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# OSCILLATOR CIRCUITS

by Thomas M. Adams

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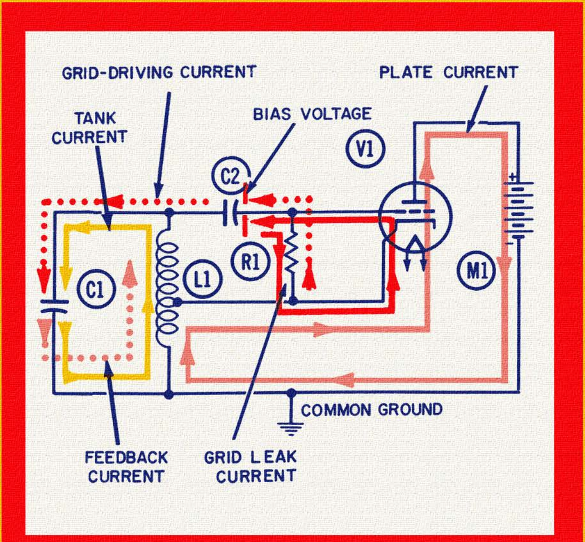

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# Basic Electronics Series
# OSCILLATOR CIRCUITS

**By Thomas M. Adams**
**Captain, United States Navy**

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# PREFACE

The objective of this book, and of the subsequent volumes in this series, is to provide an understanding of *how* standard electronic circuits operate. Fundamentally, there are only a few basic actions involving electrons. And although these actions occur over and over in all circuits, each has acquired a multiplicity of names, which are not usually descriptive of action but of application. This nonconformity of names and terminology for electronic actions is a formidable barrier to the study of electronics.

Like many that have gone before it, this book is represented as a "nonmathematical" treatment. However, much of the terminology of electronics is of necessity mathematical and quite abstract. Thus, the omission of complex formulas in a text does not make it "nonmathematical" if it still contains words and phrases understandable only to those having the necessary mathematical background. It is practically impossible to write a book on electronics without using many such words and phrases, but in every instance the terms used in this book have been clarified through the use of illustrations which portray all identifiable currents and voltages in a somewhat unique manner.

Multiple colors are used to show what takes place during successive half-cycles (or successive quarter-cycles) during the operation of each circuit under consideration. Every electron current is identified and discussed in detail, so that you can easily follow its path through all parts of the circuit. Frequently, more than one current will flow simultaneously through a component. An engineer or mathematician may rightly be interested in the *total* current through such a component, and would arrive at this figure mathematically. On the other hand, the student aspiring to become a technician or engineer must know more than the exact amount of total current or voltage; he must also be able to "visualize" each of the significant currents and voltages in order to learn how one affects the other. This ability to visualize what is happening inside a circuit can be accomplished by almost anyone, even without a mathematical background.

Electron currents in the various circuits have been treated much like "moving parts" of a machine. If we wanted to know how a piece of machinery worked, the simplest way would be to observe a cutaway model as it goes through several cycles of operation. Through the use of the illustrations in this book, we can "look inside" the individual components, and "see" what is happening. Thus, the circuit diagrams used herein are more than just abstract drawings of circuit *connections*—they are concrete "working models" of circuit *actions* in diagram form.

It is our hope that this series of texts will find acceptance at each of the three important educational levels now concerned with the teaching of electronics—high schools, technical and vocational schools, and undergraduate levels in college engineering. The material is neither too advanced for high schools, nor too elementary for colleges. Students at any of these educational levels have one great desire in common—to achieve an early understanding of *how circuits operate*. The ability of an electronics student to visualize what is happening inside electrical components is an essential building block for later studies directed either toward design engineering, or toward maintenance, repair, and usage of electronic equipment.

The book is recommended especially for engineering students in fields other than electronics. Because electronics is utilized in many fields, engineers of all categories should have a basic understanding of electronic circuit actions and applications. This series of books is intended to convey such an understanding.

Finally, the book is respectfully recommended to executives in industry. In myriad ways, management is becoming more and more involved with electronics. A greater understanding of its basic principles—without the necessity for an intense study of electronics engineering—will be of inestimable value to persons at the managerial level.

The writer is indebted to many individuals in the educational field for their guidance and help in reviewing some of the original drawings for this series. Among those most helpful are Professors G. F. Corcoran, Joseph Weber, Henry Reed, and J. H. Rumbaugh of the University of Maryland; Professor J. C. Michalowicz of Catholic University; Professors E. R. Welch, H. R. Branson, W. K. Sherman, and K. T. Chu of Howard University; Professor N. T. Grisamore of George Washington University; Lou Godla of the Fairfax County (Va.) high-school system; Donald Ingraham and John Johnson of the Arlington County (Va.) high-school system; Keith Johnson of the District of Columbia high-school system; E. H. Reitzke, president of Capitol Radio Engineering Institute, and Charles Devore and Latti Upchurch of the same Institute; Jamie Cruz of Emerson Electronics Institute, and the Institute staff; and David Lien of the Grantham School of Electronics. Also very helpful and encouraging were Dr. Hilary J. Deason of the American Association for the Advancement of Science, and my long-time friend and associate, Captain Walter H. Keen, USN, now in the Office of Naval Research.

I am also thankful for the encouragement and assistance rendered in countless ways by my wife, to whom this work is gratefully dedicated.

THOMAS M. ADAMS

April, 1961

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## Chapter 1

# INTRODUCTION

An oscillator is any nonrotating device which generates a signal at a frequency determined by the constants in the circuit. Oscillators can be placed into almost as many categories as there are oscillators. One method of classification is by the *type* of waveform produced. A second is by the *frequency* of the waveform.

Oscillator waveforms can be broadly classified into one of two types—the *sinusoidal, or harmonic;* and the *nonsinusoidal, or nonharmonic.* A sinusoidal waveform, more familiarly known as a *sine wave,* is nothing more than a graphical representation of simple harmonic motion. Most oscillators in everyday life are sinusoidal, or harmonic. Examples are the pendulum of a clock, the spring of a watch, a child's swing, or the piston of a gasoline or steam engine. All the oscillations mentioned must be reinforced or replenished periodically, or they will die out because of natural losses. The pendulum of a clock, for instance, is reinforced once each cycle by a small amount of energy released at the appropriate time by the clock mechanism.

The harmonic oscillators discussed in this volume are further classified according to the frequency range within which they operate—either the audio- or radio-frequency range. These circuits are as follows:

*Radio-frequency*
  Crystal oscillator.
  Hartley oscillator.
  Colpitts oscillator.
  Tuned-plate–tuned-grid oscillator.
  Electron-coupled oscillator.

*Audio-frequency*
  Phase-shift oscillator.

Nonharmonic oscillators, also called *relaxation* oscillators, are discussed in this volume as follows:

Thyratron sawtooth generator.
Blocking oscillator (pulse generator).
Multivibrators.

The term *relaxation oscillator* is derived from a particular property of resistance-capacitance combinations: A capacitor is "charged" with a positive or negative voltage and then permitted to "discharge" through a resistance. This process of discharging a capacitor through a resistive path gave rise to the descriptive terms *relaxing* and *relaxation.*

There is a fundamental difference between relaxation oscillators and the harmonic oscillators mentioned previously: All harmonic oscillators must have energy fed back from output to input in order for oscillation to continue, whereas relaxation oscillators need no such energy feedback. Therefore, oscillators can also be classified as either *feedback* or *relaxation* type.

## BASIC ELECTRICAL FUNDAMENTALS

All electronic circuit actions consist of free electrons moving about under controlled conditions in the three main types of components—inductors, capacitors, and resistors. Added to these three components are switching or regulating devices known as vacuum tubes (and in more recent years, solid-state devices such as diodes and transistors, which are taking over many of the functions previously performed only by tubes).

The three circuit components are each closely related to certain fundamental electrical phenomena from which their names have been derived. Before these three phenomena—inductance, capacitance, and resistance—can be understood, it will be necessary to understand the principle of *electron drift.*

Electron drift is the foundation of all electric currents (or more accurately, of all electron currents)—except the electron flow within a battery and the electron flow across the evacuated space within a vacuum tube. The first is a chemical reaction, and the second is adequately described in practically every other chapter of this book and need not be belabored here.

### Free Electrons and the Electron-Drift Process

In this day and age, almost every school child is aware of the atomic/molecular structure of matter. Each atom bears an astonishing resemblance to our solar system. At the center is the *nucleus,* where most of the atom's mass is concentrated. Orbiting around each nucleus are electrons, the number differing according to the type of material.

In our solar system the revolving planets are kept from flying off into space by the gravitational attraction between each planet and the sun, which is at the center, or nucleus, and contains most of the mass of the system. In each atom the planetary electrons are kept from flying off into space (or into the surrounding material) by an electrical rather than a gravitational attraction.

This electrical attraction exists because each electron carries within itself one negative unit of charge. The atom as a whole is electrically neutral, but its neucleus will always contain the same number of positive charge (called *protons*) as there are negative charges (meaning *electrons*) orbiting around it. For example, an atom of material which has eight orbiting electrons will have a nucleus with a positive charge of eight units; so the two charges will cancel each other.

There are several methods of setting electrons free from their positions in orbit or, in other words, "stealing" these tiny planets from their solar systems. Heat is one method; it is used in most electronic tubes. Chemical reaction, another common method, is the one used in batteries.

There would be no point in setting electrons free from their orbits unless we had some use for them. The immensity of our requirements for free electrons in everyday life is suggested in part by the definitions of electric current and voltage.

### Definitions

Electric *current* consists of free electrons in motion.

Free electrons in concentration constitute a *negative voltage.*

A concentration of positive ions, caused by a *deficiency* of free electrons from their planetary positions, constitutes a *positive voltage.*

## CONDUCTORS AND RESISTORS

Some materials release electrons from their orbits with the greatest of ease; these materials are classed as *conductors* of electricity. Other materials hold their electrons in orbit very tightly and release them only with the utmost difficulty; these materials are classified as *insulators.* Examples of both types abound in everyday life. Gold, silver, copper, and various other metals and their alloys are examples of good conductors. Glass, wood, and rubber are three familiar insulating materials.

Under the influence of an external force such as an applied voltage, electrons will move through a conductor. This movement is known as *electron drift.* As an example, if each end of a conductive wire is connected to the two terminals of a battery, electrons will leave the negative terminal and move through the wire toward the positive terminal, pushing other electrons into the positive terminal. A continuous flow from the negative to the positive terminal will exist as long as the circuit is connected (and the battery lasts).

No single electron completes the entire journey around even such a simple closed circuit as this one. Trillions upon trillions of electrons are in motion, even in a unit of current as small as one ampere. Also, the number of atoms which actually release free electrons is an infinitesimal fraction of the number of atoms within the material itself. Hence, in moving from the negative battery terminal and into the wire, each electron flows only the tiniest fraction of a millimeter before finding its path impeded by a planetary electron from another atom in the material.

Since each electron carries a like charge, the two repel each other. As a result, the planetary electron is dislodged from its orbit and starts down the wire in the same direction as—and probably ahead of—the approaching electron. The newly dislodge electron will in fact pick up some of the velocity of the other electron. The latter will be lowered down accordingly, and it then becomes an easy prey for being "recaptured" by the atom which has just lost an electron. The original electron "falls" into the orbit just vacated and again takes up planetary motion.

So we still have what we started with—an electron moving through the conductor and driven by an applied negative voltage. The interchange just described is electron drift. It will occur countless quadrillions of times for even the tiniest measurable electron current to flow—even a micromicroampere (one-millionth of one-millionth of an ampere!). The difference between a good conductor and a poor one is the relative ease or difficulty with which its electrons can be dislodged from their orbits and recaptured.

Resistors are aptly named, for they are inserted at certain points in the circuit to *resist* the flow of current. The value selected for each resistor is nothing more than a measure of the difficulty with which electron drift occurs within the resistor.

## CAPACITANCE

Electron drift can also help us understand the important electrical characteristic known as capacitance, and from this to acquire a deeper appreciation of the role that capacitors play in electronic circuits. Consider again the situation as a moving electron approaches a planetary electron. There is a space between them, however small, when the planetary electron finally yields to the repulsive force of the approaching electron and jumps out of orbit. It does not really matter to the two electrons whether the space which separates them at that moment is the open space between copper atoms, air atoms . . . or the open space between atoms of any other material—either conductor or insulator.

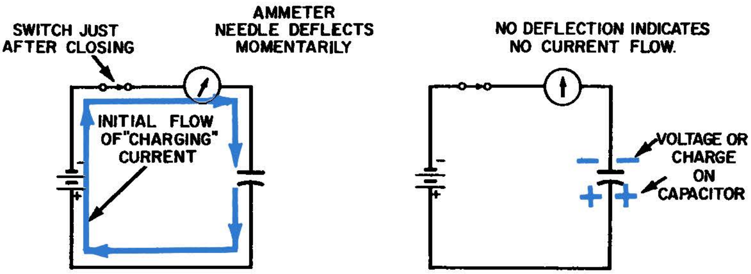
What this suggests is that the *movement* of one electron can be transferred to another electron—irrespective of whether both are contained in the same conductive material, or *in two different but adjacent conductive materials.* As a clarifying example, suppose a conducting wire is severed between the points where the two electrons will be situated when the second one breaks away from its orbit. Suppose also that the two cut ends of the wire are separated by an infinitesimal distance, perhaps a millionth of an inch. Electrically this is an "open" circuit, through which current cannot flow in the normal sense. Nonetheless, drift action can be made to occur between the two electrons. How do we explain this paradox?

We can do so by saying that the two ends of the wire *have capacitance toward each other.* It might be more descriptive, and also truer, to say that the two *electrons* have capacitance toward each other. Under these conditions, electron drift can be made to occur—*provided the first electron can be made to flow up to the break point in the wire.*

This is a fairly large proviso, of course, but it is subject to a simple laboratory demonstration which is also one of the standard capacitor checks performed by all technicians. The capacitor in question is connected across a DC voltage source such as a battery, and an ammeter is placed in the line to indicate the current flow.

The instant the switch is closed to activate the circuit, the ammeter needle will deflect, indicating an initial flow of electrons (current) into the capacitor. (This current flow exists on both sides of the capacitor.) The ammeter needle quickly drops back to zero, indicating no further current flow. We say that the capacitor is "charged" to the value of the applied voltage. (If the ammeter needle remains in a deflected position—indicating some current flow—the capacitor is "leaking" and is defective. If no initial deflection occurs at all the capacitor is "open," also a defect. In either case, the capacitor should be discarded.)

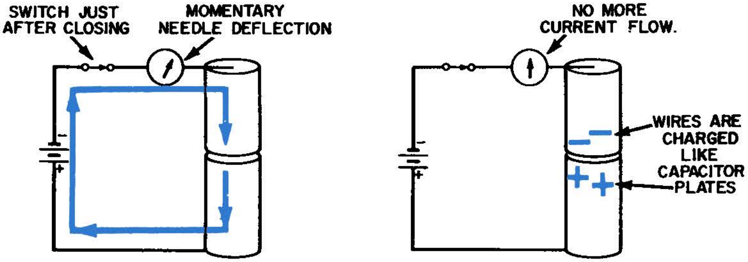
Fig. 1-1A shows the current condition for such a capacitor test the moment immediately after the switch is closed. An initial surge of charging current flows around the circuit and builds up the voltage across the capacitor, as shown in Fig. 1-1B, with negative electrons amassed on the upper plate. Since the electrons had to flow into the capacitor before they could become concentrated there, the current into a capacitor is said to *lead* (or precede) the voltage across it.



*(A) Initial flow of current from DC source into capacitor.*

*(B) Current has stopped, but voltage exists across capacitor.*

**Fig. 1-1. Current and voltage conditions for capacitor test.**



*(A) Initial flow of current.*

*(B) Condition after initial current surge.*

**Fig. 1-2. Enlarged view of conductor with a small break or opening.**

Fig. 1-2 shows the hypothetical example discussed previously, in which the two ends of a severed wire have capacitance toward each other, so that an initial charging current flows around the circuit but a continuous current does not.

When a capacitor plate has charged to the value of the applied voltage as in Figs. 1-1B and 1-2B, no more electrons can be driven onto the negative plate and the flow of current around the circuit stops.

Although capacitors will not "pass" a pure direct current, the *initial surge* of electrons into the capacitor (or up to the break point in the wire, which resembles a capacitor) is not a smooth, steady flow and hence not a pure direct current. Capacitors will "pass" an alternating current because electrons are continuously being driven onto one plate of the capacitor (charging it), and then pulled back off (discharging it) as the applied voltage reverses. Thus, electron current can be made to flow back and forth regularly on each plate of a capacitor, and in this sense the capacitor is said to be passing an alternating current.

The ability to visualize the action of a capacitor is absolutely essential to a quick and easy understanding of electronic circuit action. For this reason, wherever capacitors are mentioned in this book, their action has almost always been redescribed to fit the conditions for the circuit under consideration.

## Capacitor Construction

A capacitor (sometimes referred to as a condenser) is a manufactured device for making use of two important electrical properies associated with capacitance. These are the ability of a capacitor to:

1. Store an electric charge, either negative electrons or positive ions.
2. Pass an alternating current from one plate to the other. This property is frequently stated as the ability of a capacitor to oppose any change in applied voltage.

The *amount* of capacitance exhibited by any capacitor depends on several interrelated factors which can be tied together with the following formula:

$$C = \frac{22.35\,KA\,(n-1)}{10^8 d}$$

where,

C is the amount of capacitance in microfarads,

K is the dielectric constant (the dielectric is explained in a later paragraph),

A is the area of one plate in square inches (it is assumed all plates are the same size and shape),

n is the number of plates,

d is the distance between plates (thickness of the dielectric, as explained a little later).

It can be seen from the formula that the amount of capacitance varies *directly* with the area of the capacitor plates, and *inversely* with the distance between them. These considerations become highly significant at radio frequencies, where unwanted capacitive coupling may occur between components and cause interference.

For example, two wires passing close to each other will be capacitively coupled, the amount being determined by their diameters and by the distance between them. Also within vacuum tubes each electrode will exhibit some capacitance to the others, although the resulting *interelectrode capacitance* may have advantages as well as disadvantages.

The material between the plates of a capacitor is called the *dielectric*. It may be air or any other insulator, and its insulating ability is known as the *dielectric constant*, or K. The dielectric constant of air is unity, or 1. Mica has a dielectric constant of 5.5, and ordinary glass, slightly over 4.

Of equal if not greater importance is the dielectric strength of a material, or how high a voltage it can withstand before breaking down. The dielectric strength is expressed in volts per unit of distance. For air it is about 80 volts per .001 inch. Mica is 25 times stronger, or 2,000 volts per .001 inch.

Assuming two capacitors have equal plate area and separation, this means the breakdown voltage of one with a mica dielectric will be 25 times greater than one with an air dielectric.

The dielectric strength of the material (and its thickness) determine the working-voltage rating of a capacitor. This is the rating used by the manufacturer to indicate the maximum voltage a capacitor can safely withstand without breaking down.

### Capacitive Reactance

Capacitors offer a certain opposition to the passage of alternating currents. The amount varies inversely with the frequency of the current and the value of the capacitor, in accordance with this formula:

$$X_C = \frac{1}{2\pi fC}$$

where,

$X_C$ is the capacitive reactance (opposition to current flow) in ohms,

f is the frequency of the applied current in cycles per second,

C is the capacitance in farads.

## INDUCTANCE

The third important circuit characteristic is *inductance*, and the manufactured components most directly associated with it are called *inductors*, which include all coils and transformers. We will find an endless variety of such devices, each manufactured for a specific application. As a group they cover the entire frequency spectrum, are called on to carry tiny currents or huge ones, and often must be able to withstand enormous voltages without rupturing or otherwise failing. Regardless of the conditions under which they are used or the circuit functions they are expected to fulfill, all inductors—coil, choke, transformer, etc.—take advantage of the electrical property known as inductance.

Inductance is the electrical equivalent of mechanical inertia. Stated more simply, inductance *is* electrical inertia. Let us compare it briefly with mechanical inertia.

A given mass possesses inertia, and for this reason requires a certain amount of force to set the mass in motion, or to speed it up or slow it down. Thus, a rolling ball—in the absence of friction—will continue to roll in the same direction and at the same speed. The same ball at rest will remain at rest.

