obtainable with a variable resistance alone by incorporating a switch either to select one of several fixed capacitors or to select and parallel a number of fixed capacitors.

The time required for the retrace, or flyback, portion of the sawtooth waveform to occur is determined by the impedance of the neon gas tube when ionized, the difference between the striking and extinguishing voltages of the tube, and the value of the capacitor in the circuit. Normally, however, the impedance of the tube is so low that the retrace, or flyback, time does not become appreciable until the sweep frequency exceeds approximately 10,000 cycles per second.

FAILURE ANALYSIS.

No Output. A neon gas tube radiates a characteristic orange-red glow when ionized. An indication of gas-tube operation can therefore be obtained by visual inspection to determine the presence of the characteristic glow from the ionized gas within the tube.

If the gas tube is ionized continuously and no sweep output is obtained, it is likely that capacitor C1 is open or that resistors R1 and R2 have decreased in value. In this case the tube attempts to act as a voltage-regulator tube and it conducts continuously; the voltage developed across the gas tube remains a constant value. Capacitor C1 can be checked by using a suitable capacitance analyzer to determine whether or not the capacitor is defective. An ohmmeter measurement of resistors R1 and R2 can be made to determine whether a decrease in resistance has occurred. If the conduction current through the neon gas tube is excessive for any great length of time, the tube may be damaged and its characteristic will be impaired as a result.

Although the gas tube may appear to be glowing in the proper manner, this is not a positive indication that the tube is operating correctly; therefore, the tube itself may be suspected as a source of trouble.

If the gas tube fails to ionize, the voltage across capacitor C1 will rise to the full applied voltage, and no sawtooth output voltage will be developed. If the tube is not ionized, however, this does not necessarily mean that the tube is defective, since the same indication (lack of glow) may occur if either resistor (R1 or R2) is open, if there is no applied d-c voltage (E_{bb}), or if the charging capacitor (C1) is shorted. The value of each resistor, R1 and R2, can be checked by ohmmeter measurements to determine whether any increase in resistance or an open has occurred. Measurements can also be made across the capacitor terminals to determine whether capacitor C1 is shorted, thus causing the voltage to be either zero or an extremely low value.

Incorrect Frequency. It is reasonable to assume that any change in the values of resistance (R1, R2) or capacitance (C1) will affect the R-C time constant of the circuit and, thus, the frequency of operation. When an adjustment is provided, as for example resistor R2 in this circuit, a change in operating frequency can be compensated for by adjustment of the series resistor, R2. If the R-C time constant is increased, the frequency of operation will decrease; conversely, if the time constant is decreased, the frequency of operation will increase. A change in the value of R1 or R2 can be determined by ohmmeter measurements; the value of capacitor C1 can be measured with a suitable capacitance analyzer.

Assuming that the values of R and C remain constant, a change in the applied voltage (E_{bb}) will affect the operation of the circuit; thus, an increase in applied voltage will increase the frequency of operation, while a decrease in voltage will decrease the frequency.

The characteristics of the neon gas tube may be affected as the tube ages; therefore, the striking and extinguishing voltages of the tube may change causing the circuit to shift its operating range on the R-C charge curve. This condition may cause not only a change in operating frequency, but also changes in sweep amplitude and linearity.

THYRATRON SWEEP GENERATOR.

APPLICATION.

The thyratron sweep generator is used to produce a linear sawtooth sweep voltage waveform for radar equipments, television sets, electronic displays, and special test equipments employing an electrostatic type of cathode-ray tube.

CHARACTERISTICS.

Employs a thyratron gas tube in a relaxation oscillator circuit.

The thyratron is used as a switch to control the charge and discharge of a capacitor.

Output is a sawtooth voltage waveform.

Output amplitude is determined by the characteristics of the thyratron.

Output sweep frequency is determined primarily by the time constant of the R-C circuit.

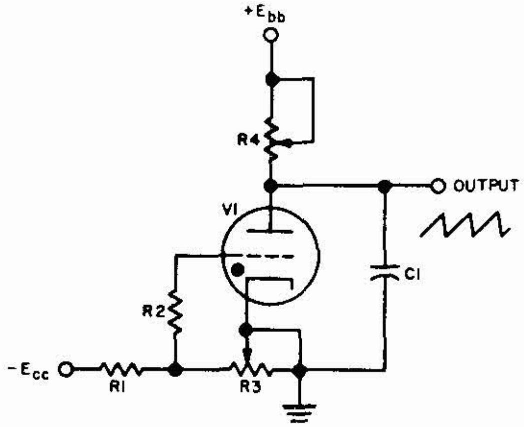
Sweep frequencies up to 75 kilocycles can be produced.

CIRCUIT ANALYSIS.

General. As explained in Section 2, paragraph 2.5.1, of this Handbook, when a series R-C circuit is connected across a constant-voltage source, the capacitor charges and the voltage measured across its terminals increases at an exponential rate until the voltage becomes equal to the source voltage. Only the initial portion of the capacitor charging curve is sufficiently linear to be used in the generation of a sawtooth wave. To generate the sawtooth wave, it is necessary to restrict the capacitor charge to a small portion of the total source voltage, and then cause it to discharge very quickly. The charging cycle is then repeated. In addition to hard tubes, a thyratron may also be used as a switch to control the charge and discharge of the capacitor, and thus produce the desired sawtooth-wave output.

In a gas-filled tube the **ionization potential** (firing voltage) determines the plate voltage at which the tube begins to conduct, and the **deionization potential** (extinguishing voltage) determines the voltage below which the tube ceases to conduct. When the plate voltage of a gas tube exceeds the ionization potential, the gas in the tube ionizes and the tube conducts very heavily. It continues to conduct heavily until the plate voltage is lowered below the deionization potential, when the gas in the tube deionizes and the tube ceases to conduct. The thyratron is a special type of gas-filled triode in which a third element, a control grid, is used to control the ionization of the tube. The control grid, however, has no effect on the deionization potential of the thyratron; it can only initiate conduction. Once triggered, the thyratron continues to conduct until the plate voltage drops below the deionization potential of the tube.

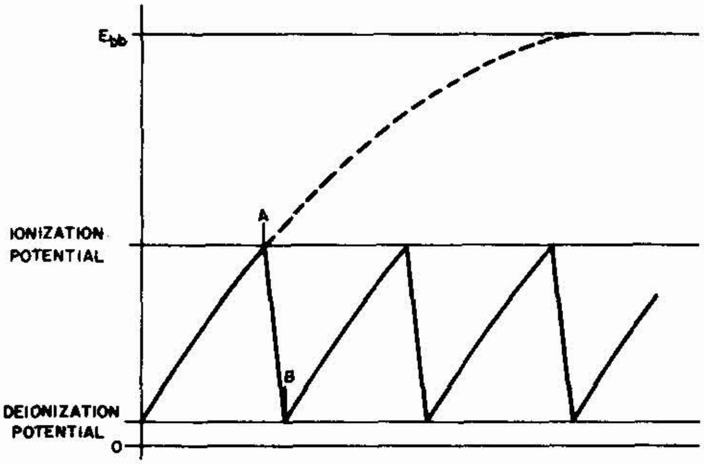
Circuit Operation. The accompanying circuit schematic illustrates a typical thyratron sweep generator.



Thyratron Sweep Generator

Capacitor C1 and resistor R4 make up the R-C charging circuit, which is used as an integrator to produce the sawtooth output wave. Thyratron V1 is connected in parallel with capacitor C1, and functions as a switch to control the charge and discharge of the capacitor. Resistors R1 and R3 form a voltage divider from the negative bias supply to ground, which supplies fixed grid bias voltage to the thyratron through grid-current limiting resistor R2. Since resistor R3 is variable, the grid bias, and thus the trigger potential of the thyratron, can be varied.

When voltage is first applied to the thyratron sweep-generator circuit, capacitor C1 begins to charge through resistor R4. As the capacitor charges, the voltage across it, and across thyratron V1, increases from zero toward the full value of the plate-supply voltage. If the capacitor were allowed to reach full charge, the voltage across it would increase exponentially to the full value of the plate-supply voltage, as shown by the broken line on the accompanying output-voltage waveform illustration.



Output-Voltage Waveform

However, when the voltage across capacitor C1 (and across thyratron V1) exceeds the ionization potential of the thyratron (point A on the waveform illustration), the tube instantly ionizes and begins to conduct very heavily. Since the conducting thyratron has very low (almost zero) impedance, it shunts capacitor C1 and causes the capacitor to discharge very quickly through the tube. Thus, the capacitor charges to the ionization potential of the thyratron, which is determined by the thyratron grid voltage, and then discharges. As the capacitor discharges, the voltage across it drops toward zero. When the voltage across the capacitor drops below the deionization potential of thyratron V1 (point B on the waveform illustration), the tube deionizes and ceases to conduct. Since the nonconducting (cut off) thyratron has a very high (almost infinite) impedance, it no longer effectively shorts capacitor C1, and the capacitor again begins to charge toward the full plate-supply voltage value. The capacitor charges until the voltage across it exceeds the ionization potential of the thyratron, at which time the tube conducts and discharges the capacitor. This charge-discharge cycle continues to repeat as long as voltage is applied to the circuit-capacitor C1 charges while thyratron V1 is cut off, and discharges when the thyratron conducts. Thus, thyratron V1 acts as a switch and causes capacitor C1 to alternately charge and discharge, producing a sawtooth output wave.