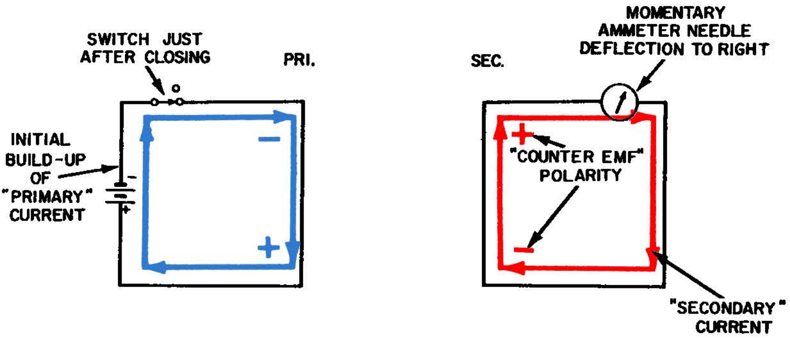
The concept of electrical inertia is easy to visualize if the foregoing analogy is kept in mind. Remember that although the mass of one lone electron seems insignificant, its contribution becomes significant when we consider that there are trillions upon trillions of electrons in a single conductor!

A given quantity of electrons, flowing through any conductive material, will tend to keep flowing in the same quantity. The reason is that the electrical property known as inductance will always operate to support this natural law. Some common descriptive statements which apply to inductance are:

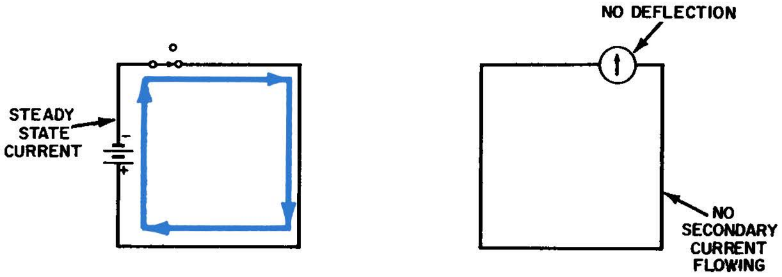
1. An inductance always tries to keep the total current constant.
2. An inductance always opposes any change in the current.
3. In an inductance, the voltage "leads" the current; or conversely, the current "lags" the voltage.
4. Inductors generate a back electromotive force which opposes the applied voltage.

These statements can be better understood from Fig. 1-3. In Fig. 1-3A the two adjacent closed circuits are "connected" only by the mutual coupling between the two wires placed side by side in the center. Even though shown as straight wires, they can be considered as two windings of a transformer, since all conductors exhibit some inductance toward all other conductors. The instant the switch in the left circuit is closed, a current will flow from the upper (negative) terminal of the battery, through the switch, *downward* through the wire we have designated as one winding of a transformer, and on around the circuit to the lower (positive) terminal. This current is shown in blue.

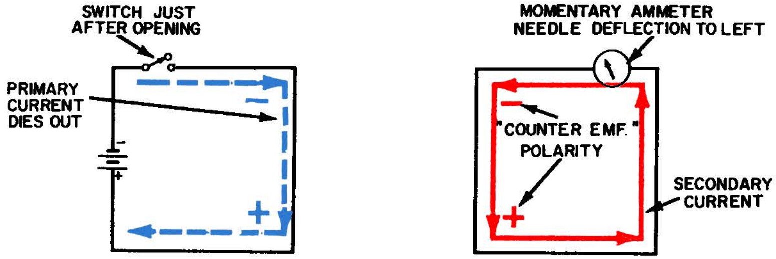
Simultaneously, in the right circuit another current begins to flow *upward* through the other transformer winding, which we will call the secondary. With a sensitive ammeter or galvan-



*(A) Initial current flow when switch is closed.*



*(B) Steady-state (DC) conditions.*



*(C) Decrease in current flow when switch is opened.*

**Fig. 1-3. Current flow in an inductive circuit.**

ometer in the circuit as shown, the needle will be deflected to the right slightly.

This secondary current has been shown in red. Where did it come from? Once we answer this question we can understand much about inductance.

This secondary current is nature's way of keeping the total current constant. Before the switch was closed, there was zero current flowing in both windings. The instant after the switch is closed, this zero total-current condition must be maintained, even though a substantial current begins flowing downward through the primary winding. As the electrons which make up the primary current begin to accelerate in the downward direction, the negative charge carried by them causes other electrons in the secondary winding to be accelerated upward. When the current flowing upward is subtracted from the one flowing downward, the remainder is zero *for the tiniest fraction of a second.*

This secondary current cannot flow forever—it is sustained only by *changes* in the amount of primary current, and the rate of change becomes less and less as the primary current approaches its steady-state value. The secondary current dies out gradually, and when the primary current finally reaches its full steady-state value, the secondary current will drop to zero as shown in Fig. 1-3B.

Fig. 1-3C depicts the conditions immediately after the switch in the primary circuit has been opened. When the primary-current flow is cut off, it must rapidly decrease (decelerate) until it reaches zero. Just as an increasing current flow in the primary winding will set up a current flow in the secondary winding, so too will a decreasing current. But this time, the current in the secondary winding will flow in the opposite direction (downward) to keep the total current through the two windings constant. A sensitive galvanometer in the secondary circuit will actually give a momentary deflection in the opposite direction from that shown in Fig. 1-3A, indicating a current reversal has occurred.

This secondary current lasts only while the primary current is changing. As soon as the primary current reaches zero, the secondary current will drop to zero also.

For every electron flow, or current, there must be a companion voltage to supply inertia. In the primary circuit of Fig. 1-3A, for example, the applied voltage is the companion and motivating force for the primary circuit. Because of the way the battery is connected, this applied voltage is negative at the top of the primary winding and positive at the bottom, causing the current to flow downward through the primary winding.

Suppose you were asked this question:

"What polarity of voltage must exist across the secondary winding in order for the secondary current to flow upward through the winding?"

There can be only one answer, since electrons *always* flow from a point of negative to a point of positive voltage—*never* in the opposite direction.

In Fig. 1-3A we can see that the polarity of the secondary voltage is positive at the top and negative at the bottom, and that the applied voltage in the primary is negative at the top and positive at the bottom. As a result, the voltage generated in the secondary "opposes" the applied voltage in the primary. This voltage associated with secondary currents in transformers and other inductors has been given the name of *counter electromotive force*, or more simply, *counter emf*.

We can also see that the applied voltage actually "leads" the resulting current. The current referred to here is the *total* transformer or inductor current, which is not achieved until sometime after the primary voltage is applied, as shown in Fig. 1-3B. Thus, attainment of the final current value has "lagged," or fallen behind, the voltage producing it.

In Fig. 1-3C we see that the polarity of the counter emf has reversed itself—now the negative voltage is at the top and the positive voltage is at the bottom. This is the only possible polarity consistent with the downward flow of secondary current at this moment. The fact that this counter emf is opposing the applied voltage may be a little difficult to visualize, since the two are of the same polarity. However, by opening the switch we have removed the negative voltage previously applied at the top of the primary winding. This is actually equivalent to applying a positive voltage at that point. In this sense, the applied voltage and counter emf are opposite in polarity.

The current in the primary winding flows in only one direction, and yet we have seen that it can cause a two-way current—better known as an alternating current—to flow in an adjacent winding. The reason is that it is a unique form of direct current known as *pulsating* DC. There will be several examples of its use in later chapters, such as in the Hartley and blocking oscillators and in the grid circuit of an electron-coupled oscillator.

## Self-Inductance

Fig. 1-4 shows how induced currents can be made to flow and a counter emf generated *within a single conductor* (shown enlarged in Fig. 1-4 for clarity). As before, the sudden application or removal of an applied voltage is required—or more specifically, a *change* in the applied voltage across the circuit is necessary for a self-induced current to flow.

As soon as the switch in Fig. 1-4 is closed and battery voltage is applied across the circuit, the primary current will attempt to rise to its full value. However, because all circuit components have self-inductance, the *total* current does not do so immediately, but remains at zero for an instant. The reason is simple—as the primary current tries to increase, the "electrical inertia" of the electrons in it will cause *other* electrons in the circuit to be accelerated in the opposite direction. Hence, the two currents cancel each other at first.

As the primary current approaches its full value, its *rate* of increase is steadily dropping, permitting the induced current to die out. The counter emf of Fig. 1-4A no longer exists when the steady-state condition shown in Fig. 1-4B has been replaced.

Fig. 1-4C shows the conditions an instant after the switch is opened. The primary current will now try to drop to zero. However, *all inductances act to keep the total current from changing.* Thus, as the electrons of the primary current start to decelerate, they induce other electrons in the same conductor to be accelerated in the same downward direction. Therefore, instead of the zero current we would expect to find upon first opening the switch, we find the full current flowing! Once again, a counter emf has come into existence, only this time its polarity is opposing the polarity we tried to apply by opening the switch to remove the negative applied voltage.

## Inductor Construction

The entire art of inductors is built upon this property of electrical inertia. In theory, a coil of wire with many thousands of closely spaced turns is still the same straight wire shown earlier in Fig. 1-4. The object of the additional turns is to provide more inductance (by multiplying the effects of electron inertia).

The opposition offered by inductors to the flow of alternating current varies directly with the frequency of the applied current and with the size of the inductor, in accordance with this formula:

$$X_L = 2\pi fL$$

where,

$X_L$ is the inductive reactance (opposition to current flow), in ohms,

f is the frequency of the applied current in cycles per second,

L is the inductance of the coil in henrys.

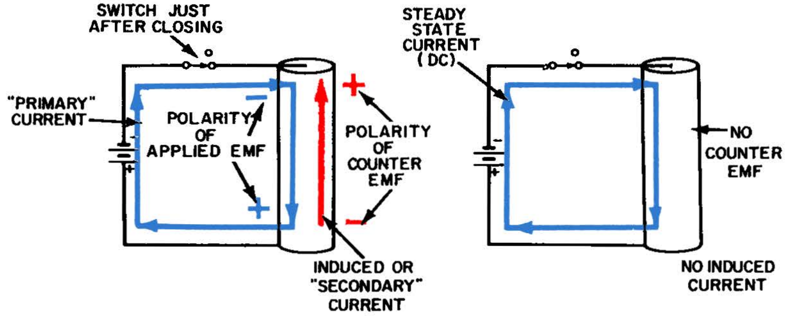
Fig. 1-5 shows cross-sectional views of the two common types of coils. Their *approximate* inductances can be calculated from the following formulas:

For a single-layer solenoid (Fig. 1-5A):

$$L = \frac{r^2 \times N^2}{9\,r + 10\,l}$$

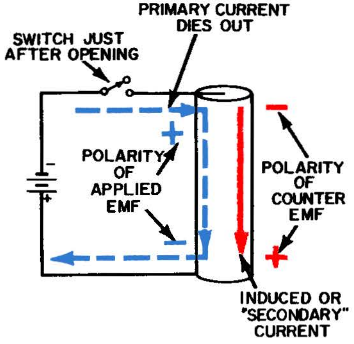
where,

L is the inductance in microhenrys,
N is the number of turns,
$l$ is the length of the coil in inches,
r is the radius of the coil in inches.



*(A) Current flow when switch is closed.*

*(B) Steady-state (DC) current.*



*(C) Current flow when switch is opened.*

**Fig. 1-4. Self-inductance in a single wire (enlarged view).**

For a multilayer coil (Fig. 1-5B):

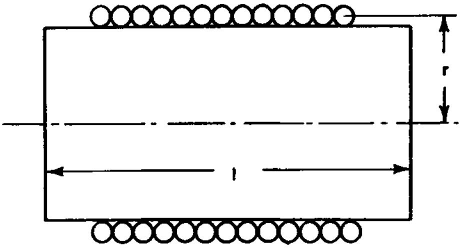
$$L = \frac{r^2 \times N^2}{6\,r + 9l + 10t}$$

where t, the only new term, is the thickness of the coil winding in inches.

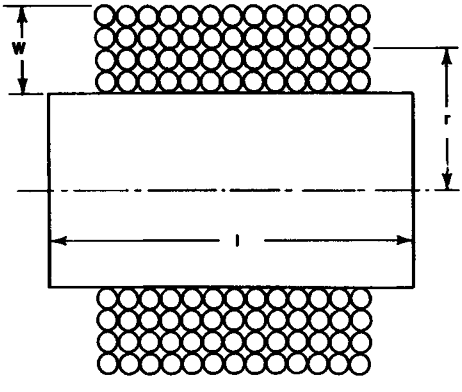
It will not be necessary for you to refer to these formulas in order to understand the circuit actions discussed in the text. But like the capacitance formula offered previously, this one shows the correlation between physical size and configuration of a coil and its resultant inductance.

## THE INDUCTANCE-CAPACITANCE COMBINATION

Inductance and capacitance in combination possess the unique characteristic of *resonating* at a particular frequency. This im-



*(A) Single layer.*



*(B) Multilayer.*

**Fig. 1-5. Cross-sectional views of single-layer and multilayer coils.**

portant and basic circuit action is employed in all types of electronic equipment. Tuned inductance-capacitance (L-C) circuits are used in practically every piece of electronic equipment—and oscillators are no exception, as we shall learn in later chapters.

Fig. 1-6 shows the conditions at the ends of the four quarter-cycles of an oscillation between an inductor L and a capacitor C. At the end of the first quarter-cycle (Fig. 1-6A), electrons are amassed on the upper plate of the capacitor (thereby constituting a negative voltage), and there is a *deficiency* of electrons (positive voltage) on the lower plate. In other words, no current is flowing through the inductor yet.

The voltage across the capacitor represents stored electrical energy. Energy in storage is potential energy. So, during the second quarter-cycle the electrons from the top plate will start to flow downward through the inductor in an effort to redistribute themselves equally between the two plates and thus neutralize the electric field. The self-inductance of the coil prevents an instantanous build-up of current by generating a counter emf of the opposite polarity. This action is not shown in Fig. 1-6B, but because of it, the current is delayed exactly one quarter-cycle in reaching its peak. So, at the end of the second quarter-cycle the current is finally flowing at its maximum rate *downward* through the inductor. At this moment, the charge has been completely redistributed—no voltage remains across the capacitor or tuned tank.

## Magnetic Lines of Force

As the current through the coil increases from zero to maximum, lines of magnetic force come into existence and expand outward from the coil. In essence, the coil becomes an electromagnet, and since the lines of force in Fig. 1-6B are entering at the top and exiting from the bottom, the coil has its north pole at the top and its south pole at the bottom.

These, then, are the conditions at the start of the third quarter-cycle—zero voltage across the tank, maximum electron current flowing downward through the inductor (coil), and maximum lines of force surrounding it.

The potential energy represented by the charged capacitor has now become kinetic energy, in the form of moving electrons. The lines of force are also a means of energy storage. So when the current tries to collapse during the third quarter-cycle, these lines of force will collapse and thereby drive additional current downward through the coil. The lines of force are trying to accomplish the effect we already know occurs with inductors—it is trying to keep the current from changing value.

As a result of this sequence, almost all the electrons which were on the upper plate of the capacitor will be delivered to the lower plate during the third quarter-cycle, and the charge distribution will look like Fig. 1-6C. As in Fig. 1-6A, this charge distribution again represents potential energy in storage, except now it has the opposite polarity.

At the start of the fourth quarter-cycle, the electrons massed on the lower plate must again redistribute themselves in order to neutralize the voltage across the capacitor. So they begin to flow upward through the inductor, and another familiar sequence begins: A counter emf with a polarity opposite that of the capacitor comes into existence. An induced current then flows downward in the coil and bucks the upward-flowing current.

A new set of magnetic lines of force ( also known as *flux lines*) develops and expands outward as long as the total current in the coil is expanding. These lines of force have a different direction from the one they had in Fig. 1-6B, because in Fig. 1-6D the main current through the coil is flowing in the opposite direction. Now the lines of force are entering at the bottom and exiting at the top, again making the coil a small electromagnet but with its north pole at the bottom and its south pole at the top.

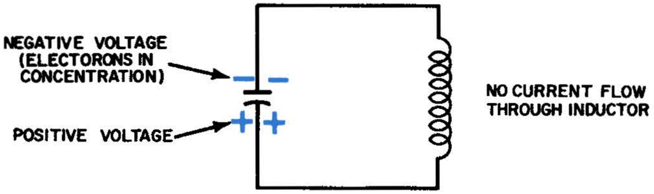
These, then, are the conditions at the start of the first quarter-cycle—zero voltage across the capacitor and tank, maximum upward flow of electrons through the inductor, and maximum number of magnetic lines of force around it.

The collapse of these lines of force during the first quarter-cycle tries to keep the current from dying out by drawing additional electrons upward through the inductor. The end result is that almost as many electrons are delivered to the upper plate as were amassed on the lower plate a half-cycle earlier.

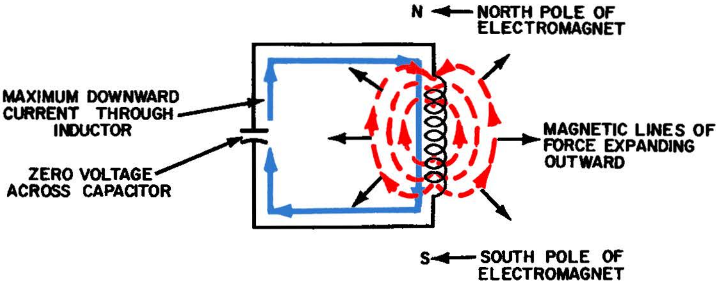
Thus, we see that one cycle of an oscillation is characterized by (1) a periodic changing of the voltage across the tank from plus to minus and back to plus; (2) periodic up-and-down alternations of the current through the inductor; and (3) periodic expansion and contraction of the magnetic lines of force around the inductor, the lines changing direction every half-cycle.

In brief, an electric oscillation consists of a cyclic interchange of energy between an electric and a magnetic field. The electric field is represented by the voltage across the capacitor in Figs. 1-6A and 1-6C; and the magnetic field, which is associated with a high current flow, is represented by the expanded lines of force in Figs. 1-6B and 1-6D.

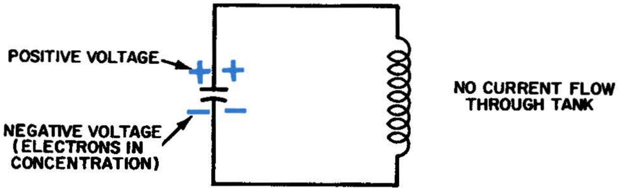
The number of cycles occurring each second is called the *frequency*. Tuned circuits of the type shown in Fig. 1-6 are used in the generation of radio frequencies ranging from a few thou-



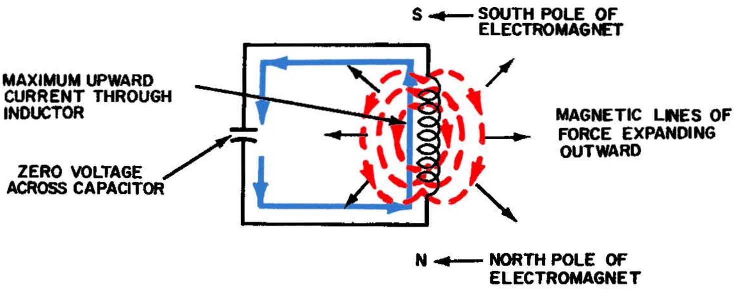
*(A) At end of first quarter-cycle.*



*(B) At end of second quarter-cycle.*



*(C) At end of third quarter-cycle.*



*(D) At end of fourth quarter-cycle.*

**Fig. 1-6. Oscillation in an L-C circuit.**

sand cycles per second, up to hundreds of kilocycles and even megacycles (a megacycle is one million cycles per second).

The values of the capacitor and inductor determine the basic operating frequency of any tuned tank, in accordance with the standard formula which states that:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where,

f is the frequency in cycles per second,
L is the inductance in henrys,
C is the capacitance in farads.

A later chapter shows how this formula is derived from the two simple reactance formulas for inductance and capacitance.

The strength of an oscillation is measured by the amount of voltage (*amplitude* of the voltage peaks) across the tuned tank. Once started, an oscillation could continue indefinitely at the same amplitude, if it were not for the inevitable *losses* due to wire resistance and other effects. Consequently, unless an oscillation is replenished from an outside source of energy, each succeeding cycle will be a little weaker than the preceding one until eventually the oscillation will die out entirely. (This "dying out" process is called *damping* of the oscillation).

The quality, or Q, of a tuned circuit is a comparative measure of its freedom from the losses which damp out an oscillation. Once started, a high-Q circuit will oscillate for many thousands of cycles, whereas an oscillation in a low-Q circuit will die out in a relatively few cycles. A convenient means of visualizing the meaning of Q is to consider it a ratio between the number of electrons in oscillation and the number which drop out each cycle due to losses. Mathematically, circuit Q is stated by several different formulas, two of which are:

$$Q = \frac{2\pi \times \text{Energy in Storage}}{\text{Energy Lost Each Cycle}}$$

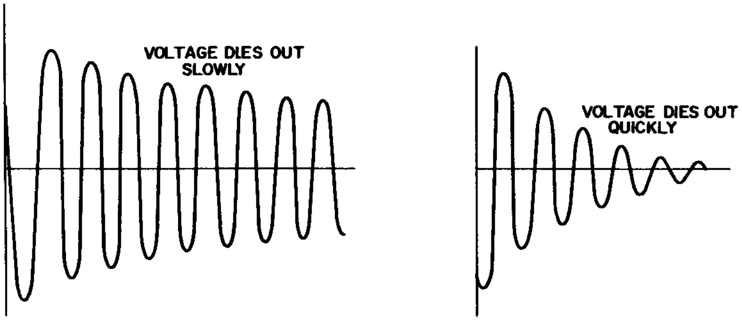
or,

$$Q = 2\pi \frac{L}{R}$$

where,

L is the coil inductance in henrys,
R is the circuit resistance in ohms.

Fig. 1-7A shows a lightly damped waveform for an oscillation in a high-Q tuned circuit, where losses are low. The heavily



*(A) Light damping from high-"Q" circuit.* *(B) Heavy damping from low-"Q" circuit.*

**Fig. 1-7. Effect of circuit "Q" on oscillatory waveform.**

damped voltage waveform in Fig. 1-7B is for an oscillation in a low-$Q$ tuned circuit, where losses are heavy.

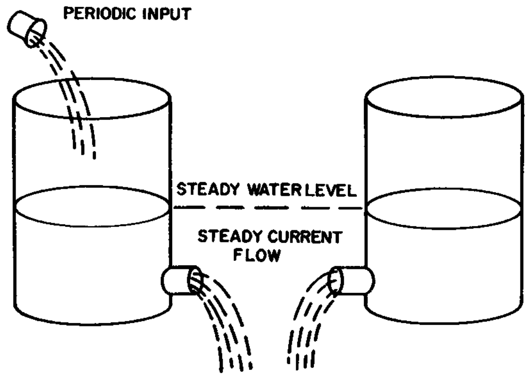
## THE RESISTOR-CAPACITOR COMBINATION

The action between resistors and capacitors in combination is the last in our discussion of the five basic actions taking place in electronic circuitry. These combinations are most easily classified into one of two broad groups, depending on (1) the values of the resistor and capacitor, and (2) the frequency of the current/voltage combination to which they must respond in the particular circuit. These two groups are the long time-constant and the short time-constant combinations. The same R-C combination will provide a long time-constant at one applied frequency and a short time-constant at a lower frequency.

Almost all circuits discussed in later chapters have at least one long time-constant R-C combination. For this reason, it is certainly worth your while to achieve an early mastery of the basic action in a resistor-capacitor combination. Of the five, it is probably the easiest to understand.

The drawings in Figs. 1-8 through 1-12 are based on an interesting set of analogies. Notice that the capacitance of a capacitor is likened to the capacity of a water tank, the resistance of a resistor is likened to the resistance of a water pipe, water level or pressure is compared to "electron level" or pressure (meaning voltage), and water flow or current is compared to electron flow or current.

Each of the five combinations in Figs. 1-8 through 1-12 shows two periods (or half-cycles) of operation—the charging half-cycle, and the "other" half-cycle. Just to keep things simple, we

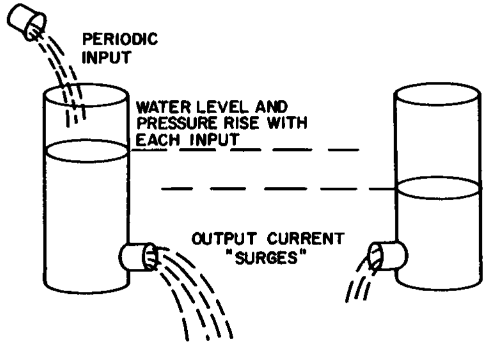


*(A) Charge.* *(B) Discharge.*

**Fig. 1-8. A water tank with a fluctuating input and steady output is comparable to a "long time-constant" resistor-capacitor combination.**

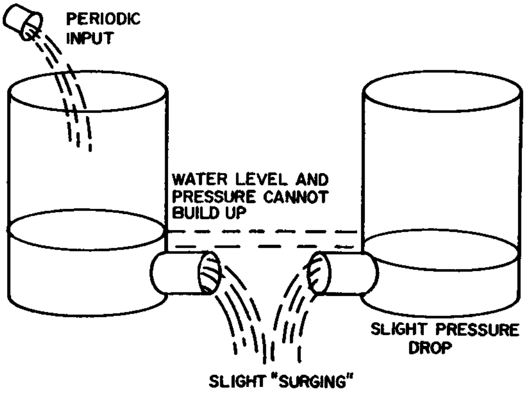
will assume the amount of water added during each one of the five charging half-cycles is always the same—say, one bucketful. Moreover, let us keep the frequency the same throughout by adding water to each tank at the rate of one bucketful per second. Hence, we can say that each one of the five combinations operates at a frequency of one cycle per second.

In Fig. 1-8 the tank is large enough, and the output nozzle small enough, that the addition of one bucketful of water each second does not significantly raise the water level. Consequently, the water pressure does not change during the charging half-cycle



*(A) Charge.* *(B) Discharge.*

**Fig. 1-9. If tank is too narrow and thus has too little "capacity," the output current will surge. This is comparable to a "short time-constant" resistor-capacitor combination.**

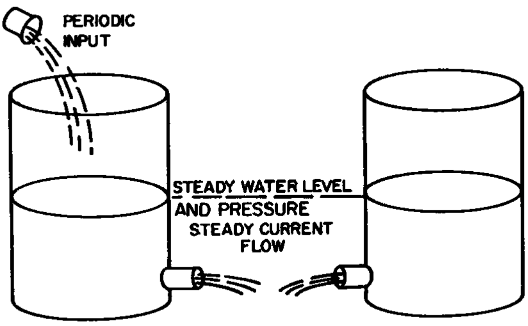


*(A) Charge.* *(B) Discharge.*

**Fig. 1-10. With a low-resistance outlet (wide, short nozzle), pressure cannot build up and the water runs out as fast as it is added. This compares to a "short time-constant" R-C combination.**

depicted in Fig. 1-8A, because the same amount of water flows out through the nozzle during the discharging half-cycle of Fig. 1-8B. In electronic circuitry, this is analogous to a long time-constant R-C combination.

Fig. 1-9 depicts the same conditions as before, only with a smaller water tank. Now a single bucketful of water *does* make a difference in the water level and consequently the pressure. Because the pressure rises as each bucketful is poured in, more water flows out through the nozzle during the charging than the



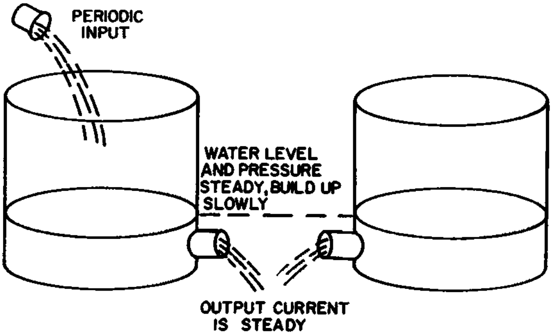
*(A) Charge.* *(B) Discharge.*

**Fig. 1-11. With a high-resistance outlet (narrow, long nozzle), a high water level and pressure will build up and current will be steady. This is also a long time-constant combination, but the same amount of input will produce a higher pressure than in Fig. 1-8.**

discharging half-cycle, since rate of flow (current) depends on water pressure. The same is true of electric current, which depends on electrical pressure, or voltage. Whenever the pressure level and consequently the amount of current in a circuit changes significantly during one complete cycle, the combination has a short time-constant at the particular frequency.

In Fig. 1-10 we have restored the tank to its original size but enlarged the outlet nozzle (thus lowering its resistance). Now it is difficult to build up water pressure, since the water flows out almost as fast as it flows in. Because the water level fluctuates, the current through the nozzle is pulsating rather than steady. Thus, as in Fig. 1-8, we have a short time-constant combination here.

In Fig. 1-11 we have narrowed the outlet nozzle down and thereby substantially *increased* its resistance. Thus, it will impede the flow, and more water will be added each cycle than can flow out, until the water level builds up to the point where there is sufficient pressure to force out the same amount that is added each cycle. However, since the water level does not decrease during the discharging half-cycle, there is no surging—the flow will gradually build up and then remain constant. Hence, this combination can be classified as a long time-constant.



*(A) Charge.* *(B) Discharge.*

**Fig. 1-12. If tank has excessive capacity, it will require more water and more time to build up to the same pressure as in Fig. 1-8. This level will be achieved eventually, however; therefore this is also a long time-constant combination. The current output is steady from half-cycle to half-cycle, but will increase as the pressure does.**

Fig. 1-12 shows the effect of greatly increasing the tank capacity. One bucketful of water each cycle will not change the water level substantially; many cycles will be required to build up a pressure equal to that of Fig. 1-8. The moral is that the water tank is probably bigger than necesary, if its function is merely to maintain a constant water pressure and thus a constant water flow through the outlet nozzle. Anyway, this combination is a long time-constant one.

## Time-Constant Formula

From the previous analogies it is possible to demonstrate the underlying meanings of several important formulas you will encounter in later chapters—in fact, in all electronic-circuit applications. The first of these is the time-constant formula.

The *time constant* of a resistor-capacitor combination is the time it requires to complete 63.2% of its charging or discharging action. The formula states that this time is equal to the *product* of the component values as follows:

$$T = R \times C$$

where,

T is the time in seconds,
R is the resistance of the charging path in ohms,
C is the capacitance in farads.

When we consider the water tanks and their outlets, it is evident that the emptying, or discharge, time from any given water pressure or level (voltage) will vary directly with the size, or capacity, of the tank and with the amount of resistance the nozzle offers to the water flow. (A wide, short nozzle offers low resistance; a narrow, long nozzle offers high resistance.)

## Coulomb's Law

Coulomb's law states another important principle referred to repeatedly in the following chapters, and it can also be demonstrated with the water-tank analogies. This law says that the attraction or repulsion between two electric charges is proportional to the product of their magnitudes, and is inversely proportional to the square of the distance between them. Hence, from this we can deduce that the amount of charge (negative electrons or positive ions) stored in any capacitor is proportional to the voltage across the capacitor. These three quantities are related arithmetically by the following formula:

$$Q = C \times E$$

where,

Q is the quantity of charge in coulombs (1 coulomb = $6.25 \times 10^{18}$ electrons),

C is the capacitance in farads,
E is the voltage, or electrical pressure, in volts across the capacitor as a result of the stored charge.

From the water-tank analogies it is evident that an increase in the amount of water stored in the tank will raise the water level and consequently the pressure. It is also apparent that a relatively small amount of water will fill up a narrow tank with a small capacity, thereby creating a high water level and pressure. This same quantity of water, when transferred to a wide tank, however, will barely cover the bottom of the tank, and the water level and pressure will be very low.

## Ohm's Law

Another important formula whose meaning can be demonstrated with the tank analogies is Ohm's law, which states that the voltage developed across a resistor is proportional to the current flowing through it. These three quantities are related arithmetically as follows:

$$E = I \times R$$

where,

E is the voltage across the resistive path in volts,
I is the current through the resistor in amperes,
R is the resistance of the path in ohms.

If the water level in one of the tanks is raised, it should be clear that the higher pressure will force more water (current) through the nozzle. Also, if the water level is not changed but a larger nozzle is substituted, its resistance will be lower and more water will flow out than before.

## Conclusion

Each of these three formulas is elaborated on whenever an R-C combination appears in one of the later chapters and it seems necessary to do so in order to clarify circuit operation. There is a truly enormous body of literature making up all the mathematics of electronics. However, it is not necessary to master it all to understand how electronic circuits operate. A working understanding of the preceding three formulas, plus the two for capacitive and inductive reactance and the frequency formula for tuned circuits, is adequate in helping you *visualize* the action of any circuit. The reason is that all circuit actions can be placed into one of seven major categories. These might be called basic actions, of the types described briefly in this chapter. They are:

Resistor.
Capacitor.
Inductor.
Inductor-capacitor combination (both at resonance and off-resonance.)
Resistor-capacitor combination.
Resistor-inductor combination (which enjoys only limited usage).
Vacuum tubes (which provide the necessary regulation).

## Chapter 2

# CRYSTAL OSCILLATORS

The crystal-controlled oscillator depends on the *piezoelectric* effect of certain crystals for their ability to generate electric oscillations at radio frequencies. The piezoelectric effect can be visualized from Fig. 2-1. One peculiar quality of such a crystal is its ability to oscillate structurally as well as electrically. Like all oscillations, this one must be sustained by adding energy from an outside source or it will die out. Using Fig. 2-1 we will discuss the condition of the crystal during four successive quarter-cycles of an oscillation.

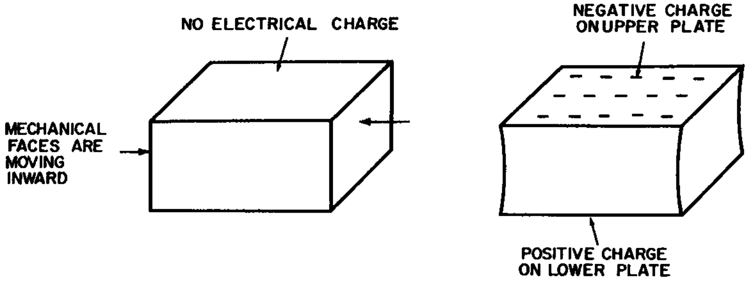
## CRYSTALS

Fig. 2-1A shows the normal physical configuration of a typical crystal. Crystals have various shapes, a flat rectangular plate being the most common. The upper and lower plates are the electrical ones, and the right and left plates the mechanical ones. When a crystal is oscillating, positive and negative electric charges will alternate between the two electric faces, and mechanical distortion will be evident on the two mechanical faces.

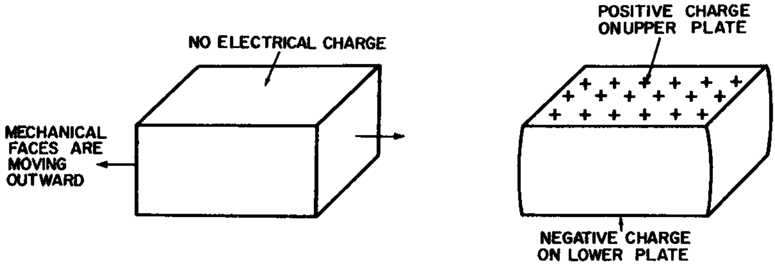
Fig. 2-1B shows the concentration of a negative charge on the upper plate of the crystal. Although not shown, positive ions are concentrated on the bottom plate. Fig. 2-1D shows the electrical conditions of the crystal a half-cycle later, when the positive charge is concentrated on the upper plate and the negative charge on the lower one.

Fig. 2-1B also shows the mechanical distortion of the crystal. Here the right and left plates are drawn *inward,* while in Fig. 2-1D they are expanded.

The arrows in Figs. 2-1A and 2-1C point in the direction these two plates are moving at the end of the first and third quarter-cycles.



*(A) First quarter-cycle.* *(B) Second quarter-cycle.*



*(C) Third quarter-cycle.* *(D) Fourth quarter-cycle.*

**Fig. 2-1. Piezoelectric effect on a typical crystal for one cycle of operation.**

The thickness of the crystal, the type of material it is cut from, and the orientation of the cut to the crystal material, all have a direct bearing on the frequency at which the crystal will oscillate. A typical quartz crystal, oscillating in the region of 500 kilocycles per second (near the low end of the broadcast band), might have the following *approximate* dimensions:

Thickness—0.25 inch
Width—1.3 inches
Length—1.0 inch

This describes a crystal about one inch square and one-fourth inch thick.

The type of material used and the orientation of the cut to the original axis of the crystal material are of major significance to the crystal grinder and circuit designer, but not to the average technician. Hence, this type of information is omitted here, since the emphasis is more on conveying a general understanding of the *electrical actions* occurring in a series of widely-used standard circuits.

## CRYSTAL-OSCILLATOR CIRCUIT

Figs. 2-2 and 2-3 show a typical crystal-oscillator circuit using a standard triode tube. The necessary circuit components, in addition to the crystal, are:

R1—Grid-drive and -return resistor.
V1—Triode tube.
C1—Plate tank capacitor.
L1—Plate tank inductor.
M1—DC power supply.

This oscillator requires energy to be fed back from the output (plate circuit) to the input (grid circuit) in order to sustain oscillation. Feedback is accomplished via interelectrode capacitance from plate to grid of the tube. There is a distinct similarity between the electrical actions in this circuit and those in the tuned-plate–tuned-grid oscillator circuit discussed in a later chapter. The main difference between the two is that the quartz crystal here takes the place of the tuned inductance-capacitance combination in the TPTG oscillator.

The electron currents at work in this circuit are:

Grid-driving current, driven by the crystal voltage (dotted green).
A small amount of grid-leak current (solid green).
Plate current of the tube (red).
Electrons in oscillation in the plate tank (blue).
Feedback electron current (also in blue).

When the cathode is heated by the filament current (not shown) and plate voltage is applied, the tube will begin to conduct electrons from cathode to plate. This current, shown in red, flows along a closed path from cathode to plate, through the tuned L-C circuit and the power supply, and into a common ground connection where it can readily return to the cathode. (As is true for all tube currents, *a closed path must be available back to the cathode.*)

The sudden arrival of plate current at the tuned circuit will inevitably cause the circuit to begin oscillating at its natural frequency. Electrons (shown in blue) will then move back and forth through the inductor, between the two plates of tank capacitor C1. Fig. 2-2 shows the electrical conditions at the end of the first half-cycle, when the oscillating current has delivered the maximum number of electrons to the top plate of C1. The voltage at the top of C1 is now reduced to a low positive value, as shown by the single plus sign at the top plate and the two at the bottom.

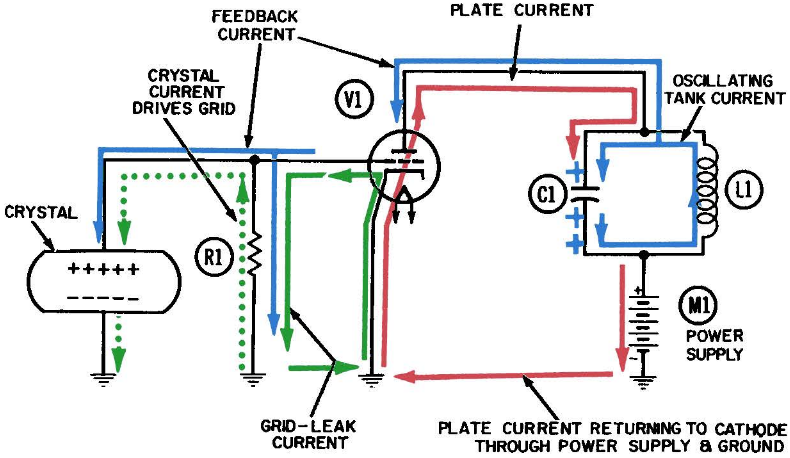


**Fig. 2-2. Operation of a simple crystal-oscillator circuit—first half-cycle.**

Since it is connected to the top of the tuned circuit, the plate of the tube will always have the same voltage as the top of the tuned circuit. The flow of a small amount of current between the two points serves to transfer the voltage from one to the other. This flow, also shown in blue, has been labeled the *feedback current.* During the time the upper plate of C1 is less positive than the lower one, the electrons which make up the feedback current will flow *toward* the plate of the tube and drive an equal number of electrons away from the grid and into the grid circuit. This occurs because of interelectrode capacitance within the tube, wherein the plate and grid act as the two plates of a small capacitor. The natural function of any capacitor is to "pass an alternating current." That is, as electrons are driven onto one of its plates, an equal number are driven from the opposite plate. The flow of electrons away from the grid is labeled "feedback current" in Fig. 2-2 and shown in blue.