The sweep frequency of the thyratron sweep generator is determined by the time it takes for capacitor C1 to

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charge to the ionization potential of thyratron V1. The charge time of the capacitor is determined by the time constant of the R-C circuit made up of resistor R4 and capacitor C1, and can be changed by adjusting variable resistor R4. Increasing the value of resistor R4 increases the time constant of the R-C circuit, which increases the charge time of capacitor C1, and thus decreases the sweep frequency. Decreasing the value of resistor R4 has the opposite effect, and increases the sweep frequency.

The amplitude of the sawtooth output wave is determined by the difference between the ionization (firing) potential and the deionization (extinguishing) potential of the thyratron. The ionization potential is controlled by varying the grid bias. Consequently, resistor R3 is used to adjust the thyratron grid bias for the desired output amplitued. Increasing the value of resistor R3 increases the negative voltage on the grid of the thyratron and raises the ionization potential. The consequent larger difference between the ionization and deionization potentials thus increases the amplitude of the sawtooth-wave output. Decreasing the value of resistor R3 has the opposite effect, and decreases the output amplitude. Adjusting resistor R3 also affects the output sweep frequency slightly, but this frequency can be corrected by readjusting resistor R4.

FAILURE ANALYSIS.

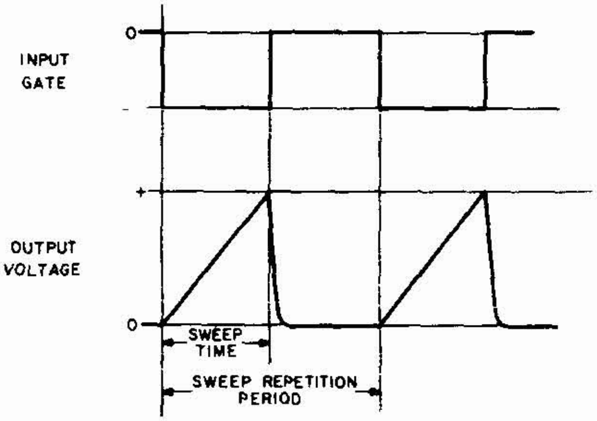
No Output. A no-output condition may be caused by lack of plate-supply voltage, an open plate resistor (R4), a faulty sweep capacitor (C1), or a defective thyratron (V1). Since the thyratron emits a characteristic glow when conducting, observation of the tube will show whether or not it is conducting. If the thyratron is glowing (conducting), lack of plate-supply voltage and an open plate resistor (R4) can be eliminated as possible troubles, since the tube must have plate voltage applied to it through resistor R4 in order to conduct. If the thyratron is not glowing, first measure the plate-supply voltage with a high-resistance voltmeter to eliminate the possibility of a faulty power supply, and then check resistor R4 for continuity with an ohmmeter. If it is determined that neither the power supply nor resistor R4 is at fault (either because they have been checked or because they have been eliminated as possible troubles), further checks must be made to locate the trouble. Use an in-circuit capacitor checker to check capacitor C1 for a shorted, open, or leaky condition. If capacitor C1 is not defective, thyratron V1 is probably at fault and should be replaced with a tube known to be good.

Incorrect Output Frequency. Any fault which changes the charge time of capacitor C1 will cause the output frequency to be incorrect. Therefore, check for changes in the value of capacitor C1 and in the setting of resistor R4, and for incorrect plate-supply voltage. It is good practice to first measure the plate-supply voltage with a high-resistance voltmeter to eliminate the possibility of a defective power supply. If the supply voltage is correct, use an ohmmeter to check resistor R4 for the correct resistance value, and a capacitance analyzer to check capacitor C1 for the correct capacitance value; replace the defective component.

Incorrect Output Amplitude. Since the amplitude of the sawtooth output wave is determined by the difference between the ionization and deionization potentials of thyratron V1, improper grid bias or a defective thyratron may cause the output amplitude to be incorrect. Measure the voltage on the grid of thyratron V1 with a high-resistance voltmeter. If the grid voltage is correct, the thyratron is probably defective and should be replaced. If the grid voltage is either high or low, the bias circuit is probably defective. Use an ohmmeter to check resistors R1, R2, and R3 for the proper resistance values.

TRIODE SAWTOOTH-WAVE SWEEP GENERATOR CIRCUITS.

Triode sweep generators use externally controlled electron-tube sweep circuits which produce symmetrical sawtooth wavforms for the duration of the trigger gate. As shown in the accompanying illustration, the output voltage rises at a linear (constant) rate during the negative input gate, and then drops back to zero between input gates.



Triode Sweep Generator Waveforms

The duration of the linear portion of the output waveform is known as the **sweep time,** and is determined by the duration of the input gate. The time from the beginning of one sawtooth wave (sweep) to the beginning of the next sawtooth wave is known as the **sweep-repetition period,** and is determined by the repetition period of the input gate. The term **linearity** is used to describe the straightness of the sweep portion of the sawtooth waveform. The more closely the sweep approaches a straight (but sloping) line, the greater the linearity.

In triode sawtooth-wave sweep generator circuits, the electron tube is used as a switch to control the charge and discharge of a capacitor which produces the desired sawtooth output waveform. During the negative input gate, the triode acts as an open switch and allows the capacitor to charge, producing the linear sweep. At the end of the input gate, the triode acts as a closed switch, causing the capacitor to discharge very quickly, and preventing it from recharging until the next input gate is applied to initiate the next sweep cycle.

Two triode swatooth-wave sweep generator circuits are in general use: The basic Triode Sawtooth Sweep Generator and the Bootstrap Sweep Generator. The major difference between the two circuits is in the linearity of the sawtooth output waveform. While the output of the basic circuit is sufficiently linear for most applications, the bootstrap circuit provides an extremely linear output for applications where the waveform distrotion in the basic circuit cannot be tolerated. Each of these circuits is discussed in detail in the following paragraphs of this section of the Handbook.

BASIC TRIODE SAWTOOTH SWEEP GENERATOR.

APPLICATION.

The basic triode sawtooth sweep generator produces symmetrical, synchronized sawtooth waveforms for sweep voltage use in radar equipments, display indicators, synchroscopes and other types of special-purpose test equipment which use an electrostatic deflection cathode-ray tube.

CHARACTERISTICS.

Employs a high-vacuum triode.

Requires a negative operating gate.

Output is a symmetrical sawtooth voltage waveform with equal intervals between sweeps.

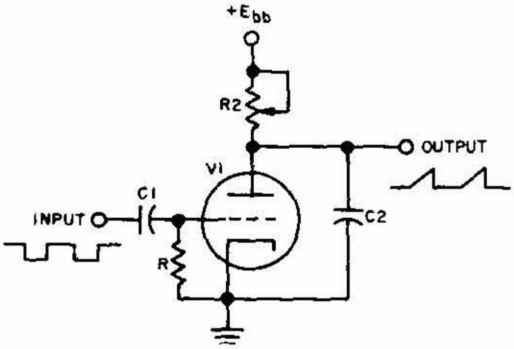
Sweep time is determined by the duration or the negative operating gate.

Sweep-repetition period is the same as the repetition period of the operating gate.

CIRCUIT ANALYSIS.

General. Recall from the elementary discussion of time constants in Section 2, paragraph 2.5.1, of this Handbook that when a series R-C circuit is connected across a constant voltage source, the capacitor charges at an exponential rate until the voltage measured across its terminals equals the source-voltage value. Since the initial portion of the capacitor charging curve is nearly linear. This portion of the curve may be used in the generation of a sawtooth wave. In the basic triode sawtooth sweep generator, the electron tube is used as a switch to control the charge and discharge of a capacitor over the initially linear portion of the charging curve, and to produce a sawtooth output wave with good linearity.

Circuit Operation. The accompanying circuit schematic illustrates the basic triode sawtooth sweep generator.

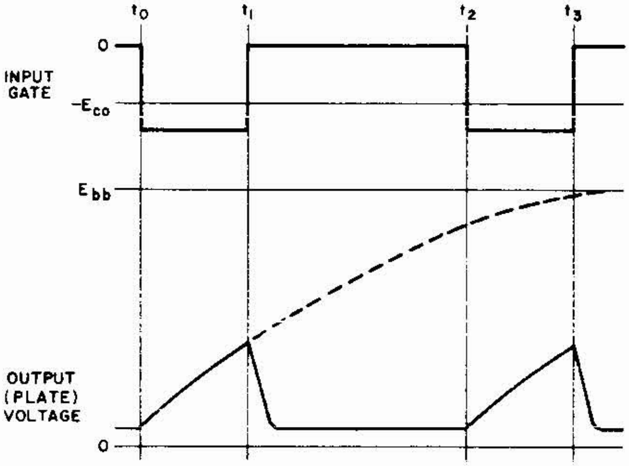


Basic Triode Sawtooth Sweep Generator

Capacitor C2 and resistor R2 form the R-C circuit which produces the sawtooth output waveform. Triode V1 is connected in parallel with capacitor C2, and acts as a switch to control the charge and discharge of the capacitor. Capacitor C1 and resistor R1 form a conventional R-C input coupling circuit, which applies the input gate to the grid of triode V1. The sawtooth output is developed across the parallel combination of triode V1 and capacitor C2.