Likewise, whenever the upper plate of C1 is more positive than the lower one, the feedback current will flow in the opposite direction—*away* from the plate of the tube and toward the tuned circuit. The withdrawal of these electrons from the tube plate now draws an equal number of electrons through the grid circuit, *toward* the grid. This condition is depicted in Fig. 2-3.

Now that we have succeeded in getting feedback current to flow in the grid circuit, we have satisfied the condition that energy in some form must be coupled back from output to input of the circuit. This coupled energy must also be of the appropriate phase so it can turn the control grid on and off at the proper times in order to sustain the oscillation. Let us now consider the action occurring in the grid circuit.

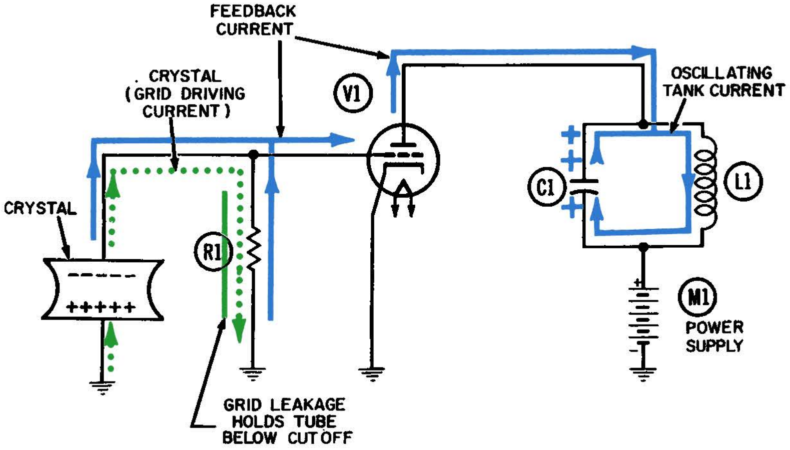


**Fig. 2-3. Operation of a simple crystal-oscillator circuit—second half-cycle.**

The first surge of feedback current should be sufficient to start the crystal oscillating. Fig. 2-2 depicts the half-cycle of oscillation when the upper face of the crystal is positively charged. This positive voltage draws a small amount of current (labeled "crystal current" and shown in dotted green) *upward* through grid resistor R1, performing the function recognized as "driving the grid."

During the same half-cycle shown in Fig. 2-2, the feedback current (shown in blue) flows *downward* through R1. Thus it appears that the feedback and driving currents, and the respective voltages developed across R1 by them, are clearly out of phase.

In Fig. 2-3 both currents have reversed direction and so they are still out of phase. These conditions are still not conducive to oscillation. (We will return to this point shortly.)

The polarities of the crystal voltage, as shown in Figs. 2-2 and 2-3, are such that they properly support the plate tank oscillation. When the top of the crystal is positive, as in Fig. 2-2, the control grid will release maximum plate current through the tube. This current will reach the top of the tuned circuit ( the upper plate of capacitor C1) at the moment the voltage at this point is least positive and, in effect, will further reduce this voltage. Thus, the oscillation is sustained by strengthening it during each cycle.

Upon reaching its most positive voltage, the grid will draw some grid-leakage electrons from the cathode. These electrons will flow downward through R1 and return to the cathode, as shown by the solid green lines. The resulting small amount of negative voltage created at the top of this resistor is called the *grid-leak bias.*

### Class-C Operation

In Fig. 2-3, when the crystal current drives the control grid to its most negative voltage, minimum plate current flows through the tube. This current reaches the top of the tuned circuit when the voltage produced at this point by the oscillating tank current is most positive. If the tube is being operated under Class-C conditions, then no plate current at all will flow when the grid is negative. (The definition of Class-C operation is that plate current shall flow for less than half of each cycle.)

The circuit here would most likely be operating under Class-C conditions. The amount of bias voltage developed by the grid-leakage electrons flowing through R1 is sufficient to cut the tube off during most of the individual cycle. The voltage swing developed by the crystal can be quite substantial, 3 to 5 volts being fairly normal with most amplifier tubes. When higher-power tubes are used, more powerful oscillations are developed in the plate tank circuit. Also the feedback impulses become stronger and may drive a crystal to oscillations of 20 to 25 volts or more. In fact, it is possible to shatter a crystal by driving it with too strong a feedback impulse.

## TIME CONSTANTS AND VOLTAGE STORAGE

In order for the grid-leakage current to create a bias voltage which will persist during that part of the cycle when the tube is not conducting, there must be some method of storing these electrons at the top of the resistor. This is normally performed by a grid-coupling capacitor. It is omitted in this circuit because the crystal and its electrodes to which the electrical faces are connected have sufficient capacity to store the electrons, or charge.

These inherent capacitances need be only a few micromicrofarads in order to provide the necessary storage. The size of the grid resistor is determined to some extent by the amount of capacitance, in accordance with the time-constant formula for resistors and capacitors. This formula tells us that the time required to discharge 63.2% of any stored voltage is equal to the *product* of the components values involved—namely, the capacitance of the unit where the voltage (electrons or positive ions) is stored, and the resistive path over which the discharge must occur. If we assume a grid-resistor value of 300,000 ohms and an inherent crystal plus holder capacitance of 10 micromicrofarads, we can solve for time as follows:

$$\begin{aligned} T &= 300{,}000 \times 10^{-12} \\ &= 3 \times 10^{-6} \text{ second, or 3 microseconds.} \end{aligned}$$

If a crystal has a natural frequency of oscillation equal to 500 kilocycles per second, then one cycle of oscillation will occur in 2 microseconds. Thus, we see that the time constant of 3 microseconds is equal to one and a half cycles of oscillation.

Under these assumptions the circuit might oscillate satisfactorily, although when successful circuit operation depends on maintenance of a grid-leak bias voltage, it is usually desirable for this voltage to discharge *much more slowly* than is indicated here. In fact, it is more normal for the R-C combination to have a time constant equal to five or ten cycles. When we consider the equation $T = RC$, it is evident that the time constant can be made longer by increasing either the resistance or the capacitance in the circuit.

If we increase the value of the grid resistor to, say, 1 or 2 megohms we may overcome one objection, only to create another one. This problem, known as *squegging,* occurs as the oscillation builds up, causing successively larger amounts of grid-leakage current to flow each cycle. Eventually this current becomes great enough to cut off the oscillation, and it will remain cut off for many cycles (perhaps even hundreds of them) until the leakage electrons can escape from storage by flowing back to ground through the grid resistor.

A much simpler means of lengthening the time constant of the grid-discharge circuit is to add a small capacitance in parallel with the crystal and grid resistor. This permits using grid resistors of nominal size, on the order of 25,000 or 50,000 ohms.

## PHASE RELATIONSHIPS

Now to return to the phasing which should exist between the feedback and crystal voltages. The crystal oscillation must be sustained electrically by receiving one voltage impulse, or "kick," each time the feedback voltage reverses polarity. However, when the plate circuit is tuned to the *exact* crystal frequency, the condition in the previous sentence will be impossible to attain because the plate tank voltage and resulting feedback voltage will always be out of phase with the crystal voltage. Under such conditions, oscillation cannot occur.

By detuning the plate tank circuit slightly, it is possible to shift the phase of the feedback voltage enough that a tiny fraction of each cycle of feedback voltage will be in phase with the crystal voltage. This momentary in-phase condition is sufficient to reinforce the crystal oscillation. Such a condition is difficult to show, either with diagrams or from the waveform. However, it is subject to intricate mathematical demonstration, which we will forego in this text.

If the plate circuit is detuned toward a higher frequency, the circuit is then said to be slightly inductive—an often-used descriptive term which merits considerable elaboration.

Suppose the plate circuit is tuned to a somewhat higher frequency than that of the plate-current pulses resulting from grid-circuit action. Because these pulses are arriving at the lower frequency, they will not "see" a resonant tank circuit waiting for them. Instead, two reactive paths—one capacitive and the other inductive—present themselves. The pulses will be divided between the two in proportion to the amount of reactance presented by each path. The one offering the *lesser* reactance will get the *larger* share of current, and the circuit will also bear its name. The smaller share of current goes over the higher-reactance path. If the two reactances are the same, the pulses will be equally divided, of course, and the circuit is said to be *resonant.*

In fact, the formula for the resonant frequency of a circuit is derived from the formulas for inductive and capacitive reactance. For example:

$$X_L = 2\pi fL$$

and,

$$X_C = \frac{1}{2\pi fC}$$

Since, at resonance, the inductive reactance must equal the capacitive reactance, the resonant-frequency formula is derived as follows:

$$2\pi fL = \frac{1}{2\pi fC}$$

$$f^2 = \frac{1}{2\pi L \times 2\pi C}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where,

$X_L$ is the inductive reactance in ohms,
$X_C$ is the capacitive reactance in ohms,
f is the frequency in cycles per second,
L is the inductance in henrys,
C is the capacitance in farads.

It is obvious, from the equations for $X_L$ and $X_C$, that if a current is being supplied at the resonant frequency of an L-C combination, and then if the frequency of this current is lowered, the inductive reactance will be less for this lower frequency. Similarly, the capacitive reactance will be higher. Such a condition exists when the plate tank circuit is tuned above the crystal frequency—the inductor will have a lower reactance (opposition to electron flow) and therefore claim a greater share of plate current (also called line current). Consequently, the tank is said to be tuned inductively.

It is well to keep clearly in mind exactly which frequency is being discussed. For example, in addition to the frequency of the applied current, there may be a resonant circuit frequency, and the two could be entirely different in value.

## DETERMINING OPERATING FREQUENCY

If the crystal oscillates at a different frequency from that of the plate tank circuit, which circuit determines the over-all operating frequency? The answer: the circuit with the higher Q.

The Q, or quality, of a tuned circuit was described in Chapter 1 as the ratio between the electrons in oscillation and those which drop out each cycle because of circuit losses. A "clean" tuned circuit, consisting of inductance and capacitance plus a small amount of internal resistance, may have a Q of over a hundred. Such a circuit can be considered fairly "high quality." A crystal, on the other hand, may have a Q of over a thousand, and in special cases as high as a half million. The crystal used in the circuit of Figs. 2-2 and 2-3 could have a Q of two or even three thousand.

Therefore, in this circuit the natural frequency of the crystal determines the operating frequency of the circuit, and a tuned plate-tank circuit must be operated off-resonance to sustain oscillations.

## Chapter 3

# THE HARTLEY OSCILLATOR

The Hartley oscillator shown in the accompanying diagrams ranks high in popularity when radio-frequency oscillator circuits are mentioned. Recall that the function of any oscillator circuit is to generate an alternating current at the desired frequency. This circuit will be explained by assuming the desired frequency to be within the broadcast band—for example, 1,000 kilocycles (1,000,000 cycles) per second.

Figs. 3-1 through 3-4 show the operation of the Hartley oscillator during each quarter-cycle. The necessary circuit components are as follows:

C1—Radio-frequency tank capacitor.
L1—Radio-frequency tank inductor (also acts as an autotransformer).
C2—Grid-coupling capacitor.
R1—Grid-leak biasing resistor.
V1—Oscillator tube.
M1—Power supply.

Here are the currents at work in this circuit, and the colors they are shown in:

1. Oscillating tank current (blue).
2. Plate current (solid red).
3. Grid-leak biasing current (solid green).
4. Grid-driving current (dotted green).
5. Feedback current (dotted red).

Feedback occurs in the Hartley oscillator as current is drawn to the cathode through the tapped portion of coil L1. As more and more tube current (shown in solid red) flows, autotransformer action occurs between the tapped portion of L1 and the whole coil, causing another component of current to flow *down-*

*ward* through the coil. This is the feedback current, shown by the dotted red lines.

How the voltage polarities and current movements in the tuned tank are correlated with those in the cathode circuit of the tube, so that the feedback will have the appropriate phase to support the oscillation, will be discussed later. First, let us look at the individual currents in detail.

## OSCILLATING TANK CURRENT

Twice each cycle, the oscillating current (shown in blue) moves from plate to plate of tank capacitor C1, via coil L1. The values chosen from C1 and L1 are such that these two com-

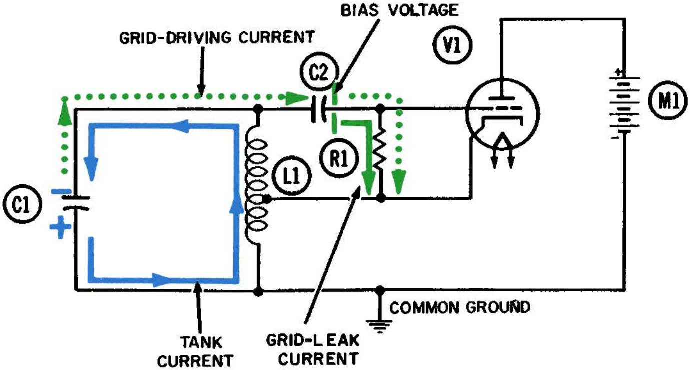


Fig. 3-1. Operation of the Hartley oscillator—first quarter-cycle.

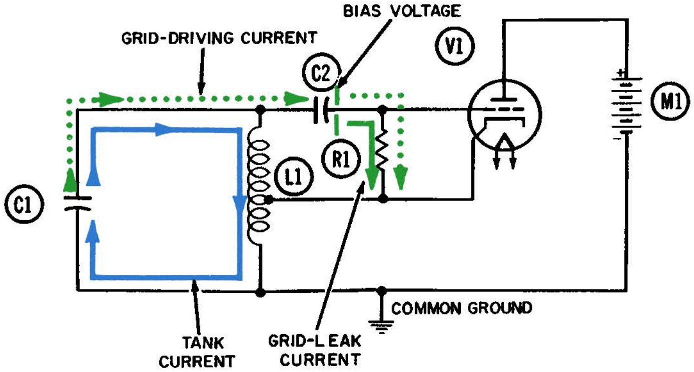


Fig. 3-2. Operation of the Hartley oscillator—second quarter-cycle.

ponents will be resonant at the desired frequency—1,000,000 cycles per second in our example. These values can be determined from the standard formula for finding the resonant frequency:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Fig. 3-1 shows the first quarter-cycle, during which the current flows from the lower plate of capacitor C1 to the bottom of coil

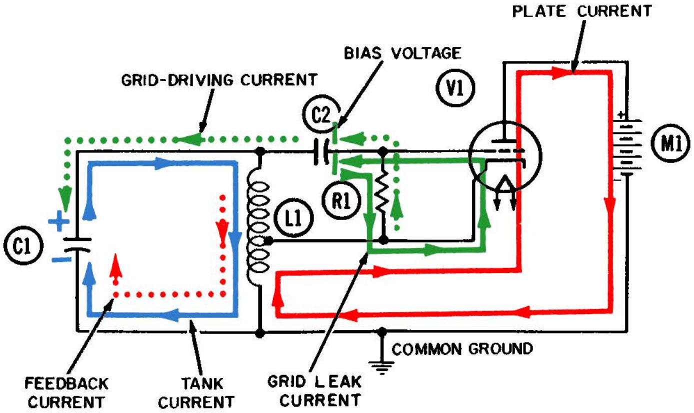


Fig. 3-3. Operation of the Hartley oscillator—third quarter-cycle.

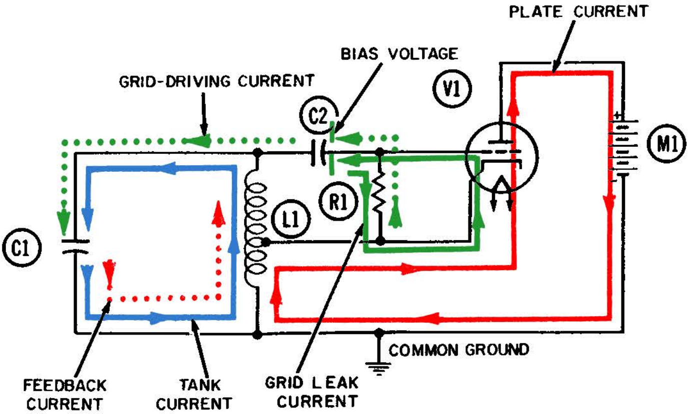


Fig. 3-4. Operation of the Hartley oscillator—fourth quarter-cycle.

L1 and through it, onto the upper plate of C1. The surplus of electrons makes the upper plate of C1 more negative than the lower one, as indicated by the blue minus sign.

This charging of the upper plate of tank capacitor C1 also delivers electrons to the left plate of coupling capacitor C2, which becomes charged to the same negative voltage. The number of electrons flowing onto the left plate of coupling capacitor C2 is accompanied by an equal number flowing *away* from the opposite plate. The resulting current, shown in dotted green, develops the grid-driving voltage across resistor R1.

The circuit diagram for the first quarter-cycle (Fig. 3-1) shows conditions as the grid-driving voltage becomes more and more negative. Electrons are flowing downward through R1, so we know it is more negative at the top, since electrons always flow from a more negative to a less negative area.

The second diagram (Fig. 3-2) denotes the second quarter-cycle, when the tank current has reversed its direction. There is no electron flow in the tank at the start, but once the flow starts, it builds up rapidly and reaches maximum at the end of the quarter cycle. The electrons formerly concentrated on the upper plate of tank capacitor C1 and the left plate of coupling capacitor C2 are distributed equally between both plates of C1 *the moment the quarter-cycle ends.* Now the tank voltage (measured at the top of the tank) is zero.

The waveform diagrams in Fig. 3-5 show this relationship. In interpreting sine-wave diagrams of current and voltage, it would be wise to clarify some basic assumptions. In the waveform representing tank current, the half-cycles *above* the reference line are arbitrarily chosen to represent electron current flowing *from* the upper plate of tank capacitor C1 *to* the lower plate (through tank coil L1, of course).

The half-cycles below the reference line represent electron current flowing in the opposite direction, or *upward* through L1. Whenever the sine waves cross the reference line, current is flowing in *neither* direction (meaning there is zero current). At this time the current is changing direction. As an example, at the *end* of the first quarter-cycle, electrons have been flowing upward and charging the upper plate of C1 with a negative voltage. During the second quarter-cycle, this current reverses and begins flowing downward.

By the end of the second quarter-cycle, the current is flowing downward through L1 at the maximum rate, and the negative voltage on the upper plate of C1 has discharged to zero. During the third quarter-cycle (Figs. 3-3 and 3-5), this downward electron flow continues, building up a peak negative voltage on the lower plate, and a peak positive voltage on the upper plate, of capacitor C1.

At the start of the fourth quarter-cycle, the electron current in the tank again reverses direction, as shown in Figs. 3-4 and 3-5, and begins flowing *upward* through coil L1. This action begins discharging the negative voltage on the lower plate of C1. So, at the end of the fourth quarter-cycle, the voltage on both capacitor plates is again equalized and the voltage at the top of the tank is zero.