In the quiescent state, with no negative input gate applied, there is practically no bias on the grid of triode V1. Consequently, the tube conducts very heavily and the plate voltage drops to a very low value. Since capacitor C2 is connected in parallel with triode V1, the capacitor charges to the low value of plate voltage existing across the tube, and remains charged to this voltage until an input gate is applied.

When a negative input gate is applied to the basic triode sawtooth sweep generator, it drives the grid of triode V1 below plate current cutoff and the tube ceases to conduct. When the triode cuts off, the plate voltage tends to rise instantaneously to the full value of plate-supply voltage, Ebb. However, capacitor C2 is connected in parallel with the triode and thus prevents the plate voltage from rising instantaneously. Instead, the plate voltage rises exponentially toward the plate-supply value at a rate determined by the time constant of the R-C circuit consistting of capacitor C2 and resistor R2. As the capacitor charges, the voltage across it (and therefore on the plate triode V1) rises at an exponential rate as shown, beginning at time t_0 on the accompanying output (plate) voltage waveform illustration.



Theoretical Input and Output Waveforms

If triode V1 remained cut off indefinitely the voltage across capacitor C2 (and on the plate of V1) would rise exponentially to the plate-supply value, as shown by the broken line in the illustration. However, at time t_1 the negative input gate ends and the grid bias on triode V1 returns to zero. Therefore, triode V1 again conducts heavily and the plate voltage tends to fall instantaneously to a very low value (the initial quiescent value). Since capacitor C2 is connected in parallel with triode V1, the plate voltage cannot change instantaneously, but rather falls at a rate determined by the discharge time of the capacitor. Since the conducting triode has a very low impedance, it effectively shunts (shorts) capacitor C2, and the capacitor discharges very quickly through the low impedance offered by the tube. As the capacitor discharges, the plate voltage measured between the plate of triode V1 and ground decreases exponentially to the original quiescent value, and remains there until the next negative input gate is applied. Thus, the basic triode sawtooth sweep generator produces one sawtooth wave each time a negative input gate is applied, and remains in the quiescent (off) state between input gates.

It can be seen from the preceding discussion that the output waveform characteristics of the basic triode sawtooth sweep generator are determined in part by the duration of the negative input gate. If the duration of the input gate is increased, capacitor C2 charges for a longer period of time, and thus charges to a higher potential. Since a larger portion of the capacitor charging curve is used when the duration of the input gate is increased, the linearity of the sawtooth output wave is decreased. Thus, increasing the input gate duration (for example, by decreasing the input frequency) affects the sawtooth wave in three ways: the sweep time (duration) increases, the sweep amplitude increases, and the sweep linearity decreases.

Changing the charge time of capacitor C2 also affects the characteristics of the sawtooth output wave. Since capacitor C2 charges through resistor R2, the charge time of the capacitor is changed by varying the resistance of R2. Adjusting resistor R2 for a higher resistance value increases the charge time of capacitor C2; thus, for a given input gate duration, a smaller portion of the capacitor charging curve is used, and the capacitor charges to a lower potential. Consequently, the sweep amplitude decreases and the sweep linearity increases, since only the relatively small straight-line portion of the sweep is used.

Both the duration of the input gate and the setting of resistor R2 affect the sweep amplitude and linearity; therefore, resistor R2 is used to compensate for changes in sweep characteristics caused by changes in the input gate duration. Thus, resistor R2 can be adjusted to cause the circuit to produce a sawtooth output waveform of constant amplitude and linearity, even though the input gate duration changes.

FAILURE ANALYSIS.

No Output. A no-output condition may be caused by either lack of an input gate, lack of plate supply voltage, or a defective tube or circuit component. It is good practice to first check the input gate with an oscilloscope, and the plate-supply voltage with a high-resistance voltmeter, to determine that the trouble is definitely in the sweep generator circuit. If the correct input gate is observed and the proper plate-supply voltage is measured, use the oscilloscope to observe the waveform on the grid of triode V1. If no grid waveform is observed, either capacitor C1 is open or grid resistor R1 is shorted. Use an in-circuit capacitor checker to check the capacitor, and an ohmmeter to check the resistor. The correct waveform on the grid of triode V1 indicates that the trouble is in the plate circuit (C2, R2, V1) of the sweep generator. Check capacitor C2 for a short circuit with an in-circuit capacitor checker, and resistor R2 for the proper resistance value with an ohmmeter. If no defective component is found, triode V1 is probably at fault and should be replaced with a tube known to be good.

Distorted Output. Any defect in the circuit which causes capacitor C2 to charge for a greater than normal portion of the capacitor charging curve will cause a distorted sawtooth output wave. Possible causes of distortion are: A distorted input gate, incorrect plate-supply voltage, changes in the values of capacitor C2 and resistor R2 (including wrong adjustment of resistor R2), and low emission in triode V1. First, observe the input gate with an oscilloscope to be certain that no distortion is present, and then measure the plate-supply voltage with a high-resistance voltmeter to be certain that the supply voltage is correct. If the input gate and the plate-supply voltage are normal, further checks must be made to isolate the trouble. Use a capacitance analyzer to check capacitor C2 for the proper value. Use an ohmmeter to check resistor R2 for the correct value and setting. If these checks fail to locate a faulty component, triode V1 is probably at fault. Replace it with a tube known to be good.

BOOTSTRAP SWEEP GENERATOR.

APPLICATION.

The bootstrap sweep generator is used to produce an extremely linear sawtooth waveform for use in navigation equipment, radar test sets, and in other types of electronic equipment where an extremely linear sweep voltage is required.

CHARACTERISTICS.

Employs one triode as a switch tube, and another as a constant-current generator.

Uses positive feedback to produce the linear sawtooth sweep.

Requires a negative input gate.

Output is a symmetrical sawtooth voltage waveform with equal intervals between sweeps.

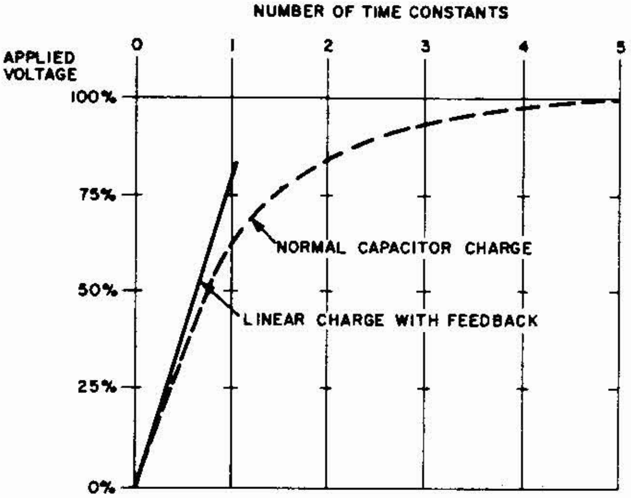
Sweep time is determined by the duration of the input gate.

Sweep-repetition period is determined by the repetition period of the input gate.

CIRCUIT ANALYSIS.

General. Most sawtooth sweep generator circuits use the charging action of a capacitor to produce a sawtooth waveform. By using only the initial portion of the exponential capacitor charging curve, a fairly linear sawtooth output waveform is produced. However, some nonlinearity (curvature) is present in the output waveform because even the initial portion of the capacitor charging curve is not perfectly linear. The bootstrap sweep generator uses a feedback loop to straighten out the curvature in the initial portion of the capacitor charging curve, and thus, to produce an extremely linear sawtooth waveform.

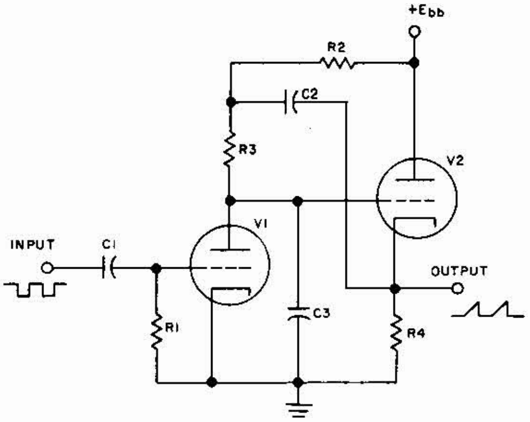
Before discussing the operation of the bootstrap sweep generator, it is necessary to review the charging action of an R-C circuit. The charge time of the capacitor in the R-C circuit is determined by the time constant of the circuit. At the first instant that a series R-C circuit is connected across a constant voltage source, the entire supply voltage appears across the resistor. As the capacitor charges, the voltage drop across it increases, and at the end of one time constant interval, 63 percent of applied voltage appears across the capacitor, and the remaining voltage (37%) appears across the resistor. During the next time constant, the capacitor further charges to 63 percent of the voltage remaining across the resistor, that is, to 86 percent of the total applied voltage. During each successive time constant, the capacitor charges to 63 percent of the voltage remaining across the resistor. Thus, as shown by the dashed line in the accompanying illustration, the voltage across the capacitor rises exponentially toward the supply voltage as the capacitor charges. Although the capacitor theoretically never fully charges, after five time constants it is charged to over 99 percent of the supply voltage and is considered to be fully charged.



Generation of a Linear Sweep

The voltage across the capacitor of a series R-C circuit increases at an exponential rate because the capacitor charges to 63 percent of the voltage across the resistor each time constant. Since the voltage across the resistor decreases as the capacitor charges, the capacitor charges a smaller amount each time constant, resulting in an exponential increase in the voltage across the capacitor. If the applied voltage were increased as the capacitor charged, so that the voltage across the resistor remained constant, the capacitor would charge the same amount each time constant. This is, the voltage across the capacitor would increase at a linear (constant) rate. The bootstrap sweep generator uses a feedback circuit to cause the effective supply voltage for the R-C circuit to increase as the capacitor charges. Thus, the circuit produces an extremely linear sweep, as shown in the sweep generation illustration.

Circuit Operation. The accompanying circuit schematic illustrates one type of bootstrap sweep generator.

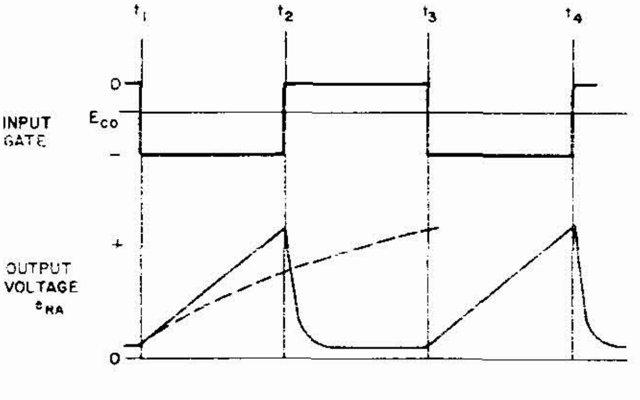


Bootstrap Sweep Generator

The portion of the circuit made up of coupling capacitor C1, grid resistor R1, switch tube V1, charging capacitor C3, and plate resistor R3 is a conventional basic triode sawtooth sweep generator. Triode V2 is a cathode follower which provides feedback to charging capacitor C3 through d-c blocking capacitor C2. The input gate is applied through capacitor C1 to the grid of triode V1, and the output sawtooth waveform is taken from the cathode of triode V2 across cathode resistor R4.

In the quiescent state, no negative input gate is applied to the bootstrap sweep generator, and therefore, no bias is applied to triode V1. Consequently, the tube conducts very heavily, and the plate voltage is very low. Since capacitor C3 is in parallel with triode V1, it charges to the low value of plate voltage existing across the tube. The voltage across capacitor C3 also appears on the grid of triode V2 (because of the direct coupling from the plate of V1 to the grid of V2), and causes V2 to conduct. The plate current of triode V2 flows through cathode resistor R4 and causes a small, but constant, voltage drop across the resistor. So long as no input gate is applied the circuit remains in this quiescent state, and the output voltage across resistor R4 remains at the low quiescent value.

When a negative input gate is applied to the bootstrap sweep generator, it is applied through coupling capacitor C1 to the grid of triode V1. When the input gate is of sufficient amplitude to drive the grid of triode V1 below plate-current cutoff, plate current ceases to flow, and the plate voltage tries to rise instantaneously to the plate-supply value. However, capacitor C3 is connected in parallel with triode V1, and prevents the plate voltage from changing instantaneously. Instead, the plate voltage rises relativily slowly as the capacitor charges. Normally, capacitor C3 would charge exponentially at a rate determined by the values of resistance and capacitance in the circuit, as shown by the dashed line on the accompanying theoretical waveform illustration.



Theoretical Input and Output Voltage Waveforms

In the bootstrap circuit, however, the voltage across capacitor C3 is also applied to the grid of triode V2, which is connected as a cathode follower with almost unity gain. The changing voltage on the cathode of triode V2 (which is nearly equal to the voltage on the grid) is fed back through d-c blocking capacitor C2 to the junction of plate resistors R2 and R3. This feedback loop operates in the following manner. As capacitor C3 charges positive with respect to ground, the voltage impressed on the grid of triode V2 also rises and becomes more positive. The increasing plate current flow through cathode resistor R4 causes the cathode voltage on triode V2 to increase, also in a positive direction. This increasing positive voltage is fed back through capacitor C2 to the junction of resistors R2 and R3, aiding the voltage across resistor R3, and effectively increasing the voltage applied to the R-C circuit. Thus , as capacitor C3 charges, the applied voltage is effectively increased so that the voltage appearing across resistor R3 remains constant, instead of dropping as the charge increases. Since the capacitor always charges to 63 percent of the voltage across the resistor in each time constant, and the resistor voltage remains constant, the capacitor charges the same amount each time constant, or in other words, at a linear rate.

When the negative input gate ends, the grid bias on triode V1 returns to zero and the tube again begins to conduct heavily. The low impedance of the conducting tube effectively shunts (shorts) capacitor C3, and the capacitor discharges very quickly through the tube. As capacitor C3 discharges, the voltage on the grid of triode V2 decreases, causing the voltage on the cathode to decrease accordingly. The cathode voltage drops to the quiescent value, and the circuit remains in the quiescent state until the beginning of the next input gate.

Thus, the output voltage of the bootstrap sweep generator rises at a linear rate during the input gate, and returns quickly to the quiescent value at the end of the input gate. It remainsat the quiescent level until the next gate is applied.

FAILURE ANALYSIS.

No Output. A defect in nearly any component in the bootstrap sweep generator may cause a no-output condition. Therefore, it is good practice to use an oscilloscope to locate the defective portion of the circuit. First, use the oscilloscope to observe the input gate to make certain that the proper input is applied. If the correct input gate is observed, use the oscilloscope to observe the signal on the grid of triode V1. No negative gate at this point indicates either an open in capacitor C1 or a short in resistor R1. Use an ohmmeter to check these components. If the normal waveform is observed on the grid of triode V1, observe the waveform on the plate of the tube. No signal on the plate of triode V1 indicates a defect in capacitor C3, resistor R2 or R3, or in the tube itself. If checking capacitor C3 with an in-circuit capacitor checker, and resistors R2 and R3 with an ohmmeter, does not reveal a defective component, triode V1 is probably at fault, and should be replaced with a tube that is known to be good. If the sawtooth waveform is observed on the plate of triode V1, the trouble is either a defective cathode resistor, R4, or a faulty cathode-follower tube, V2. Check resistor R4 with ohmmeter for the correct resistance valve. If no defect is found, triode V2 is probably at fault. Replace the tube with one known to be good.

Low Output. A sawtooth output of incorrect amplitude may be caused by low plate-supply voltage, or by a circuit defect which affects the charge time of capacitor C3. First, use a high-resistance voltmeter to measure the plate-supply voltage to be certain that the power supply is not at fault. If the correct plate-supply voltage is observed, use a capacitance analyzer to check capacitor C3 for the proper value and an ohmmeter to check resistor R2 and R3 for the proper values. If no defective component is found, triode V1 is probably at fault. Replace it with a tube known to be good.

Poor Linearity. If the linearity of the sawtooth output is poor, probably either capacitor C2 or resistor R4 is at fault. Use an in-circuit capacitor checker to check the capacitor for a shorted or open-circuited condition, and an ohmmeter to check the resistor for the correct value. If neither of these components is defective, triode V2 is probably at fault, and should be replaced with a tube that is known to be good.

TRIODE TRAPEZOIDAL-WAVE SWEEP GENERATOR.

APPLICATION.

The triode trapezoidal-wave sweep generator produces a trapezoidal waveform for use as the sweep voltage in television sets, radar equipment, test and other electronic equipment using electromagnetic cathode-ray tube displays.

CHARACTERISTICS.

Employs a triode as a switch to control the charge and discharge of a series R-C circuit to produce the output.

Requires a negative input gate.

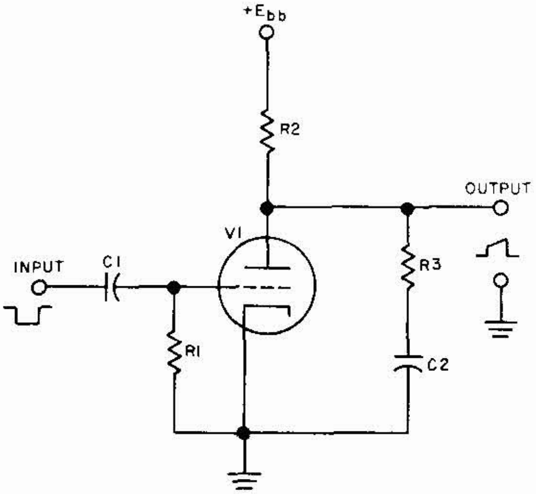
Output is a series of trapezoidal waves.