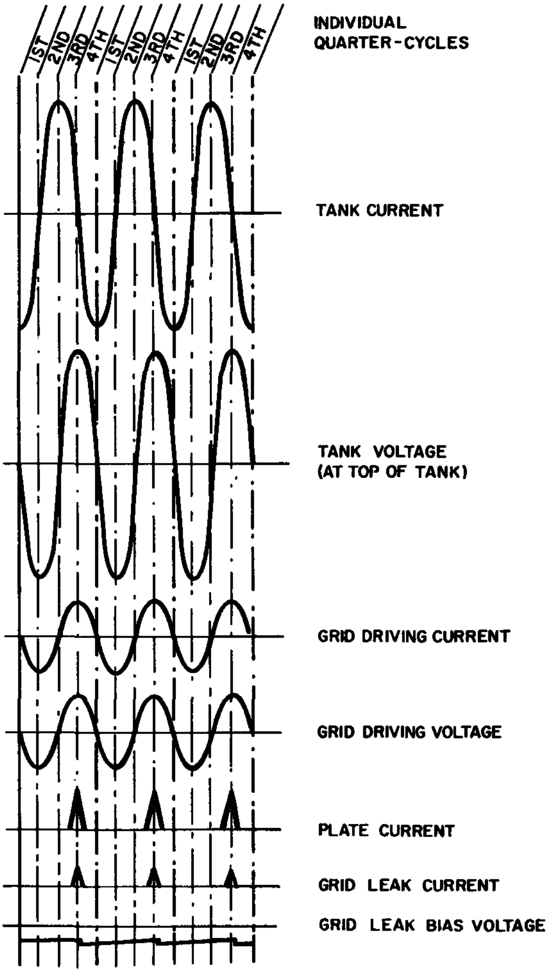


Fig. 3-5. Hartley-oscillator waveforms.

During the entire first two quarter-cycles, no current can flow through the tube itself because of the combination of permanent negative bias and instantaneous grid-driving voltages. The origin of the negative bias voltage becomes apparent when we study the action during the third quarter-cycle, depicted in Figs. 3-3 and 3-5. The tank current has now completed its journey through the inductor to the lower plate of the tank capacitor, charging the plate negatively and at the same time leaving a deficiency of electrons on the upper plate (which we know to be a positive voltage). Electrons are also being drawn away from the left plate of coupling capacitor C2 and, in turn, away from the grid area of the tube and upward through grid resistor R1. (This electron flow is shown in dotted green to differentiate it from the grid-leak current shown in solid green.) An instantaneous positive voltage is created at the grid and momentarily exceeds the permanent negative bias voltage. The result is that current is permitted to flow from cathode to plate at the end of the third quarter-cycle.

The plate current (shown in solid red) flows during the latter part of the third and first part of the fourth quarter-cycles, as shown in Fig. 3-5. This current will flow whenever the grid voltage is less negative than the cutoff voltage of the tube.

Grid-leak current (in solid green) flows for an even shorter time. This occurs at the end of the third and the start of the fourth quarter-cycles, when the instantaneous grid voltage is positive enough that the grid wires will attract and capture the negative electrons.

It is during the third quarter-cycle that the control-grid voltage is raised above the cutoff value and tube current flows. For the remainder of the cycle, the control-grid voltage becomes less and less negative as the tank current completes its journey through the tank inductor to the lower plate of the tank capacitor. As the grid voltage becomes less negative, the current through the tube continues to increase. The complete path for this tube current (shown in solid red) includes the lower portion of tank inductor L1.

When tapped in this fashion, an inductor is called an *autotransformer*. The action of an autotransformer is identical to that of a conventional transformer, where the windings are separated. The tube current shown in solid red can be considered the *primary* current in this transformer action, and the current it sets up in the tank circuit (shown in dotted red) is the *secondary* current. The latter is appropriately labeled the feedback current, since it transfers energy from the output (plate circuit) to the input (grid circuit).

Feedback in an oscillator circuit hinges on two essentials: One is a means for transferring energy from output to input. The other is that this energy must be in the proper phase to reinforce the oscillation in the grid tank circuit. The following discussion will show how the second essential is achieved.

The tube current in the cathode circuit flows in one direction only—from the common ground to the cathode, through the tube to the plate, then through the power supply and back to ground. However, transformer action will occur just as readily whenever a direct current increases or decreases as it will for outright reversals in the direction of current flow.

In Fig. 3-5 we see that plate current begins to flow during the third quarter-cycle, and that it builds up to maximum at the end of this quarter-cycle. Since all inductors act to oppose *any change* in current, this build-up will cause another current to flow in the opposite direction and buck the tube current as it passes through the lower portion of coil L1. This bucking current is called the counter emf (also, the back emf or back voltage) of the inductor and is shown in dotted red in Fig. 3-3.

As the third quarter-cycle comes to a close, this counter-, or secondary, current (shown in dotted red) also stops flowing in the tank circuit. During its brief life it has been flowing in the same direction as the tank current, thereby being at least partially in phase with the tank current and thus reinforcing it. The fact that such reinforcement has occurred can also be deduced from the following observation: At the end of the third quarter-cycle, both currents have independently delivered electrons to the lower plate of the tank capacitor and increased its negative voltage.

This secondary current both *starts and stops* during the latter part of the third quarter-cycle. Therefore, as depicted in Fig. 3-6 by the distorted sine wave representing feedback current, an entire half-cycle has occurred in less time than a quarter-cycle of tank current.

At the beginning of the fourth quarter-cycle, the tank current begins to flow upward through tank inductor L1, tending to neutralize the positive voltage on the upper plate of C1. An examination of the sine-wave relationships for this circuit (Fig. 3-5) will reveal that the tank voltage, plus the resultant grid-driving current and its attendant voltage developed across resistor R1, are all essentially in phase. Consequently, during the fourth quarter-cycle the positive tank-voltage decreases to zero and the positive grid voltage also disappears.

A reduced grid voltage in turn lowers the plate current flowing through the tube and, of course, through the lower portion of the inductor. This decrease in what we earlier identified as "primary" current results in transformer action between the whole winding and its lower portion. As before, the transformer action will oppose any change in current, so a secondary current starts flowing *upward* through the winding in a steadily increasing amount to compensate for the corresponding drop in the primary current.

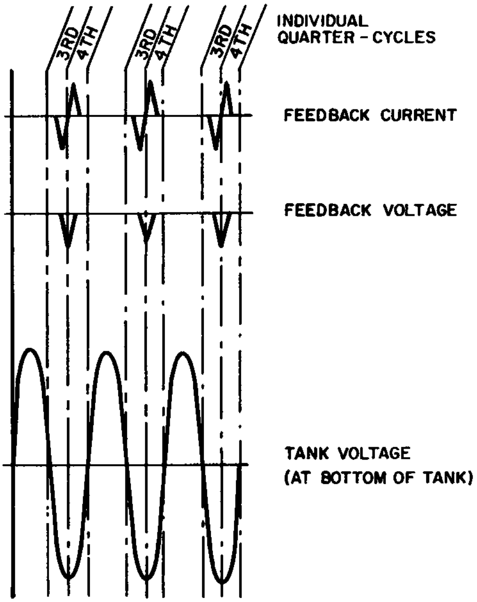


**Fig. 3-6. Feedback-current and -voltage waveforms in the Hartley oscillator.**

The plate current is cut off midway in the fourth quarter-cycle, and this secondary current also quickly drops to zero. During its brief span the secondary current flowed in the same direction as the tank current and the two can be considered roughly in phase. Again, the secondary current thus reinforces the oscillation in the tank. Fig. 3-6 shows that the feedback current will again go through half a cycle in less time than the tank current and voltage require for a quarter-cycle. It is also fairly obvious that the whole cycle of feedback current is a very distorted sine wave. Although not shown on its sine wave, the tank voltage (and current) will in turn be distorted, resulting in higher positive than negative peaks. An even more important phenomenon resulting from this and most other feedback is a shift in the tank frequency. In a Hartley oscillator, this shift is toward the lower end of the spectrum; therefore the circuit oscillates at a somewhat lower frequency than that computed using the standard frequency formula.

The feedback current drives additional electrons to the lower plate of tank capacitor C1. As a result, a negative pip (pulse) of voltage occurs at the end of each third quarter-cycle, as shown in Fig. 3-6. This extra component is then added to the tank voltage. Fig. 3-5 shows the changes in voltage, measured at the top of the tank, during each quarter-cycle.

For the sake of convenience, this sine wave has been inverted in Fig. 3-6 to show the tank voltage at the bottom of the tank. As you can see, the feedback-voltage pips are now in phase with the tank voltage and will reinforce it each cycle.

## Chapter 4

# THE COLPITTS OSCILLATOR

The Colpitts oscillator is another widely used circuit whose function is to generate a continuous alternating current at a fixed radio frequency. The Colpitts oscillator is usually operated under Class-C conditions, which means plate current flows during less than half of each cycle. Figs 4-1 through 4-4, depicting successive quarter-cycles, serve to explain how this circuit operates. The essential circuit components and their functional titles are as follows:

L1—Radio-frequency tank inductor.
C1 and C2—Radio-frequency tank capacitors.
C3—Grid coupling capacitor.
R1—Grid-leak biasing resistor.
V1—Oscillator tube.
C4—Feedback and blocking capacitor.
L2—Radio-frequency choke.

Each of the currents at work in the circuit is shown in a separate color for easier identification and analysis. The currents and their corresponding colors are:

1. Radio-frequency tank current (solid blue).
2. Unidirectional plate current (solid red).
3. Grid-leak biasing current (solid green).
4. Grid-driving current (dotted green).
5. Feedback current (dotted red).

Fig. 4-5 shows representative waveforms of the currents and voltages in this circuit. Two complete cycles are included, with dividing lines between each quarter-cycle so that momentary points on the waveforms can be related to their respective current directions and voltage polarities.

As in the Hartley oscillator, the feedback impulse is applied at the end of the tank opposite the grid connection. When the top of the tank is negative, the bottom is positive, and vice versa. Figs. 4-1 and 4-2 show the tank current flowing in a direction which delivers electrons to the lower plate of tank capacitor C2. At the end of the first quarter-cycle there is no voltage on the plates of C1 and C2, although maximum tank current is flowing between them. Proper interpretation of the tank-current sine wave of Fig. 4-5 tells us that peak amplitude is also the moment of maximum current. This particular sine wave has been drawn so that any displacement *above* the reference line means electrons are flowing downward through the tank coil, or *away* from the upper plate of C1, resulting in a positive voltage at this point.

By the same token, any displacement of the sine wave *below* the reference line means just the opposite—electrons are flowing *upward* through the tank coil, toward the upper plate of C1, resulting in a negative voltage there. The tank voltage waveform of Fig. 4-5 is the waveform appearing at this point.

At the end of the second quarter-cycle, the tank current has stopped flowing; this is also the moment the current sine wave crosses the reference line. Electrons have been delivered to the lower plate of C2, giving it maximum negative voltage. Likewise, the upper plate of C1 has an equivalent deficiency of electrons, or a peak positive voltage. These two voltage peaks are indicated in Fig. 4-2 by appropriate minus and plus signs on C2 and C1 respectively.

The grid-driving currents, shown in dotted green in Figs. 4-1 through 4-4, are driven by the oscillating voltage in the tank circuit and constitute the main load on it. The grid driving current is external from the tank current/voltage combination and, as such, is in phase with the voltage at the bottom of the tank. The voltage which this current develops across grid resistor R1 will be in phase with the driving current at all times (because current and voltage in a resistive path are always in phase with each other). Consequently, the grid-driving voltage will be in phase with the tank voltage when measured at C2, and exactly out of phase with the tank voltage when measured at the top of the tank, as portrayed in Fig. 4-5.

The directions indicated in Figs. 4-1 through 4-4 for the grid-driving current are the result of electron concentration (negative voltage) or deficiency (positive voltage) on the lower plate of tank capacitor C2. For instance, during the second and third quarter-cycles, there is always some negative voltage on C2, so the grid-driving current is repelled from it. But during the first and fourth quarter-cycles, the positive voltage on C2 draws the grid-driving current toward this point.

As explained previously, current does not actually flow through grid coupling capacitor C3—the electrons flowing onto one side of the capacitor drive an equal number off the other side. Conversely, whenever electrons are drawn off one plate of a capacitor, an equal number will be attracted to the other plate.

The grid-driving current will develop a positive-going voltage across resistor R1 during the fourth quarter-cycle. Midway through this quarter-cycle, the positive voltage cancels out the more permanent negative voltage resulting from grid-leak biasing action. The grid voltage is now less negative than the cutoff voltage, and plate current will start to flow through the tube. (The cutoff voltage is a negative value below which tube current cannot flow, and above which it can.)

Plate current begins to flow during the fourth quarter-cycle, as indicated in Fig. 4-5, and steadily increases until the grid voltage reaches zero just before the fourth quarter-cycle ends.

The conventional path for unidirectional plate currents is through the tube from cathode to plate; then through any load, where the essential work of the circuit is done; and finally, through the power supply to a common ground which provides the necessary return to the cathode. This plate circuit is no exception, as you will note by the solid red path in Fig. 4-4. The load is made up of feedback capacitor C4 and radio-frequency choke L2. It is necessary that the plate current flow onto the right plate of C4, and the radio-frequency choke is placed in the circuit to make sure it does.

A radio-frequency choke, as its name implies, will stifle the passage of radio-frequency currents. A choke is nothing more than an inductor, and the universal property of any inductor is that it will oppose any change in current. The *amount* of opposition depends on the inductance and on the *frequency* of the current trying to flow, as related by the mathematical formula for inductive reactance:

$$X_L = 2\pi fL.$$

While the plate current is increasing, it is unable to enter the choke, even though the normal path is through the choke to the power supply. Momentarily succumbing to this opposition, the plate current is diverted down the only other path available to it and heads for the right plate of feedback capacitor C4. This influx of electrons onto one plate of C4 drives an equal number away from the other plate and toward the tank circuit.

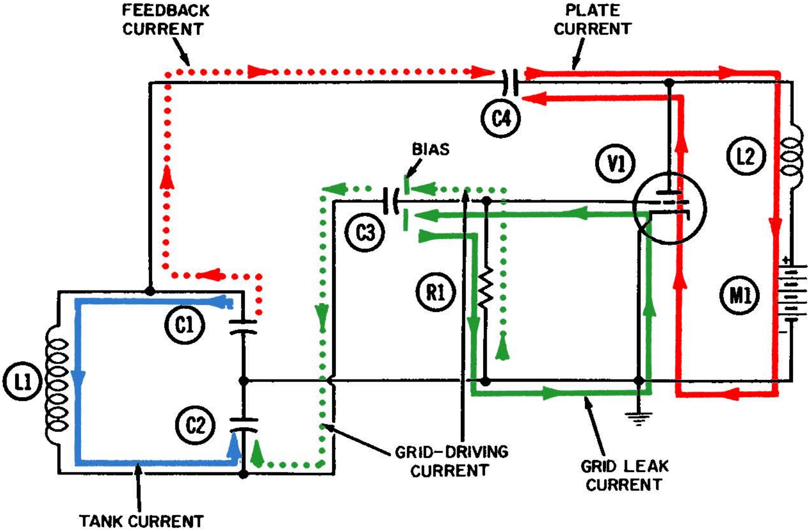


Fig. 4-1. Operation of the Colpitts oscillator—first quarter-cycle.

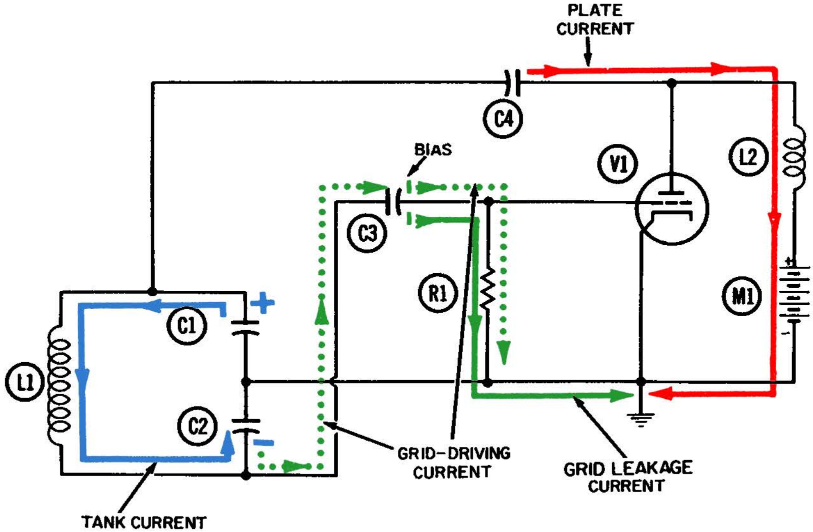


Fig. 4-2. Operation of the Colpitts oscillator—second quarter-cycle.

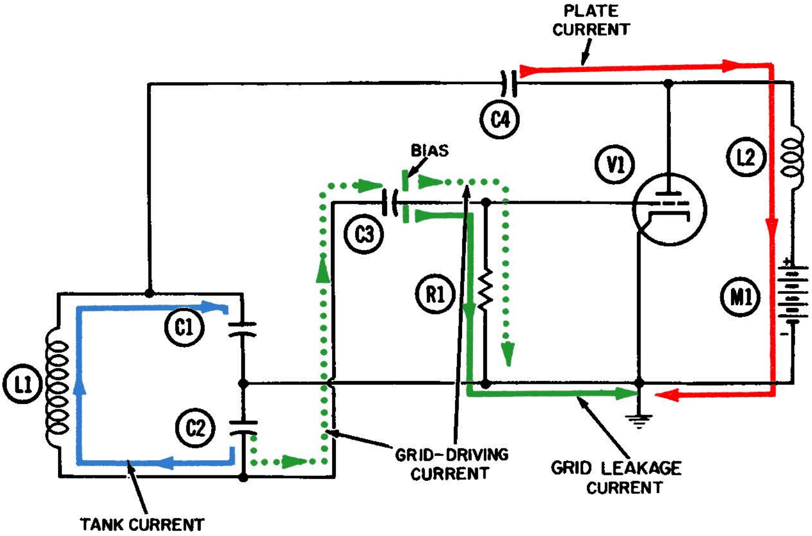


Fig. 4-3. Operation of the Colpitts oscillator—third quarter-cycle.

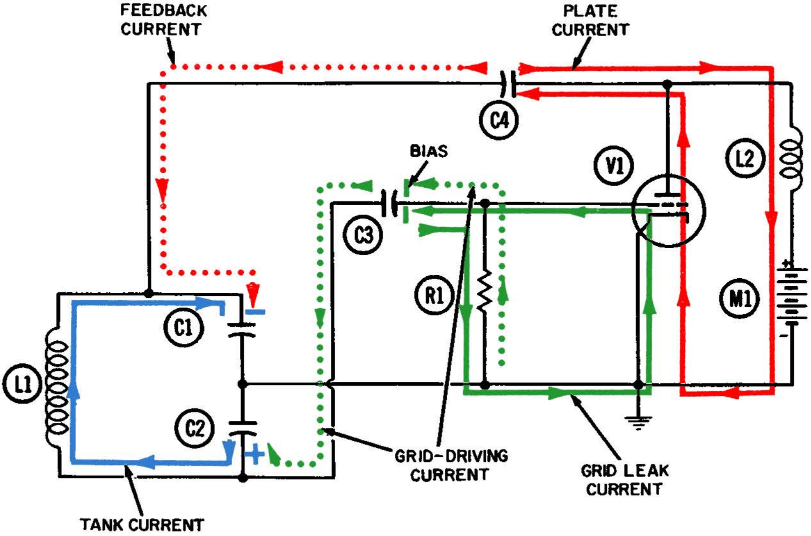


Fig. 4-4. Operation of the Colpitts oscillator—fourth quarter-cycle.

This is the way a feedback pulse is delivered from the output to the input circuit. The feedback current, shown in dotted red, should arrive in phase with the tank current in order to offer maximum support to the oscillation.

On static displays like circuit diagrams, it is obviously impossible to show the *exact* phase relationships between all different current-voltage combinations in a circuit. This can be done only with animated drawings, although it can be demonstrated graphically by using waveform diagrams like the one in Fig. 4-5.

An approximation of the phase relationship between feedback current and tank current is indicated in Fig. 4-5. As the fourth quarter-cycle draws to a close, both currents are delivering electrons to the top of the tank, where they go into temporary storage on the upper plate of C1. The peak value of the tank voltage is thus increased by the amount of feedback voltage resulting from the feedback current, and the cycle of oscillation is replenished or reinforced. Since one feedback pulse is provided for each cycle of oscillation and it is in the same approximate phase each time, the oscillation will continue indefinitely. The inevitable losses due to wire resistance, interaction with nearby objects, etc., are compensated for by the regular feedback pulse.