Sweep duration and sweep-repetition period are determined by the characteristics of the input gate.

CIRCUIT ANALYSIS.

General. The deflection coils of an electromagnetic cathode-ray tube require a sawtooth wave of current to produce a linear sweep across the face of the tube. Because of the inductance and resistance characteristics of the deflection coils, a trapezoidal voltage waveform must be applied across the coils to produce the desired linear sawtooth wave of current through them. The triode trapezoidal-wave sweep generator discussed below produces such a voltage waveform. Since the trapezoidal wave is essentially a sawtooth wave superimposed on a rectangular wave, the triode trapezoidal-wave sweep generator is similar to the triode sawtooth-wave sweep generators discussed previously in this section of the Handbook.

Circuit Operation. The accompanying circuit schematic illustrates one type of triode trapezoidal-wave sweep generator.

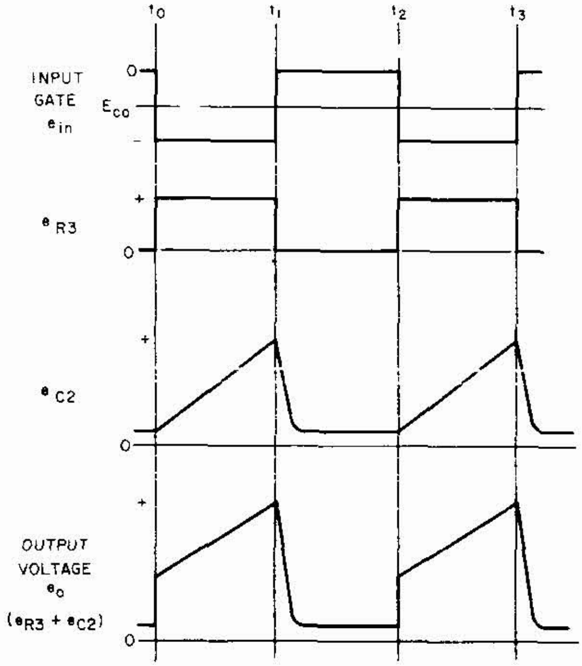


Triode Trapezoidal-Wave Sweep Generator

Capacitor C1 and resistor R1 form a conventional R-C input coupling network used to couple the input gate to the grid of triode V1. Triode V1 acts as a switch to control the charge and discharge of capacitor C2. The charge time of the capacitor is determined by the time constant of the R-C circuit made up of resistors R2 and R3 connected in series with capacitor C2. The trapezoidal output waveform is taken from the plate of triode V1 (across the series combination of capacitor C2 and resistor R3).

In the quiescent state (with no input gate applied to the circuit), contact bias is applied to the grid of triode V1; consequently, the tube conducts very heavily. Since triode V1 conducts nearly at plate-current saturation, the voltage drop across plate resistor R2 is very large and the effective plate voltage is very low. Capacitor C2 charges through resistor R3 to the low value of voltage existing across the tube, and the circuit remains in this quiescent state so long as no input gate is applied. The quiescent output is the small constant voltage across capacitor C2.

A negative input gate, such as that shown in the accompanying illustration of theoretical waveforms, must be applied to the circuit to produce a trapezoidal output waveform.



Theoretical Waveforms

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The negative gate is applied through coupling capacitor C1 to the grid of triode V1, and is of sufficient amplitude to drive the tube below plate-current cutoff. Consequently, plate current ceases to flow, and the plate voltage attempts to rise instantaneously to the plate-supply value. However, since the series combination of capacitor C2 and resistor R3 is connected across the tube, the plate voltage rises in accordance with the charging action of the R-C circuit made up of resistors R2 and R3 and capacitor C2. When triode V1 first cuts off (time t_0 on the waveform illustration), only the small quiescent charge is present on capacitor C2, and the remainder of the supply voltage appears instantaneously across the series combination of resistors R2 and R3. Thus, at time t_0, the voltage across resistor R3 (e_{R_3}) rises instantaneously from nearly zero to a high positive value determined by the total resistance in series with capacitor C2 and the power supply. The voltage drop across resistor R3 produced by the initial flow of charging current to capacitor C2 determines the amplitude of the voltage step shown as e_{R_3} at time t_0 in the waveform illustration. At the same time, capacitor C2 charges from the quiescent value to the effective plate voltage value, and the voltage across it (e_{C_2}) increases toward the plate-supply value. Though the capacitor charges at an exponential rate, only the initial (relatively straight) portion of the capacitor charging curve is used; therefore, the capacitor charge (from time t_0 to time t_1) is nearly linear. The output from the circuit is taken across the series combination of resistor R3 and capacitor C2, and is the sum of the voltages across these components. The output voltage, therefore, rises instantaneously from the quiescent value to a more positive value at the beginning of the input gate (time t_0), and then increases at a nearly linear rate until the end of the input gate (time t_1).

When the negative input gate ends (time t_1), the grid bias on triode V1 returns to zero, and the tube again conducts heavily. The low impedance of the conducting tube effectively shunts (shorts) the series combination of resistor R3 and capacitor C2, and the capacitor discharges very quickly through the resistor and the conducting tube. As capacitor C2 discharges, the voltagee across it decreases from maximum to the quiescent value. The voltage remains at this value until the beginning of the next input gate.

FAILURE ANALYSIS.

No Output. An incorrect input gate, a defective input coupling network (C1, R1), an open plate resistor (R2), a defective tube (V1) or a lack of plate-supply voltage may cause a no-output condition. First, use an oscilloscope to observe the input gate waveform to be certain that the correct input signal is applied. If the normal input gate is present, observe the waveform on the grid of triode V1. No input gate at this point indicates either an open coupling capacitor (C1) or a shorted grid resistor (R1). Use an ohmmeter to check these components for defects. If the correct input gate is observed on the grid of triode V1, use a high-resistance voltmeter to measure the voltage on the plate of the tube. If no plate voltage is present, the trouble may be either a lack of plate-supply voltage or an open plate resistor (R2). Measure the plate-supply voltage with the high-resistance voltmeter, and check resistor R2 with an ohmmeter. If the correct voltage is measured on the plate of triode V1, the tube is probably at fault and should be replaced with one that is known to be good.

Distorted Output. An output waveform with poor linearity or low amplitude may be caused either by a defective tube or by a change in value of resistor R2, R3, or capacitor C2. Use an ohmmeter to check the values of resistors R2 and R3, and a capacitance analyzer to check the value of capacitor C2. If no defective component is found, triode V1 is probably at fault and should be replaced with a tube that is known to be good.

Incorrect Output Waveshape. An output waveform of sawtooth shape (with no initial step) will result if resistor R3 is shorted, while an initial step of incorrect amplitude indicates a change in value of resistor R3. In either case, the resistor must be replaced.

An output waveform of square-wave shape may be caused either by an open or short-circuited condition in capacitor C2 or by an open in resistor R3. Use an ohmmeter to check resistor R3, and an in-circuit capacitor tester to check capacitor C2, and replace the defective component.

PART B. SEMICONDUCTOR CIRCUITS

SAWTOOTH-WAVE CIRCUITS.

The operation of the sawtooth-wave sweep-generator circuits described in the remainder of this section is similar to that of the electron-tube sweep-generator circuits (see Part A of this section). Although electron tube sweep-generator circuits are divided into two classes, the vacuum (hard) tube sweep-generator and the gaseous (soft) tube sweep-generator, they are not so divided for semiconductors. Actually, the semiconductor sweep-generator circuits are analogous to the gaseous (soft) tube circuits, utilizing special transistors which are comparable to the thyratron type of electron tube.

Two general types of transistors are used, that is, the unijunction or double-based diode with three terminals and the four-layer diode having only two terminals. These transistors may be used as switches or as relaxation oscillators, and can produce other than sawtoothed waveforms if desired. The discussion in this section, however, will be limited to the production of sawtoothed waveforms by use of the relaxation oscillator form of circuit. The advantages and utility of these semiconductor circuits lie in their extreme simplicity and their use of relatively few components; plus the fact that one unijunction is considered the equivalent of two normal transistors. In most cases only a capacitor and a transistor are required to produce a sawtooth sweep. Where adjustable frequencies of periodic recurrence are desired, a resistor may be added, with the RC combination governing the period of oscillation. The basic principle of operation is that of charge and discharge of a capacitor, controlled by the semiconductor operating as a negative resistance oscillator.

Operation is normally restricted to frequencies from a lower frequency of approximately one or two cycles per minute to an upper frequency which lies between 500 kc and 1 megacycle for presently available transistors. In some experimental units the upper frequency has exceeded 1 mc, but not 3 mc. Although the upper frequency limit of the transistor is not as high as that of the electron tube, the range is sufficient for normal applications of sawtooth waves. The recovery time is shorter for semiconductors than the deionization time of tubes (on the order of 30 microseconds as compared with 100 microseconds or more), which offers some advantage over the electron tube.

UNIJUNCTION (DOUBLE-BASE DIODE).

APPLICATION.

The unijunction transistor is used as a switch or as an oscillator to produce pulses, amplify pulses, and produce a sawtooth or triangular waveform for sweep generators. It is used mostly in computers, memory circuits, and electronic clocks, but it may be used wherever the solid state equivalent of the thyratron tube is needed.

CHARACTERISTICS.

Is the equivalent of two normal junction transistors in power handling ability (one unijunction transistor effectively replaces two standard transistors).

Uses the stable N-type open-circuit negative-resistance characteristics inherent in its construction to provide astable, bistable, or monostable operation.

Any of its three terminals may be used as an input trigger connection or output load connection.

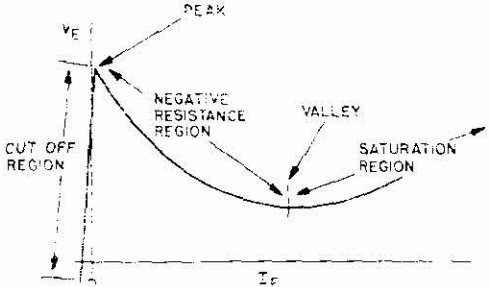
Provides two different output levels for one input signal, and may be similarly or oppositely polarized.

Is temperature-sensitive, with an almost constant linear response (base resistance changes) from -40 to approximately +150 degrees C.

Is photosensitive, and may be made to respond to changes in illumination.

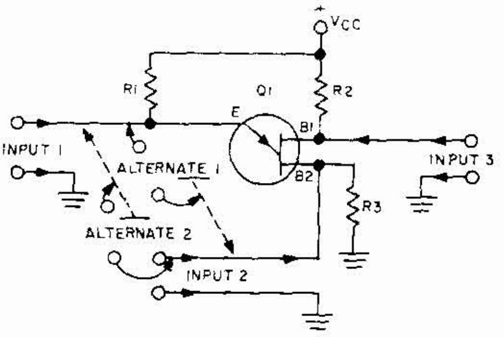
CIRCUIT ANALYSIS.

General. Read Unijunction Transistor, paragraph 3.6.3.3 in section 3 for background before proceeding with the circuit discussion. By virtue of its construction, the unijunction transistor is basically a negative-resistance device, as indicated by the emitter voltage-current characteristic illustrated below. By setting the load line so that it touches only one point on the curve (operation in cutoff or saturation regions only), the unit may be made a one-shot device. By operating only over the negative-resistance portion, on-off operation (oscillation) can be obtained and by operation in all three regions, flip-flop operation may be obtained. These characteristics are inherent in the transistor, and may be obtained if the proper bias and load connections are made. In this circuit discussion we shall be concerned only with operation in the **negative-resistance region** with the transistor operating as a relaxation-type oscillator, to produce a sawtooth (sweep) waveform.



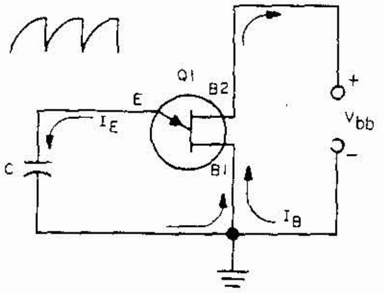
Emitter Characteristics

As constructed, [illegible] three points [illegible] which an output may be taken or to which an input may be applied [illegible] base 1, from base 1 to emitter or ground, and from base 2 [illegible] as shown in the accompanying [illegible]. When any of these points are used as an input, the other two points will supply an output. As conventionally used, a negative [illegible] trigger is supplied to B2, with a synchronized sawtooth output between emitter and ground, and with a positive pulse available at B1. When synchronization is not employed, the unit will operate as a free-running oscillator at a frequency set by the circuit [illegible] constants, either [illegible] internal and external.

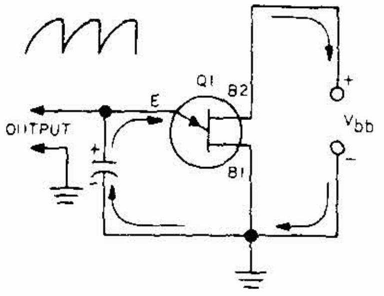


Input and Output Points

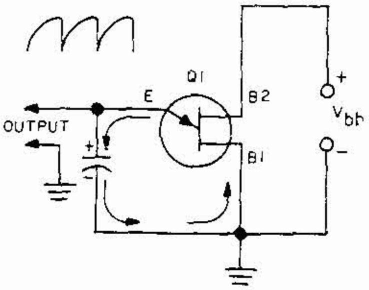
Circuit Operation. A simple sawtooth generator circuit using a unijunction transistor is shown in the accompanying figure. Note that only the unijunction transistor, a capacitor, and a power supply are necessary to produce the sawtooth waveform. With the power supply connected, electron flow is from base 1 to base 2, thus placing an initial reverse bias on the PN junction. With the capacitor connected between emitter and ground, a small amount of reverse current flows through the PN junction because of a flow of hole current from the emitter to base 2. The capacitor charges slowly through the path shown in the following figure. The rate of charge depends on the time constant, which is equal to the product of the capacitance of C and the internal resistance of the reverse-biased junction. As C charges, the positive d-c voltage across it rises. When this voltage is greater than the voltage gradient opposite the P-type material, the PN junction becomes forward-biased and the capacitor discharges very rapidly. (This corresponds to the ionization point or voltage of the gaseous thyratron tube.) This action is caused by a heavy electron flow from base 1 to the emitter and a heavy hole flow through the P material of the junction, which causes an electron flow out of the emitter as shown in the following figure. Thus, the capacitor is effectively short-circuited through the PN junction. The time of discharge is determined by the capacitance of C times the forward resistance of the PN junction. Since the forward resistance is very low (on the order of 5 ohms), it is essentially equivalent to a short circuit. After capacitor C discharges, the voltage across C is too small to maintain the forward bias (this corresponds to the deionization point or voltage of the gaseous thyratron tube); the reverse bias again resumes control, charging the capacitor through reverse-leakage current, as previously indicated, and the cycle is repeated. This slow charging and rapid discharging of capacitor C produces the sawtooth output waveform.



Basic Sawtooth Generator

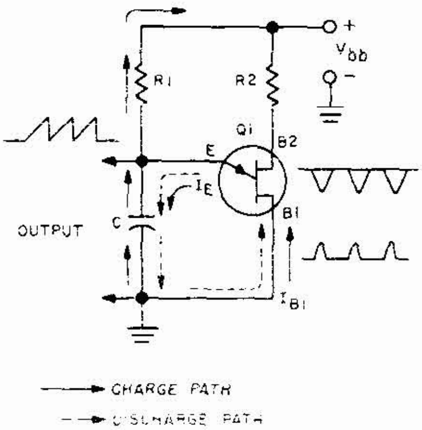


Charge Path



Discharge Path

The recurrence rate of the basic circuit just discussed is fixed by the inherent base leakage resistance of the transistor plus the value of capacitance used. To ensure stable operation at the desired sweep rate, and to provide protection against thermal runaway, an emitter resistor and a base 2 resistor are usually used, as shown in the following schematic. The operation of this circuit is identical to that of the basic sweep generator previously discussed except for the change introduced by the addition of R1 and R2. During the time of heavy conduction (deionization period), the portion of the interbase region between the emitter and base 1 is a very low resistance, whereas the portion between the emitter and base 2 is of high resistivity. Therefore, practically all the power supplied by the interbase power supply is dissipated across the narrow region near base 2. In the absence of R2, a relatively



Stabilized Sawtooth Generator

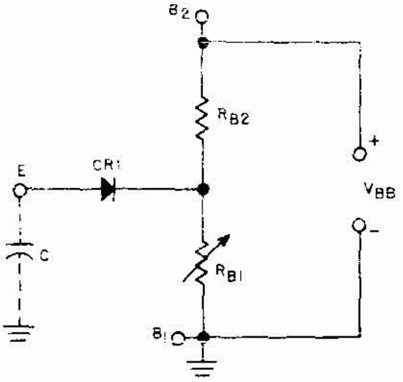
heavy electron current flows through the base 2 region and causes heating of this small semiconductor area. As a result, this thermal effect causes an increased electron flow through the base 2 to emitter portion of the bar. As the heat is built up by current flow, more and more electron current flows through the bar because no external resistance is provided to limit the flow. Thus a local hot spot is produced. Since this thermal action is accumulative, thermal runaway can occur and destroy the transistor. The use of R2 in the position shown provides sufficient current limiting to prevent the formation of the hot spot and any possibility of thermal runaway. While the circuit is sensitive otherwise to thermal variations, any thermally produced current flow can never be as great as that produced at the location of the hot spot when no limiting resistance is employed. No other form of protection is needed to prevent thermal failures.