As soon as the next quarter-cycle begins (which corresponds again to Fig. 4-1), the tank current begins its journey from the upper to the lower side of the tank, through the inductor. This action begins delivering electrons to the lower plate of tank capacitor C2. The high positive tank voltage at this point begins to decrease, in turn reducing the voltage at the grid. The lower grid voltage immediately reduces the electron stream through the tube, as indicated by the waveform in Fig. 4-5, and the plate current falls to zero about midway through the first quarter-cycle.

Figs. 4-1 through 4-4 shows that a continuous current flows through radio-frequency choke L2 and the power supply. The choke and the feedback capacitor form an inductance-capacitance filter which maintains a fairly steady current flow into the power supply, even though the plate current is arriving in spurts. The tube current flows only at the end of the fourth and beginning of the first quarter-cycle.

During a brief portion of this plate-current flow, the grid-tank oscillation drives the grid positive, and grid-leak current (shown in solid green) begins to flow. It originates at the cathode with the plate current, but exits at the grid as a result of the negative electrons striking the momentarily-positive grid wires. From the tube, the current flows onto the right plate of grid capacitor C3, forming a pool of electrons (or negative voltage) there until they can drain off ("leak") back to ground and the cathode through grid resistor R1. This leakage goes on continuously, as indicated by the solid green lines on all four circuit-operation diagrams.

The negative voltage created at the grid by these grid-leak electrons is known as the grid-bias voltage, or more simply as the bias voltage. The instantaneous grid voltage is always the product of the permanent bias and grid-driving voltages, the current of which is shown in dotted green. The bias voltage very

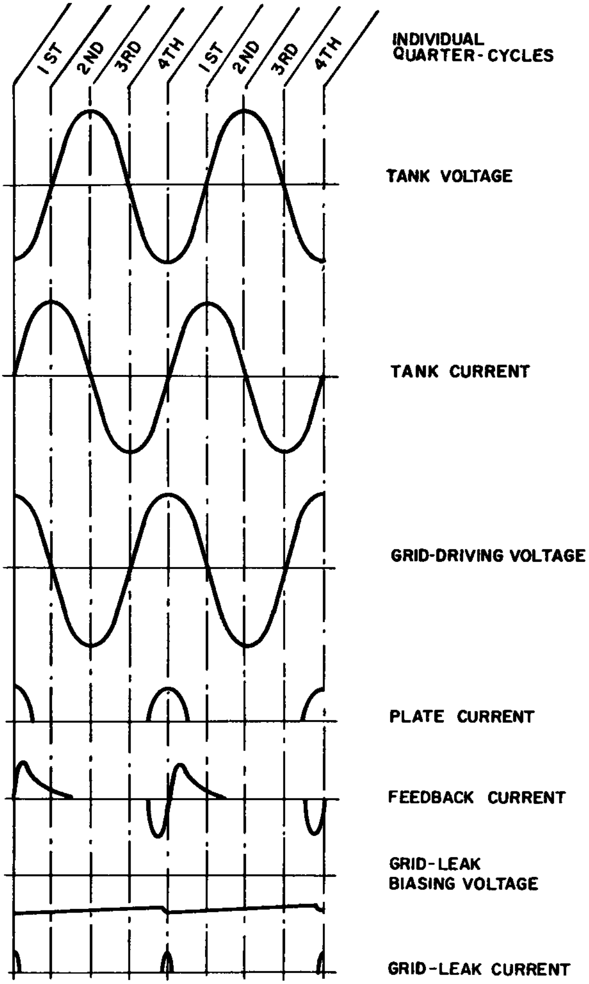


**Fig. 4-5. Voltage and current waveforms in the Colpitts oscillator.**

quickly stabilizes at an average value. When this value has been reached, we know that during each cycle, the number of electrons flowing into the "electron pool" on the right plate of C3 must equal the exact number flowing out. Otherwise, the bias voltage would not be stable. If more electrons come in during the fourth quarter-cycle than are drained down through the resistor during the whole cycle, the negative bias voltage will increase and act like the closing of a throttle to the electron stream through the tube. Now, fewer electrons will also be attracted from the electron stream to the control-grid wires, and the number coming into the electron pool on the capacitor will likewise be reduced. Therefore, the grid-leak voltage is automatically prevented from increasing indefinitely.

It can happen that more electrons will be drained away from the capacitor each cycle than will come in from the tube. This will occur when for any reason the oscillation is weakened, reducing the value of the grid-driving–current-voltage combination. When this happens the negative bias voltage must decrease until the outgoing electrons no longer exceed the incoming ones, at which time the bias voltage will again be stabilized. Thus, we see that natural limitations existing in either direction prevent the unlimited growth or decay of the grid-leak bias voltage, so that the oscillator tends to be self-stabilizing.

The values of grid-resistor R1 and capacitor C3 are important in the design of a grid-leak system. They are regulated by the time-constant formula, explained in Chapter 1, which states that:

$$T = R \times C$$

where,

T is the time constant of the combination in seconds,
R is the resistance in ohms,
C is the capacitance in farads.

It is usually more convenient to use microfarads rather than farads for the capacitance, in which case T will be in microseconds instead of seconds.

If, in this example, the tank current were suddenly stopped, the grid-driving–current-voltage combination would also die, and no more leakage electrons would flow out of the tube to the grid capacitor. The electrons which are stored there and make up the grid-bias voltage will immediately begin discharging through the grid resistor to ground. During one time-constant, 63.2% of this discharge will have been completed . . . after another equal period has passed, 63.2% of the remaining electrons will have discharged to ground . . . and so on.

Theoretically, it would take an infinite number of periods for any voltage to completely discharge itself. Practically speaking, as few as ten time-constant periods are more than sufficient, for in this length of time a voltage will discharge down to about a millionth of its original value!

In choosing suitable values of R and C for providing the grid-leak bias, we try to select ones whose product (in other words, time constant) is at least five times the period required for one cycle of the basic oscillation frequency. In other words, five or more cycles of oscillation (and grid leakage) will occur during each time constant. This assures us that the bias voltage will have relatively little chance to discharge to ground before another "shot" of electrons arrives from the tube. When this condition is satisfied, the combination of resistor and capacitor is identified as a long time-constant combination. That is, it is a long time constant *with respect to the particular frequency under consideration*—the basic oscillator frequency.

There is still another important consideration in choosing the size of the resistor, and that is the amount of load the grid circuit places on the oscillating tank current. It is desirable for this loading to be as small as possible (consistent with getting the job done). The task being performed here is driving the grid at the tank frequency, and the grid-driving current (shown in dotted green) performs this task, as discussed previously. If allowed to become too large, this current will overload the tank oscillation. The grid-driving current can be kept small by increasing the value of the grid resistor. If the latter has an extremely low resistance, it will constitute a heavy load on the tank voltage because it will permit an extremely large grid-driving current to flow—so large, in fact, that the tank voltage could never reach the desired peak value. On the other hand, if the grid resistor has an extremely high value, it will constitute a very light load on the tank voltage because it will allow only a very small grid-driving current to flow.

The *amount* of grid-driving voltage will always equal the amount of tank voltage. The former can be developed by either a small current flowing through a large resistor, or a large current through a small resistor. This is in accordance with Ohm's law, which tells us the amount of voltage developed across a resistor is proportional to the amount of current flowing through it, and also to the size of the resistor.

## Chapter 5

# THE TUNED-PLATE – TUNED-GRID OSCILLATOR

The tuned-plate–tuned-grid (TPTG) oscillator, as its name implies, utilizes tank circuits in both the plate and grid circuits. Feedback from output to input, a necessary function in any self-sustained oscillator, is accomplished by using the interelectrode capacitance between the plate and grid.

Figs. 5-1 and 5-2 show the circuit and the currents flowing for each half-cycle of operation. The circuit components are as follows:

L1—Grid tank inductor.
C1—Grid tank capacitor.
C2—Grid coupling capacitor.
R1—Grid-leak bias resistor.
V1—Oscillator tube.
L2—Plate tank inductor.
C3—Plate tank capacitor.
C4—Output coupling capacitor.
C5—Decoupling capacitor.

The output voltage of the oscillator is capacitively coupled, via C4, to the next stage. Capacitor C5 acts as a decoupling filter to keep pulses of plate current from entering the power supply and affecting its output voltage.

There are three main groups of electron currents whose movements, if analyzed, will lead to understanding the operation of this oscillator circuit. These groups might be labeled as follows:

1. Alternating radio-frequency currents.
2. Unidirectional radio-frequency currents.
3. Pure direct currents.

## ALTERNATING RADIO-FREQUENCY CURRENTS

There are two tank currents in the alternating RF category. One is in the grid circuit and is shown in dotted blue; the other is in the plate circuit and is shown in solid blue. The feedback currents, which are driven by the plate tank current, appear in dotted red; and the output current, which provides the driving

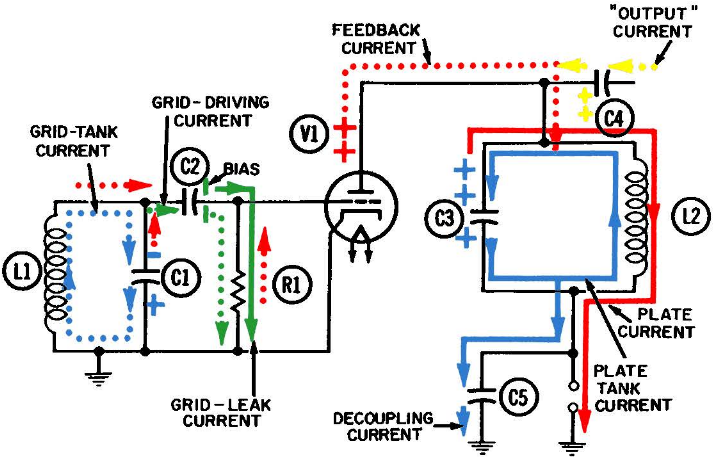


Fig. 5-1. Operation of a tuned-plate–tuned-grid oscillator—first half-cycle.

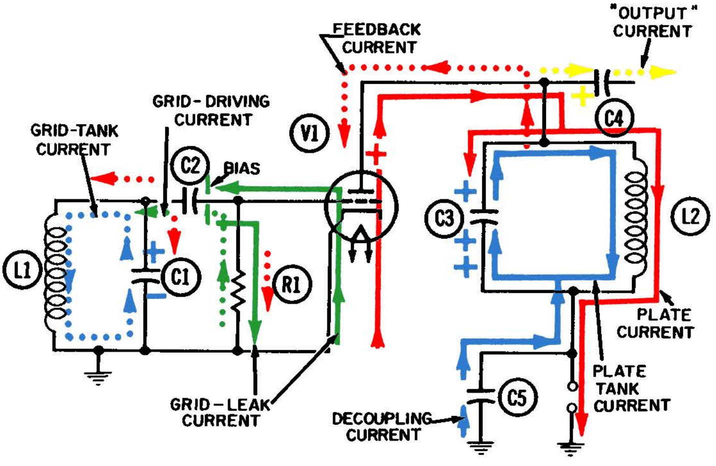


Fig. 5-2. Operation of the tuned-plate–tuned-grid oscillator—second half-cycle.

current and consequently the driving voltage for the next stage, is in gray.

For successful self-oscillation, the two tank circuits must be tuned to approximately the same frequency. When the tube is first turned on, the initial surge of plate current sets up oscillation in the plate circuit at its natural, or tuned, frequency. Recall that even a single surge of current or a sudden voltage change will cause any tuned circuit to oscillate at its natural frequency. Even though the oscillation is not sustained by further voltage or current changes, it will continue for several cycles before the initial energy is expended. The purpose of oscillator circuitry is to continue the oscillation indefinitely by providing such a voltage or current change, usually once each cycle. This repetitive action is provided here by pulses of plate current.

As the initial surge of tube current reaches the plate circuit, its voltage-current conditions will correspond roughly to those in Fig. 5-2. The voltages at the plate of the tube, the entrance to coupling capacitor C4, and the top of the tuned tank will all be positive, as indicated by the plus signs, but these voltages will be lower in value than the supply voltage present on the other side of the tank.

Once this uneven distribution of current and consequently voltage exists across the tuned tank circuit, the charge will redistribute itself in an attempt to overcome the unbalance. Since the lower plate of tank capacitor C3 is more positive than the upper plate, current will flow from top to bottom. If there were no inductance or resistance in the current path, this redistribution would occur instantaneously. However, the primary characteristic of any inductance is that it tends to oppose any change in current: If no current is flowing, an inductance tends to oppose any build-up; and once current flows, the inductance tends to prevent it from decaying.

These properties of inductance should enable us to see why an oscillation is set up when electrons are redistributed. Instead of taking place instantaneously, the current requires the equivalent of a quarter-cycle of oscillation to build up from zero to maximum. After maximum current is flowing, the inductive effect will try to keep it from dying out. At this instant the voltages are the same on each side of the tank capacitor, meaning both charges have been equally distributed. The current, however, requires another quarter of a cycle to decay to zero. At the end of this cycle the charge again is unevenly distributed, but in the opposite direction. The flow of electrons from top to bottom during the next quarter cycle—*after* the voltages on the two capacitor plates have been equalized—has charged the bottom plate to a lower positive voltage than the top plate.

The first half-cycle is shown in Fig. 5-1. The greater number of plus signs on the upper plate indicates that midway in the first half-cycle the upper plate is more positive than the lower one. This is confirmed by the sine-wave representation of tank voltage in Fig. 5-3, which shows the voltage at the *top* of the tank—in this case, also the point where output voltage is taken off.

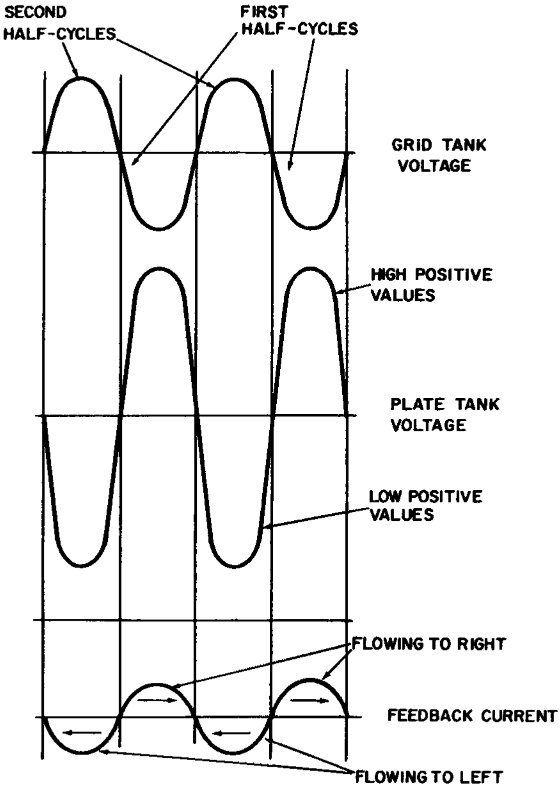


**Fig. 5-3. Current and voltage waveforms in the tuned-plate–tuned-grid oscillator.**

Fig. 5-2 depicts current-voltage conditions during the second half-cycle of oscillation. The voltage unbalance across the tank capacitor will again attempt to neutralize itself in the following manner: Since there is an excess of positive ions on the upper plate, current will be drawn from the lower plate, through tank inductor L2. Again the inductor will oppose both the build-up and the decay of electron current. As a result, redistribution of the electric charge will again go too far—the voltage unbalance across the tank will be reversed a second time, with the top plate now less positive.

In order to see how this oscillation sustains itself indefinitely, we must now consider what has been happening in the rest of the circuit. During the single cycle just described, certain inevitable losses will have occurred. Hence, at the end of the first complete cycle, the voltage difference between the two plates of tank capacitor C3 will be smaller than it was at the beginning. Another way of visualizing this condition is to consider that fewer electrons will complete the cycle than started it, some dropping out because of internal circuit resistances. These losses, which must be replenished before the next cycle begins, are supplied by "turning on" the plate current at the appropriate moment. Let us see how this is accomplished.

The oscillating current (shown in solid blue) in the plate tank circuit feeds three external paths, or loads, These paths are decoupling filter capacitor C5 (also shown in solid blue), output coupling capacitor C4 (shown in gray), and the feedback path to the plate and grid, shown in dotted red. (The interelectrode capacitance between these two elements couples the feedback to the grid.) During the first half-cycle in Fig. 5-1, this feedback current draws electrons away from the plate. In Fig. 5-2 the polarity of the oscillating voltage is reversed and feedback current is driven back toward the plate, as shown by the arrow on the dotted red feedback line.

There are three alternate paths in the grid circuit, and current flows in each one, in response to the feedback current in the plate circuit. These grid components are also shown in dotted red to help tie them in with the feedback current, and also to differentiate them from the grid-driving current (in dotted green) and the grid-leak current (in solid green) which are also flowing in the grid circuit.

Note how all three components of the feedback current are flowing in unison. During the first half-cycle they are all drawn to the *right,* and during the second half-cycle they are all flowing to the *left*—both times being driven by the plate tank voltage. These current components are said to be *in phase* with the plate tank voltage.

The components of current to the left of the grid capacitor actually "deliver" the feedback pulse to the grid tank circuit and thereby set up an oscillation of appropriate phase to support the plate-circuit oscillation. The oscillation current in the grid tank has been shown in dotted blue.

The oscillation in the tuned-grid circuit will build up to a maximum strength determined by:

1. The strength of the feedback pulses from the plate circuit.
2. The amount of losses during each cycle.

The grid-circuit oscillation will have internal losses due to electrical resistance, dielectric leakage, etc. Normally they will be very small, only a fraction of one per cent each cycle. Thus, this is a "high-*Q*" circuit as explained previously.

In addition, the oscillation actually drives the control-grid voltage to its two extremes by sending the grid-driving current (shown in dotted green) up and down through grid resistor R1. This current flows in phase with the oscillating voltage in the grid tank and thus acts as a load on the oscillation by adding to its total losses during each cycle.

The oscillation will build up until the total losses during each cycle are equal to the energy supplied by the feedback pulse. When energy lost equals energy supplied, the grid oscillation will become stabilized.

## UNIDIRECTIONAL CURRENTS

Currents which flow essentially in only one direction are classified as direct, or unidirectional, currents. In our circuit they are the pulsating DC of the plate current (shown in solid red), and the grid-leakage current (shown in solid green). The plate current replenishes each cycle of oscillation, and the grid-leak current provides the grid voltage (also called operating bias) for the tube.

In any vacuum tube, electrons in the tube stream will tend to strike the control grid whenever it is more positive than the cathode. We have already seen how the grid voltage is made positive, midway in the second half-cycle, by the grid tank oscillation. Electrons (shown in solid green) will now be attracted to the grid wires and leave the tube via the control grid. Thus, three separate electron currents are flowing in the grid circuit. Shown in solid green, dotted red, and dotted green, they represent the grid-leak, feedback, and grid-drive currents respectively.

Fig. 5-3 shows the waveform for the feedback current as being in phase with the plate tank voltage. This means that during the first half-cycle (Fig. 5-1) the plate tank voltage, being at its most positive value, draws the electrons to the *right,* or toward the high positive voltage. Conversely, during the second half-cycle the plate tank voltage has its lowest positive voltage and repels the electrons of the feedback current, moving them to the left as in Fig. 5-2.

The grid-leakage electrons accumulate on the right plate of the grid capacitor and build up a permanent negative voltage there, as indicated by the solid green minus signs. These electrons drain continuously downward through grid resistor R1, the amount of current depending on the quantity of electrons in storage, the size of the grid capacitor, and the resistance of grid resistor R1.

This current flow through the resistor is pure DC; consequently, it is represented by a solid green line in both Figs. 5-1 and 5-2. Grid resistor R1 and grid capacitor C2 form a conventional long time-constant R-C combination so the grid-leak voltage will remain steady in the face of the pulsating electron current coming to it from the tube. This current enters the grid capacitor during the second half-cycle only, when the control grid has been driven positive. (During the first half-cycle the control grid has been driven negative and no grid-leak electrons can leave the tube.)

The amount of grid-leak voltage can be computed from two separate formulas. The first one, known as Coulomb's law, states that:

$$Q = C \times E$$

where,

Q is the quantity of the charge in coulombs,
C is the value of the capacitor in farads,
E is the voltage in volts.

The second formula—much more widely used—is Ohm's law, which states that:

$$E = I \times R$$

where,

E is the voltage across a resistor in volts,
I is the current flowing through the resistor, as a result of that voltage, in amperes,
R is the resistance of the resistor in ohms.