By adjusting the value of R1, the emitter voltage can be controlled and the operating point (where the emitter changes from reverse bias to forward bias) fixed for the desired operating voltage. By proper design, if the resistance of R1 is less than that of the internal reverse leakage resistance of the base bar, the charging of sweep capacitor C is determined mainly by the value of R1. Thus, variances produced by production tolerances in unijunction transistors can be minimized, and the sweep time controlled independently of the transistor. If required, R1 can be made variable to provide an adjustable sweep. Regardless of the arrangement used, however, the value of R1 together with that of C determine the frequency of the sweep oscillations.

In this improved circuit, then, operation occurs through the charging of capacitor C through R1. When the voltage across C reaches the breakdown voltage, the initially reverse-biased junction breaks down temporarily, becomes forward-biased, and discharges the capacitor through the low base 1 emitter resistance. (This action is similar to that of the gaseous thyratron tube at the point where the voltage reaches the ionization level.) When the capacitor discharges to the point where the voltage across the emitter junction can no longer sustain a forward bias, the transistor stops conducting, and the original reverse-bias condition again exists. (This action is similar to that of the gaseous thryratron tube, which stops conduction automatically when the voltage across the tube reaches the deionization point or level and is insufficient to sustain ionization of the gas.)

Detailed Analysis. Before proceeding with the following discussion, be certain to read the explanation of the construction and operation of the unijunction transistor given in Section 3, paragraph 3.6.3.3, of this Handbook.

A simplified equivalent circuit for the unijunction transistor may be developed as shown in the accompanying figure.

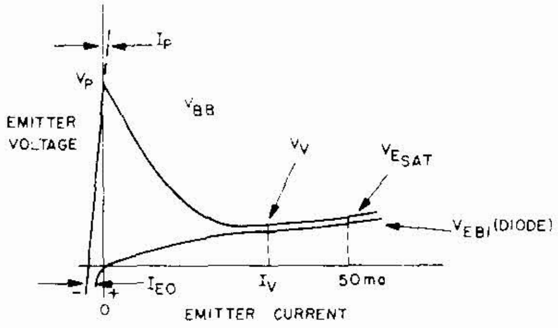


Simplified Equivalent Circuit

Diode CR 1 can be considered to be a conventional junction diode, with R_{B2} representing the resistance of base 2, and R_{B1} the resistance of base 1; R_{B1} is shown as variable since it does vary as a function of the emitter base 1 current (the greater the current, the lower the resistance, and vice versa).

Assuming that the capacitor is not connected to the emitter and that both R_{B1} and R_{B2} are of a high value, it is clear that the resistors form a voltage divider across the base supply, V_{bb}. Thus, a positive potential exists at the cathode of the diode, and the diode is reverse-biased. The current flow through base 1 and base 2 will be that permitted by the conductivity of the base bar (the resistance of R_{B1} plus R_{B2}), and the emitter current will be zero (cutoff). When the capacitor is connected between emitter and ground, it charges exponentially through the reverse leakage current of the diode. The charge path is from ground through the capacitor, diode CR_1, and R_{B2}. At this time the value of R_{B1} is high. As the capacitor charges, the emitter voltage increases and the reverse bias across the junction diode is reduced. Examine the emitter characteristic curve which follows.

With the emitter biased off, the current due to reverse leakage (I_{eo}) can be considered negative as shown in the figure. As the capacitor voltage builds up it reaches the peak value of emitter voltage at zero emitter current. At



Static Emitter Characteristics

this peak point the reverse bias is no longer sufficient to prevent conduction, and emitter (positive) current flows. As soon as emitter current flows capacitor C1 starts to discharge, and the forward resistance of the junction is decreased; this action becomes regenerative, multiplying the discharge current in a somewhat exponential fashion. Once started, this action cannot be reversed or stopped until the lower voltage level (deionization point) is reached. As this current increases, the diode forward resistance decreases and the emitter voltage decreases. The region of decreased emitter voltage with increased emitter current is due to negative resistance, which is the phenomenon upon which the operation of this unit is based. The negative resistance is caused by the injection of holes into the base bar with forward bias change causing increased conductivity between the emitter and base 1 portion of the bar, with base 2 current remaining essentially constant. The sequence of action is such that each enhances the other. That is, as the forward resistance is decreased, so is the amount of reverse bias decreased, and the emitter current increases similarly. This cumulative action continues until the valley point is reached and the base enters the saturation region. At this point any increase in emitter current merely causes an increased drop in the emitter base 2 portion of the bar. If operation is allowed to enter this saturation region, the unit will merely rest in a stable conducting condition with a fairly low base 1 resistance.

The turn-off action of the unijunction transistor is initiated by the dropping emitter potential as capacitor C discharges through base 1. When the valley point on the curve is reached, the emitter voltage (which is produced by the remaining charge in the capacitor) is insufficient to continue conduction. More emitter voltage would be needed to produce more current, or the emitter voltage would have to remain constant at the valley point to keep the same value of current. Since the capacitor continues to discharge below this point, the initial condition of reverse-biased diode then exists. This action is also regenerative, since a reduction of conductivity of the bar (an increase in resistivity) reduces the amount of current it will carry, and the forward resistance is effectively increased. The increased forward resistance further reduces the conductivity of the bar; thus, the path between emitter and base 1 is quickly reduced to zero current or cut-off, whereupon the reverse bias resumes control, holding until the capacitor is again charged to the forward breakdown voltage. In this respect the unijunction diode operates differently from the normal PN junction. The typical response of a normal diode is shown at the bottom of the static emitter characteristic for comparison. In this case, once current flow is initiated, current flow continues in a relatively steady manner as long as the voltage is applied. The ability of the unijunction transistor to revert from a reverse-biased condition to a forward-biased condition and back again under control of the voltage levels applied to its elements is inherent in its construction. While the previous simplified diode representation was used to help explain its operation, it should be understood that a conventional diode connected schematically with two resistors, as illustrated previously, will **not** operate as a unijunction transistor.

FAILURE ANALYSIS.

No Output. An open-circuited capacitor will cause the emitter circuit to be open and produce a no-output condition. The few components involved may be quickly checked by a resistance or continuity test with a high-resistance volt-ohmmeter. If the components appear to be normal, the trouble can only be in the power source or in the transistor itself. Substitution of a known good transistor would be necessary to determine whether it is defective, since there is no other simple check possible. A short-circuited capacitor would also prevent the circuit from operating, but this is not necessarily true of any of the other components, as the circuit usually will operate with the capacitor alone. Where the components and transistor appear to be normal, a poorly soldered joint or broken wiring might be suspected.

Low Output. Poorly soldered joints or defective resistors can cause low output, as can a defective power supply or transistor. Resistance and voltage checks will determine whether the components are defective. Use of an oscilloscope to examine the waveforms on the emitter, base 1, and base 2 elements should help isolate the defective portion of the circuit. With a sawtooth output, there should be a negative pulse on base 2, with a similarly shaped but smaller-amplitude current pulse in the base 1 circuit. (Place a 100-ohm resistor in series with base 1 and observe the voltage waveform produced by the base current.) Capacitor leakage may prevent the circuit from operating properly, or may reduce the amplitude of the output waveform. Leakage may be suspected if the recurrence rate is different from the original rate. (A change in emitter resistor R1 can also produce a similar condition.)

Distorted Output. The shape of the sawtooth sweep will depend upon the capacitor to a great extent. If only a small portion of the capacitor charge is used, it will be linear, otherwise, the waveform will curve at the top because of the exponential discharge of the capacitor. The values of the components and voltages applied will also determine the linearity of the output waveform. Operation at too high a frequency for the transistor used will produce a rounding off of the waveform and, if excessive, produce a sine wave. Check the waveform with an oscilloscope. The recovery time is determined by the base 1 current pulse width and the sweep capacitor value. If the recovery time is excessive, a triangular wave may result.

FOUR-LAYER DIODE.

APPLICATION.

The four-layer diode is used to generate a sawtooth (sweep) voltage waveform for applications where the output waveshape is not critical, and where an extremely simple circuit is desired.

CHARACTERISTICS.

Acts as a switch to control the charge and discharge of a series R-C circuit.

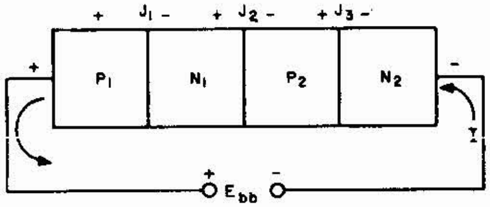
Output is a sawtooth voltage waveform.

Output frequency is determined by the values of resistance and capacitance in the R-C circuit.

Output amplitude is determined by the characteristics of the four-layer diode.

CIRCUIT ANALYSIS.