The presence of this fixed biasing voltage at the grid accounts for the fact that the grid voltage is always lower than the grid tank voltage driving it. The voltage at the top of the grid tank fluctuates around zero as a reference point, whereas the voltage at the grid fluctuates around the negative biasing voltage, represented by the solid green minus signs. The control-grid voltage momentarily becomes positive in the middle of each half-cycle and allows leakage electrons to leave the tube via the control grid.

The plate current will flow for a longer part of each cycle than the grid current. For every value of plate voltage there is a negative grid voltage below which plate current cannot flow and above which it can.

Note that the tube conducts electrons when the plate voltage is at or near its lowest value. In the middle of the second half-cycle, for instance, we see the lowest concentration of plus signs—representing positive ions—at the plate and at the top of the tuned tank. This condition is brought about by the oscillating electrons in the plate tank circuit of course, and can be confirmed from the sine waves of voltage in Fig. 5-3. Each pulse of plate current arrives at the top of the tank and adds to the oscillating electrons concentrated there, thus replenishing the oscillation. The amount of this reinforcement must compensate exactly for the internal resistance losses and the output and feedback loads faced each cycle by the oscillation.

## POWER-SUPPLY DECOUPLING

In Figs. 5-1 and 5-2, capacitor C5 is placed in parallel with the power supply to sidetrack, or decouple, large fluctuations in current before they reach the power supply. Otherwise, in flowing through the power-supply filters, these currents could cause corresponding voltage fluctuations which would be reflected into other vacuum-tube stages.

It was shown previously that the oscillating electrons in the plate tank will flow out along any available path, such as the line to the power supply. When a capacitor is placed in parallel with this line (as C5 has been), the oscillating current will choose this alternate path because of its lower impedance. Thus, most of the current fluctuations are diverted harmlessly into C5.

This decoupling current is shown in solid blue so you can see its relationship to the oscillating tank current driving it. The decoupling network constitutes one more load, or loss, for the oscillating voltage, along with the feedback and output currents described previously.

A small decoupling resistor is often added in the power-supply line to provide additional filtering. Even without it, the power-supply impedance and the filter capacitor constitute an effective filtering combination.

## TANK-CIRCUIT TUNING

In this oscillator circuit the plate tank must be tuned "slightly inductive" with respect to the grid tank. In other words, the plate tank should have a somewhat lower resonant frequency. One way of accomplishing this is to add more inductive reactance to the plate tank by increasing the inductance of L2.

However, it is also possible to lower the resonant frequency of a tuned circuit by adding capacitance and thereby lowering the capacitive reactance. Now the inductive reactance is greater, and the circuit will again be tuned slightly inductive as before.

Conversely, tuning a circuit "slightly capacitive" means to *increase* its natural frequency. Here the capacitance must be lowered in order to increase the capacitive reactance of the circuit. As before, the same result would be obtained by lowering the inductance to decrease the inductive reactance in the circuit.

Figs. 5-1 and 5-2 give no hint of a frequency difference between the two tanks. If the phase relationships were exactly as shown in these diagrams, the circuit would be unable to support its own oscillation for these reasons: The plate current reaches the plate tank at the precise moment it can give the most support to the oscillation in the tank. However, the feedback current from the plate tank will deliver a pulse to the grid circuit at the wrong instant to support the grid-tank oscillation. In fact, the oscillation will be dampened because the current-voltage combination in the grid circuit is always exactly out of phase with the grid tank voltage. The dotted red arrows in Figs. 5-1 and 5-2 represent the feedback current in the grid circuit. As you can see, it is flowing in the opposite direction from the external grid-driving current produced by the grid tank oscillation. It is likely, under these phase conditions, that the oscillation in the grid tank would not be allowed to build up at all.

When the oscillation in the plate tank is lower than the resonant frequency of the grid tank circuit, the feedback current will "see" two different impedances in the grid tank—one in the direction of the tank capacitor, and the other in the direction of the tank inductor. At the lower feedback-current frequency, the inductor will have much lower reactance than the capacitor, so most of the feedback current will be shunted into the inductor path.

Because the two tanks have different natural frequencies, neither operates at its own resonant frequency. The pulses of plate current, released once each cycle at the grid-tank current frequency, will arrive slightly early for maximum reinforcement of oscillation in the plate tank. This will shorten each cycle of oscillation by hastening the end of one and the beginning of the next one. Instead of being a true harmonic waveform, each cycle will be somewhat distorted, and the plate oscillation will occur at slightly *higher* than the resonant frequency of the plate tank.

By similar reasoning, the grid oscillation is slightly *lower* than the resonant frequency of the grid tank. This oscillation is sustained by the feedback pulses coupled from the plate to the grid via interelectrode capacitance. The feedback current, in dotted red, is driven by the tank voltage in the plate circuit and must stay in phase with it at all times.

It is impossible to show, in Fig. 5-1 and 5-2, how the phase relationship of the feedback current is able to support the grid oscillation. This can be demonstrated graphically and mathematically, but it would require extraordinarily complex waveforms and computations.

It is sufficient to say that the feedback current has a slightly lower frequency than the grid oscillation and can thus provide sufficient "kick" to sustain oscillation during each cycle. In the process the feedback current, itself driven by a distorted current waveform, manages to distort the oscillating current waveform in the grid circuit. Also, the feedback current lengthens each cycle so that oscillation will occur slightly below the resonant frequency of the grid tank.

## Chapter 6

# THE ELECTRON-COUPLED OSCILLATOR

The name *electron-coupled oscillator* (ECO) is derived from the way the oscillation in the plate tank circuit is supported or replenished by fluctuations in the electrons streaming through the tube. Upon reflection we will realize that the name *electron coupling* does not describe something unique to this circuit, since the oscillation in *any* plate tank circuit is likewise replenished by fluctuations in the electron stream.

Figs. 6-1 and 6-2 show the operation of the electron-coupled oscillator for each half-cycle. Inspection of the circuit will reveal a Hartley-type oscillator between the grid and cathode. Since the Hartley oscillator was covered in detail in Chapter 3, its mode of operation will be reviewed only briefly here. The necessary components of an electron-coupled oscillator include:

C1—Grid tank capacitor.
L1—Grid tank inductor (used as an autotransformer).
R1—Grid-leak bias resistor.
C2—Grid coupling capacitor.
V1—Tetrode vacuum tube.
C3—Screen-grid bypass or filter capacitor.
R2—Variable resistor used for adjusting the screen-grid bias voltage.
C4—Plate tank capacitor.
L2—Plate tank inductor.
M1—Power-supply or other voltage source.

These components form convenient *combinations:*

C1 and L1 form a tuned oscillatory circuit.
C2 and R1 form a conventional RC filter with a long time-constant.
C3 and the upper part of R2 form another long time-constant RC filter.
C4 and L2 form a second tuned oscillatory circuit.

The currents at work in this circuit include:

1. Grid tank current (dotted blue).
2. Feedback current (dotted green).
3. Plate and screen-grid currents (solid red).
4. Grid-leak bias current (solid green).
5. Screen-grid "biasing" current (dotted red), which might also be considered a voltage-divider current.
6. Plate-tank oscillating current (solid blue).

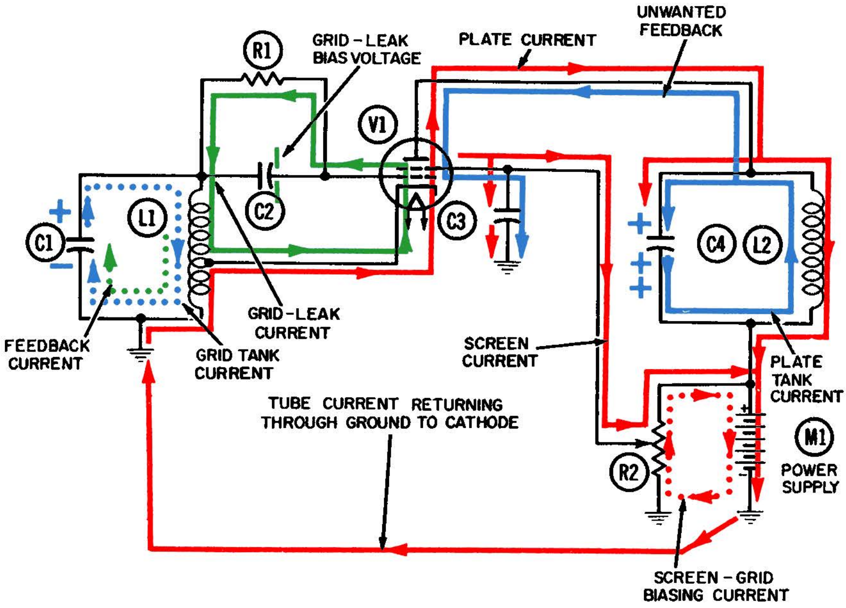


**Fig. 6-1. Operation of the electron-coupled oscillator—positive half-cycle.**

The grid tank current (dotted blue line in Figs. 6-1 and 6-2), oscillates between the upper and lower plates of capacitor C1 through inductor L1, alternately driving the grid negative and positive. To keep the tank current oscillating, it is periodically replenished or strengthened by the feedback current (dotted green line). The latter in turn is driven by the plate current through the lower portion of inductor L1.

Fig. 6-1 depicts the positive half-cycle of operation. Grid tank electrons are amassed on the lower plate of capacitor C1, making the upper plate positive—and also the control grid, since it is coupled to the top of the tank through capacitor C2. A pulse of plate current is released through the tube and arrives at the top of the tuned tank (L2-C4) at the moment its voltage is least positive (depicted by the single plus sign on the upper plate of C4 in Fig. 6-1). Being composed of negative electrons, the plate-current pulse lowers the already low positive voltage and thereby replenishes the oscillation in the plate tank.

Some of the current exits from the tube at the screen grid and flows through the upper portion of potentiometer R2, through the power supply to ground, and back to the cathode.

Another current leaves the tube at the control grid in the form of grid-leak current, shown by the solid green lines. This occurs only once each cycle, when the control-grid voltage becomes momentarily positive. Because of the high resistance of grid resistor R1, these electrons cannot immediately return to the cathode, but will accumulate on the right plate of grid capacitor C2, building up the negative grid-leak bias voltage. Throughout the entire cycle, there has been a slow and continuing drain of electrons back to the cathode, through the grid resistor and the upper portion of L1.

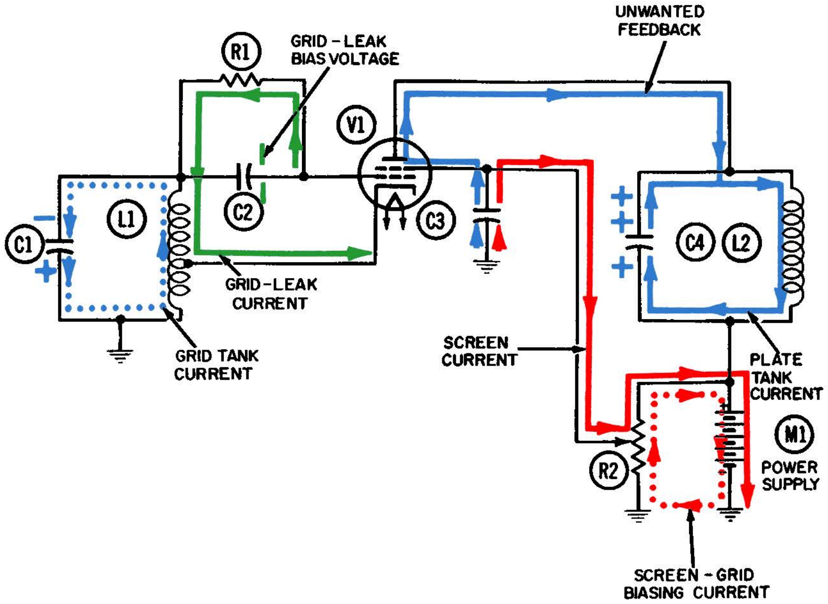


Fig. 6-2. Operation of the electron-coupled oscillator—negative half-cycle.

As with plate and screen currents, a closed path back to the cathode must be available. Otherwise, enough electrons will accumulate on the grid capacitor and on the grid itself that the flow of tube current will be cut off entirely (known as "grid blocking").

Fig. 6-1 also shows a feedback current (dotted green line) flowing in the grid tank. This current is produced by the autotransformer action of the inductor. (For a fuller treatment of the phase relationships between the grid-tank, plate, and feedback currents, refer to the chapter on the Hartley oscillator.)

This electron-coupled oscillator is a special tuned-plate–tuned-grid configuration. Its distinguishing feature is that the grid and plate oscillations are isolated from each other by the screen grid. Hence, there can be no feedback from plate to grid. An unwanted feedback current (solid blue line in Figs. 6-1 and 6-2) flows from the top of the plate tank and back to the plate, where it is coupled into the screen-grid circuit by interelectrode capacitance. In the screen circuit we see it being bypassed harmlessly to ground through capacitor C3.

There is nothing mysterious about this coupling from plate to screen by means of interelectrode capacitance, nor about the bypassing the feedback to ground. The same electrical principle is employed for both—namely, the natural ability of a capacitor (including two objects having a capacitance toward each other) to pass an alternating current. Fig. 6-1 shows a half-cycle of this unwanted feedback current flowing from the plate tank to the plate, from the screen grid to the upper plate of capacitor C3, and finally from the lower plate of C3 to ground. In the negative half-cycle of operation of Fig. 6-2, these directions are reversed.

You may wonder why feedback from the plate tank is unwanted in this circuit; in others such as the crystal or TPTG, the continuance of the oscillation *depends directly* on feedback between the output (plate) and input (grid) circuits. Obviously, the reason is the Hartley oscillator in the grid circuit. As explained in Chapter 3, it needs no feedback from the plate, since it generates its own between the cathode and grid circuits.

One of the virtues of an electron-coupled oscillator circuit is its frequency stability, made possible by the isolation between the load circuit (plate tank) and the basic oscillation in the grid tank.

The oscillating current in the plate tank is generated for the sole purpose of getting it to perform some useful function. But in order to do so, it must first be coupled out of this circuit and into another one. One way is by transformer coupling between L2 and another inductor (not shown). Another is to connect the coupling circuit directly to the normal output point at the top junction of C4 and L2.

Whichever means is used, it is inevitable that a new current will flow in the coupling circuit. Driven by the current/voltage combination in the plate tank, it will have the *same frequency* as, and its strength will be *proportional* to, the plate tank oscillation driving it. Thus, it constitutes a load on the plate tank oscillation and both weakens and detunes it. The detuning can perhaps be better visualized by considering the frequency formula:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

and then recognizing that the proximity of additional coupling components—whether they be capacitors, inductors, resistors, or any combination—will change the effective values of L and C, and consequently the frequency.

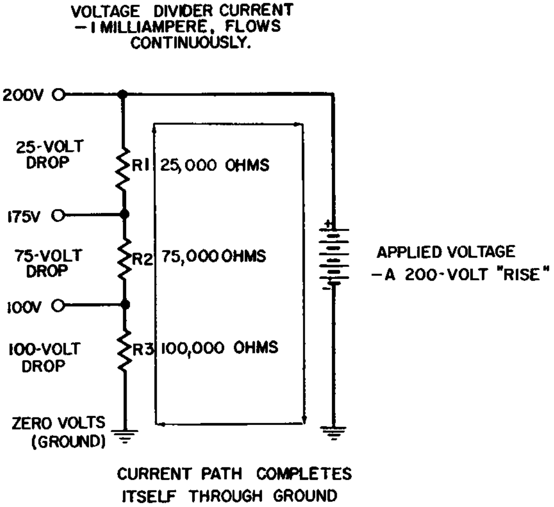


Fig. 6-3. A simple voltage-divider network.

The purpose of the screen grid and its bypass capacitor is to shunt the feedback current harmlessly to ground before it reaches the grid. The strength and frequency of the feedback will vary with changes occurring in the plate tank oscillation as a result of loading. Hence, if allowed to reach the grid circuit, such feedback will change the basic oscillator frequency being generated in the grid tank.

A pentode tube is often used in place of the tetrode shown in Figs. 6-1 and 6-2. Because its plate current is relatively unaffected by variations in plate voltage, a pentode will make a significant contribution to the *amplitude* stability of the plate tank oscillation. In simpler terms, any variation in coupling or loading between the plate tank circuit and the next stage or circuit may modify the strength of the oscillation, and accordingly, the strength of the voltage peaks at the top of the tank. However, these variations in plate voltage will cause no significant change in the plate current coming through a pentode. It is true that an unvarying plate current cannot correct existing deviations in amplitude or strength—but at least it will not be the source of new ones. In this respect, the pentode has the advantage over the less stable tetrode. If the tetrode of Figs. 6-1 and 6-2 is replaced by a pentode, all other currents will remain relatively unchanged.

The screen-grid biasing current (dotted red line) deserves special mention. Driven by the power-supply voltage, this current flows from the negative terminal of the power supply (the ground or neutral point, in other words), upward through potentiometer R2, and back into the positive terminal of the power supply. As a result of this current, a voltage is developed across R2 and a partial voltage exists at any point along this resistor, the amount depending on the distance between the two segments on each side of the contact point. Calculation of the voltage at any point is a straight Ohm's-law problem.

When a potentiometer is connected across a voltage source as is done here, this combination becomes a special form of voltage divider. Resistor R2 might be considered as being made up of five or even ten smaller resistors, all connected in series across a voltage source. Each resistor serves to divide the available voltage into smaller ones which will always add up to the applied voltage. This is the meaning of Kirchhoff's law that all voltage drops and all voltage increases around a closed circuit must add up to zero. (Watch those polarity signs!) The following paragraph makes the meaning a little clearer.

In interpreting Kirchhoff's law, an applied voltage is considered a voltage increase and given a positive sign, whereas voltages developed across resistive loads are considered drops and given an opposite, or negative, sign. Thus, when a certain number of positive units are added to an equal number of negative units, the sum is zero of course.

Fig. 6-3 shows a sample voltage-divider circuit closely resembling the one used in the screen circuit of Figs. 6-1 and 6-2. Three resistances in series—R1, R2, and R3—have replaced the potentiometer. Their values are 25,000, 75,000, and 100,000 ohms, so the series resistance of the combination is 200,000 ohms. With an applied voltage of 200 volts, we can calculate the current flowing in this closed circuit by using Ohm's law, as follows:

$$
\begin{aligned}
I &= \frac{E}{R} \\
&= \frac{200 \text{ volts}}{200{,}000 \text{ ohms}} \\
&= .001 \text{ ampere} \\
&= 1 \text{ milliampere.}
\end{aligned}
$$

Since this same current flows through each resistance, the voltage developed—or dropped—across each resistor can also be calculated from Ohm's law.

Call the voltage across R1 $E_1$:

$$
\begin{aligned}
E_1 &= IR \\
&= .001 \text{ ampere} \times 25{,}000 \text{ ohms} \\
&= 25 \text{ volts.}
\end{aligned}
$$

Call the voltage across R2 $E_2$:

$$
\begin{aligned}
E_2 &= .001 \text{ ampere} \times 75{,}000 \text{ ohms} \\
&= 75 \text{ volts.}
\end{aligned}
$$

Call the voltage across R3 $E_3$:

$$
\begin{aligned}
E_3 &= .001 \text{ ampere} \times 100{,}000 \text{ ohms} \\
&= 100 \text{ volts.}
\end{aligned}
$$

Note that the sum of these voltage drops is 200 volts, the amount of voltage rise represented by the power supply.

Voltage dividers are widely used in electronic circuitry for obtaining an infinite variety of partial voltages from a single source such as a power supply. They are usually the essence of simplicity. Paradoxically, they can be quite difficult to recognize on a schematic, particularly for someone with an untrained eye. First of all, they are rarely labeled voltage dividers. Also, the resistors frequently are widely separated from each other and from the applied voltage, often by a full page of the schematic.