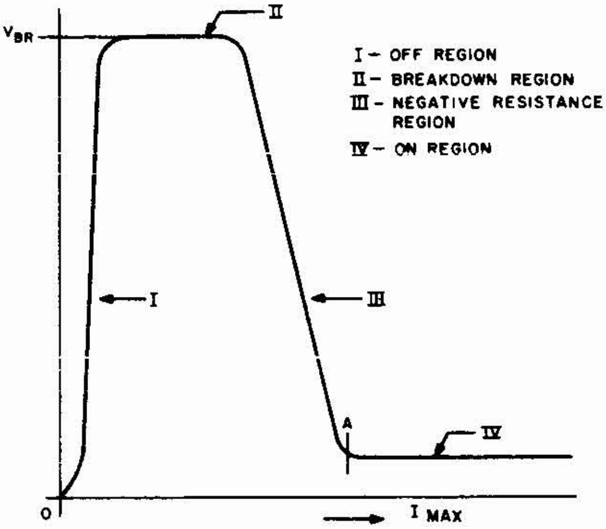
General. The four-layer diode is a two-terminal semiconductor device consisting of four alternate layers of P-type and N-type silicon. The accompanying pictorial diagram shows the construction and biasing of the diode.



Four-Layer Diode

For convenience in discussing the four-layer diode, its three PN junctions are labeled J_1, J_2, and J_3. To bias the diode correctly, the positive battery terminal is connected to the P-type diode terminal, and the negative battery terminal is connected to the N-type diode terminal. With the bias voltage applied is this manner (layer P_1 positive with respect to layer N_2), a voltage gradient is set up along the diode as shown by the polarities placed above the junctions on the four-layer diode illustration. The voltage gradient forward-biases junctions J_1, and J_3, and reverse-biases internal-junction J_2. Since a forward biased junction exhibits very low resistance and a reverse-biased junction exhibits very high resistance, junction J_2 (the reverse-biased junction) primarily determines the current flow through the diode. Therefore, the action of junction J_2 determines, to a great extent, the operation of the four-layer diode.

Over the first portion (region I) of the accompanying dynamic transfer characteristic curve, which covers from zero level to breakdown voltage VBR, maximum current flow through the diode is limited to the value of the minority carrier current flowing through reverse-biased junction J_2.

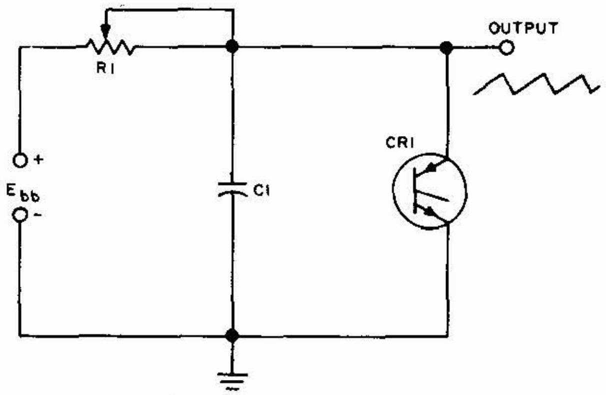


Dynamic Transfer Characteristic Curve

Therefore, over region I of the characteristic curve (also known as the **off** region), diode current flow remains at a relatively constant but low value while the applied input voltage increases. When the voltage applied to the diode exceeds voltage VBR, an action similar to the avalanche breakdown in a Zener diode occurs in junction J_2. That is, the applied voltage temporarily is relatively constant while the current increases (region II on the characteristic curve). Although the breakdown action is not completely understood at the present state of the art, once breakdown occurs and current increases, the characteristic curve passes through another region, known as the negative resistance region (region III), where the voltage across the diode rapidly decreases as the current through it increases. (This corresponds to the action in a gas-filled electron tube which breaks down at the ionization point and passes a heavy current at a low voltage.) At point A on the curve, the end of the negative resistance region is reached, and the voltage across the diode remains relatively constant throughout the **on** region (region IV). (This corresponds to the action in a gas-filled electron tube which, one broken dow, operates at a level slightly above the deionization point until the applied voltage drops below this point.)

Although the four-layer diode has many applications, it is most widely used as a switch with two stable states. To use the diode as such a switch, it is operated in regions I and IV of the characteristic curve. The diode remains in the high resistance or **off** state (region I) until the bias voltage exceeds the diode breakdown voltage, VBR. The diode then switches to the low resistance or **on** state (region IV) and remains in this state until the bias voltage drops below the diode turnoff voltage level. It then switches back to the **off** state. The four-layer diode is operated in this manner to control the charge and discharge of an R-C circuit to produce a sawtooth-wave sweep voltage output.

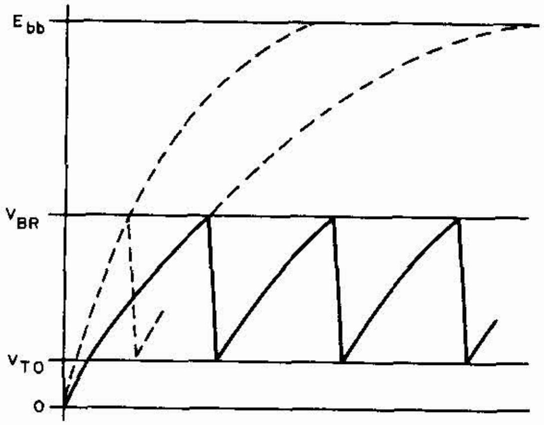
Circuit Operation. The accompanying circuit schematic illustratee a sawtooth-wave generator using a four-layer diode and only two other components.



Four-Layer Diode Sweep Generator

The power supply (E_{bb}) is connected directly across the series R-C circuit made up of capacitor C1 and resistor R1. The four-layer diode, CR1, is connected in parallel with capacitor C1, and controls the charge and discharge of the capacitor. The sawtooth waveform is taken from across the parallel combination of capacitor C1 and diode CR1.

When voltage is initially applied to the circuit, diode CR1 is in the high resistance **off** state, (because of the reverse bias applied to internal junction, J_2), and capacitor C1 begins to charge through resistor R1 toward the supply voltage value. If the capacitor were allowed to charge fully, the voltage across it would increase to the supply voltage value at an exponential rate, as shown by the dashed curve in the accompanying output voltage waveform illustration.



Theoretical Output Voltage Waveform

However, when capacitor C1 charges to the breakdown voltage of diode CR1 (voltage V_{BR} on the waveform illustration), the diode breaks down (effectively forward biasing internal junction J_2) and switches to the low resistance **on** state. Since diode CR1 is connected in parallel with capacitor C1, the diode effectively shunts capacitor C1 and causes it to discharge very quickly. As capacitor C1 discharges through the conducting diode, the voltage across the capacitor decreases until it drops below the turnoff voltage of the diode (voltage V_{TO}). At this time, the internal junction is again reverse-biased and the diode switches back to the **off** state, and the capacitor again begins to charge through resistor R1. Thus, capacitor C1 alternately charges relatively slowly through resistor R1 and discharges quickly through diode CR1. Since capacitor C1 charges only during the initial portion of the capacitor charging curve (about 10% of the total time available), the resulting output voltage across the capacitor is a fairly linear sawtooth waveform.

The amplitude of the sawtooth output waveform is determined by the characteristics of the four-layer diode. Since the sawtooth amplitude is equal to the difference between the breakdown voltage (V_{BR}) and the turnoff voltage (V_{TO}), and since these voltages are constant for any particular diode, the output amplitude is fixed. The only way that the output amplitude may be changed is by using a four-layer diode with different breakdown and turnoff voltage characteristics.

The frequency of the sawtooth output waveform is determined by the charge time of capacitor C1, and therefore by the time constant of the R-C circuit made up of the capacitor and resistor R1. Resistor R1 is usually made variable so that the output sweep frequency may be varied. Decreasing the value of resistor R1 decreases the time constant of the R-C circuit, which decreases the time required for capacitor C1 to charge to the breakdown voltage of diode CR1. The resulting waveform (shown by the dotted curve on the waveform illustration) is a sawtooth wave of shorter time duration than the original sawtooth wave, and therefore one of higher frequency. Increasing the value of resistor R1 has the opposite effect, and decreases the output sweep frequency.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of the standard 20,000 ohms-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since the diode may be forward-biased and break down, causing a false low-resistance reading.

No Output. A defect in any circuit component, or a lack of supply voltage may cause a no-output condition. Because of the simplicity of the circuit, the trouble can easily be located by making several quick voltage and resistance checks. First, use a vacuum-tub voltmeter to measure the supply voltage. If the correct voltage is measured, use an ohmmeter to check resistor Rl for an open or short circuited condition. Next, use an in-circuit capacitor checker to check capacitor Cl for defects. If these checks fail to locate a defective component, diode CR1 is probably at fault and should be replaced with one that is known to be good.

Distorted Output. A distorted sawtooth output waveform may be caused by low supply voltage, by changes in value of the components in the R-C circuit (C1,R1), or by a defective diode (CR1). First, use a vacuum-tube voltmeter to measure the supply voltage to determine that the power supply is not at fault. Next, use an ohmmeter to check the value of resistor R1, and use a capacitance analyzer to check the value of capacitor C1. If no defective component is found, diode CR1 is probably at fault. Replace it with a diode that is known to be good.

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