It is evident from Fig. 6-1 that the same positive voltage that exists at the tap on the potentiometer will be applied to the screen grid. It is also evident that the screen-grid current must flow through the upper portion of R2 in order to reach the power supply. The voltage at R2 will be altered somewhat when this happens. It is possible, by adjusting the tap, to compensate for variations in amplitude of the plate tank oscillation (caused by corresponding variations in the loading or coupling current from circuits which come after the plate circuit). This self-compensation enables the tetrode to exhibit some of the amplitude

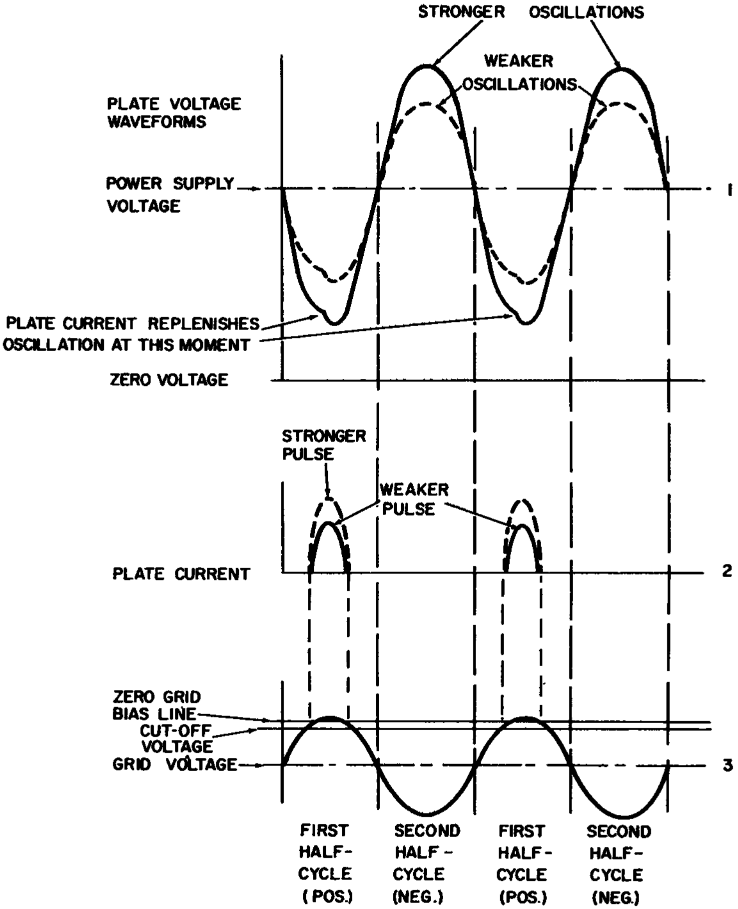


Fig. 6-4. Grid and plate waveforms in the electron-coupled oscillator.

stability previously attributed to the pentode. Now let us consider an example.

Fig. 6-4 shows one cycle of plate voltage for an electron-coupled oscillator. (The plate voltage is the same as the oscillating voltage in the plate tank.) The positive half-cycle of Fig. 6-4 corresponds to the current/voltage conditions depicted in Fig. 6-1. That is, the grid voltage (line 3 of Fig. 6-4) reaches its most positive voltage in the middle of the half-cycle, releasing a pulse of plate current (solid curve in line 2 of Fig. 6-4). The current arrives at the top of the plate tank when the latter is least positive (solid curve of line 1 of Fig. 6-4) and thereby reinforces the oscillation.

The negative hump in the middle of the first half-cycle of plate voltage (solid curve of line 1) represents the addition of plate-current electrons to the voltage across the plate tank capacitor. Arriving as they do during this half-cycle, the electrons *increase* this voltage and thereby reinforce the oscillation.

Continuing with our example, assume this plate tank oscillation is weakened by, say, a variation in the load current being driven by the tank current. Also assume the dotted curve in line 1 now represents the voltage waveform at the plate and at the top of the tank. Since the oscillation has been weakened, the plate voltage at the center of the first half-cycle will not swing to *as low a positive value* as before. So now a larger pulse of plate current can be drawn across the tube. This condition, depicted by the dotted curve of line 2 in Fig. 6-4, stems from the fact that the plate voltage of a tetrode (unlike the pentode) *does* affect the plate current somewhat.

As the plate current increases, more and more electrons flow through the positively charged screen grid on their way to the plate. Thus, more and more electrons are captured by the screen grid and flow through the upper portion of R2, increasing the voltage drop across the top of the potentiometer.

Subtracting this greater voltage drop from the power-supply voltage, we end up with a lower positive voltage than before at the potentiometer tap and consequently at the screen grid. The lower screen-grid voltage now weakens the plate-current pulse which had originally lowered the screen voltage. So, a form of self-compensation exists.

These cumulative actions do not necessarily *correct* the amplitude variation already in the plate oscillation, but they do keep the plate current from following the changes in loading. In this sense they contribute to the over-all stability of the circuit—including the frequency stability of the oscillation in the grid circuit, because any change in the plate current drawn by the tube will also change the strength of the feedback in the cathode-to-grid tuned circuit. As is true for any tuned-circuit oscillator, any such variations in the feedback, or in loading, coupling, etc., will raise or lower the basic frequency.

## Chapter 7

# PHASE-SHIFT OSCILLATOR

The phase-shift oscillator circuit is widely used in laboratories for generating an audio frequency, and for other testing where precision is a must. A special combination of resistors and capacitors are employed to achieve regenerative feedback and thus permit the circuit to generate a continuous alternating current. Unlike other oscillators, the phase-shift oscillator has no tuned circuit and hence is not as susceptible to detuning by occasional stray capacitances and inductances. Consequently, the output remains fairly stable at the desired frequency.

Figs. 7-1 and 7-2 show one of the several possible configurations for this special application of the R-C oscillator. The circuit components and their functions are as follows:

V1—Conventional pentode amplifier tube.
C1—Cathode bypass capacitor for preventing degeneration.
R1—Cathode biasing resistor.
C2—Screen-grid bypass or filter capacitor.
R2—Screen-grid voltage-dropping resistor.
R6—Plate-load resistor.
C3, C4, and C5—Feedback, coupling, and phase-shifting capacitors.
R3, R4, and R5—Phase-shifting resistors.
M1—DC power supply.

There are five electron currents at work in this circuit, and each one needs to be analyzed before you can understand how the circuit operates. These currents are:

1. Cathode-to-plate current (conventional tube current) (red).

2. Screen-grid current (solid blue).
3. Current in the first R-C combination (R3 and C3) (dotted green).
4. Current in the second R-C combination (R4 and C4) (dotted blue).
5. Current in the third R-C combination (R5 and C5) (solid green). Its associated voltage is applied to the control grid as the feedback voltage.

## CURRENT PATHS

Fig. 7-1 shows the current flow during the first half-cycle, which begins when the grid is most negative and ends when it is most positive. Conditions are just the opposite for the second half-cycle in Fig. 7-2—it begins when the grid is most positive and ends when it is most negative. In both illustrations, significant voltage polarities are shown as they exist *at the end* of the half-cycle.

At the start of the first half-cycle, you will recall that the grid voltage is most negative. However, in this circuit (unlike the ones discussed previously), plate current must flow at all times. Therefore, the most negative grid voltage merely restricts the flow of plate current, instead of cutting it off completely. A low plate current always leads to a high positive plate voltage, particularly when this current must flow through a resistive load such as R6 on its journey to the power supply.

Line 1 of Fig. 7-3 shows a sine wave of plate voltage. At the start of the first half-cycle this plate voltage has its maximum positive value.

Line 4 of Fig. 7-3 shows two sine waves of grid voltage. The one in dashed lines is developed across R5 by the current indicated in solid green in Figs. 7-1 and 7-2, and represents the actual voltage applied at the grid. The solid line is its hypothetical value if the signal could pass through the R-C network unattenuated.

It is of course significant that the grid-voltage waveforms on line 4 and the plate voltage on line 1 of Fig. 7-3 are 180° out of phase with each other—or more simply, "out of phase," or "of opposite phase." This out-of-phase condition is necessary for the oscillation to continue. Now let us see how this phase shift between output and input can be achieved from the combination of resistors and capacitors making up the phase-shifting network in Figs. 7-1 and 7-2.

Fig. 7-1 shows the current conditions at the end of the first half-cycle. Prior to this, the grid voltage has been increasing steadily from negative to positive. Consequently, the plate current, shown in red, has also been steadily increasing, until it reaches maximum. Now it is drawn across the tube by the positive voltage applied to the plate from power supply M1. (Although shown as a large battery, the power supply can be a vacuum-tube rectifier or any other device capable of furnishing DC).

Ohm's law tells us the voltage developed, or "dropped," across a resistor by the current flowing through it is proportional to the amount of that current. Consequently, the voltage drop across resistor R6 will be much larger at the end than at the beginning of the first half-cycle. Since the voltage at the plate is always the supply voltage *minus* the voltage developed across the plate load resistor, we can see why the plate voltage is lowest when the grid voltage is at its highest.

At the end of the first half-cycle, when maximum plate current is flowing, it is convenient to visualize the consequent reduction in plate voltage resulting from the excess of plate-current electrons flowing out of the tube, into load resistor R6, and on to the power supply. Until these electrons can enter the load resistor, they are in a sense "dammed up" at the junction of R6 and coupling capacitor C3. For this reason, during the first half-cycle they are shown flowing *onto* the left plate of C3.

Conversely, during the second half-cycle, when the flow of plate current is restricted by the negative grid voltage, it is convenient to equate the drop in number of plate-current electrons with the corresponding rise in plate voltage. This is done by picturing it as current being drawn out of the left plate of capacitor C3 and into load resistor R6, to the power supply.

Fig. 7-1 shows current (solid green line) flowing upward through grid-driving resistor R5 during the first half-cycle. Note that if there were no 180° shift in phase as the voltage pulse from the plate passes through the three R-C combinations, the current in R5 would flow *downward* instead.

Likewise, during the second half-cycle, the normal downward flow of current through R5 would be reversed if it were not for this 180° phase shift.

Suppose this phase shift did not occur? Then, when electrons flowed onto the left plate of capacitor C3, other electrons would flow in unison and in the same direction through all these capacitors, much as they would through a straight wire. Also, when electrons flowed out of the left plate of C3, other electrons would flow in the same direction through all three capacitors.

How, then, does a shift in phase occur in an R-C network? Unfortunately, it is impossible to show the voltage pulse actually changing phase. The dashed diagonal lines in Fig. 7-3 are meant to strengthen your conviction that such a phase shift does occur, even though not clarifying exactly how. Let us now look more closely at these waveforms, to see what makes them do so.

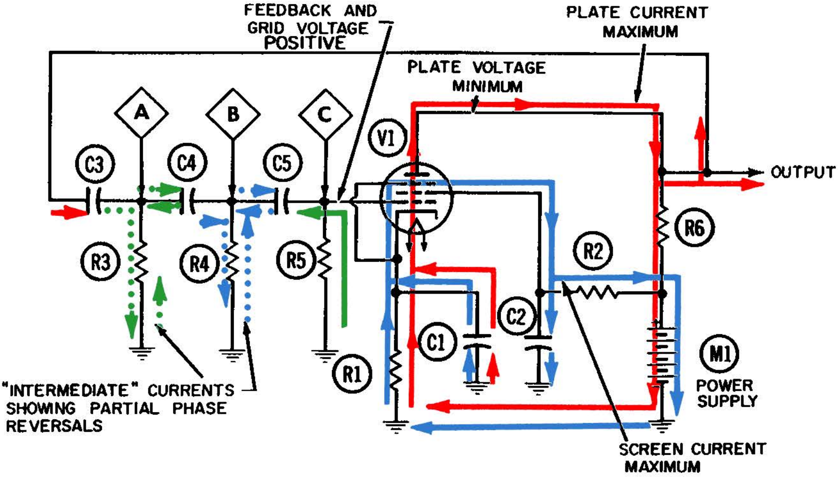


Fig. 7-1. Operation of the phase-shift oscillator—positive half-cycle.

## PHASE-SHIFT NETWORK

Suppose resistor R3, R4, and R5 each have the same resistance, and C3, C4, and C5 the same capacitance. Then it is safe to assume that each of the R-C combinations (R3-C3, R4-C4, and R5-C5) will produce equal portions of the total phase shift of 180°; in other words, the applied voltage will be shifted 60° by each R-C combination.

What would happen if no phase shift occurred in any R-C combination during the entire first half-cycle of Fig. 7-1? Then, the electron current shown by the dotted green line would flow down through R3 and reach its maximum value at the same instant the plate voltage drops to its minimum at the end of the half-cycle. However, the voltage peak across R3 must occur 60°, or one-sixth of a cycle, later. For this reason, the green arrows in Fig. 7-1 point in both directions through R3. Admittedly this is a crude presentation of what is happening within the resistor and will require help from your imagination.

Fig. 7-3 shows the voltage waveforms at the plate and at feedback points *A*, *B*, and *C*. Each successive waveform is displaced 60° in phase, and consequently in time, from the preceding one. As a result, a positive-voltage peak at point *C* occurs 180°, or half a cycle, after the identical peak at the plate. Since the grid is connected directly to point *C*, this positive-voltage peak will release maximum plate current through the tube. We already know that in a vacuum tube a high plate current usually coincides with a low plate voltage because of the voltage drop across plate load resistor R6.

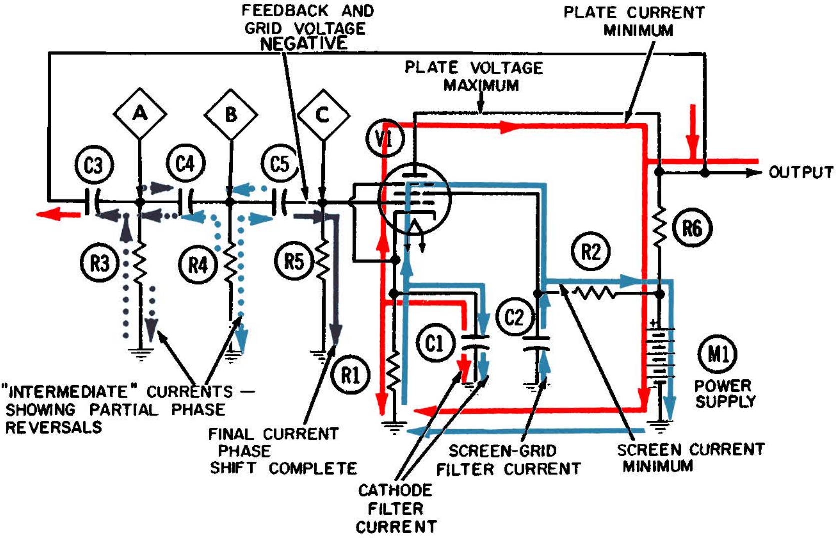


**Fig. 7-2. Operation of the phase-shift oscillator—negative half-cycle.**

Also in Fig. 7-3, we see that a negative-voltage peak occurs at point *C* a half-cycle, or 180°, after the plate voltage reaches its minimum. This peak, applied to the control grid via the feedback line, drastically reduces the flow of plate current. Minimum plate current usually coincides with maximum plate voltage, because the lower current through load resistor R6 reduces the voltage drop across it.

From the two preceding paragraphs and Fig. 7-3 we may conclude that the feedback has the appropriate phase to control the current flow in the tube and deliver an alternating current or oscillation at the output point. Several important approximations have been made in arriving at Fig. 7-3. The signal voltage will of course be attenuated as it passes through the R-C network. The solid curves of lines 2, 3, and 4 represent the theoretical voltage waveforms at point *A*, *B*, and *C*, respectively, if no attenuation occurred. The waveforms shown in dashed curves indicate the actual reduction in strength at each point. The feedback voltage at point *C* is only a small fraction of the output voltage which causes it. This is normal for all oscillators—the

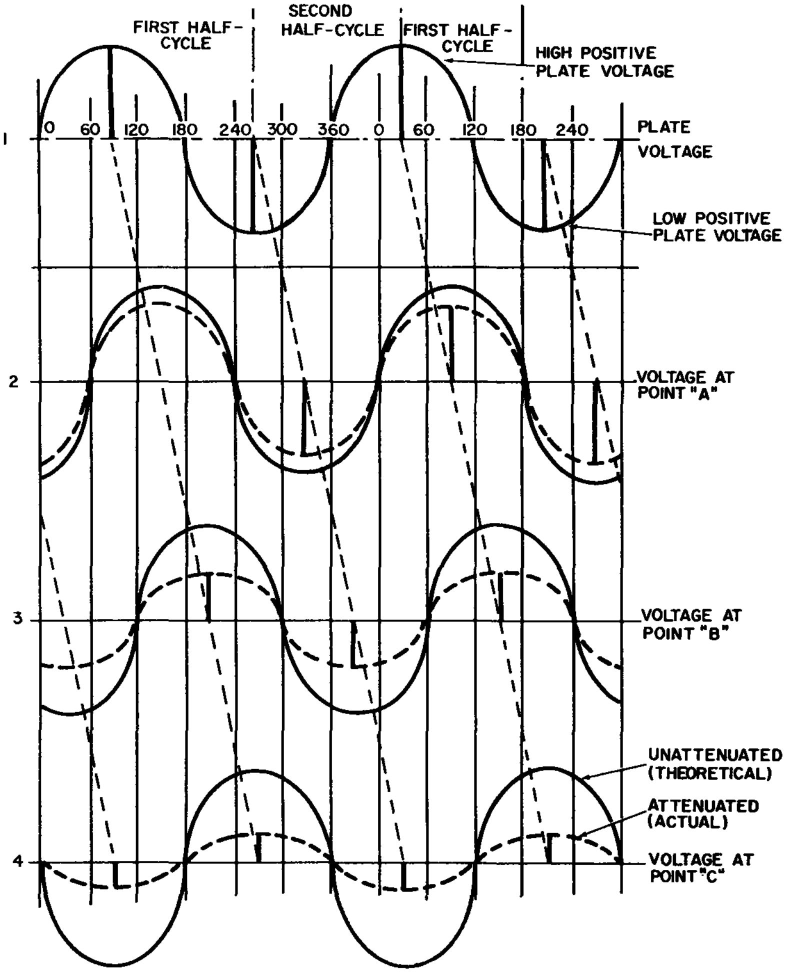


**Fig. 7-3. Voltage waveforms at four key points in the phase-shift oscillator.**

tube acts as an amplifier; hence, only a small grid-driving voltage is required to control a much larger plate current through the tube and thereby contribute to large swings of plate voltage.

The values of resistors R3, R4, and R5 and capacitors C3, C4, and C5 determine the basic frequency of the voltage delivered to the output point. As an example, if each capacitor has a value of .01 microfarad, and each resistor a value of 10,000 ohms, the circuit will oscillate in the region of 700 or 800 cycles per second, well within the range of the human ear.

Let us consider each R-C combination separately (an approximation which the actual currents and voltages refuse to recognize). It is often said of capacitors that the current "leads" the voltage, frequently cited as unassailable evidence that some other related condition exists or will occur. Recall that in inductors the opposite is true—the current lags the voltage. (This latter property has been adequately described in earlier chapters.) Let us give some thought now to the significance of the axiom that the current leads the voltage in capacitors.

This statement is directly related to another widely quoted truth that capacitors will oppose any change in *voltage*. The existing voltage across the plates of a capacitor can be changed only by adding or withdrawing charged particles (electrons) and these electrons must enter or leave the capacitor *first*, in order for the voltage to change.

By using trigonometry it is possible to calculate the exact number of degrees the voltage developed across the capacitor will lag the current which produces it. The resultant is called the *vector relationship* between reactances and resistances, or between reactive and resistive voltages.

The maximum voltage developed across R3 should occur one-sixth of a cycle after the maximum current flow into C3. Hence, the reactive voltage across the capacitor will be 1.73 times the resistive voltage. The only frequency which satisfies these conditions turns out to be 920 cycles per second.

The reactance and resistance at the given frequency are arrived at from the trigonometric relationship existing between two legs of a right triangle with an included angle of 60°, as follows:

$$C = .01 \text{ microfarad } (10^{-8} \text{ farads}),$$

$$R = 10{,}000 \text{ ohms } (10^{4} \text{ ohms}),$$

$$X_C = 1.73R$$

We know the formula for capacitive reactance is:

$$X_C = \frac{1}{2\pi fC}$$

Therefore, substituting this formula for $X_C$ we have:

$$\frac{1}{2\pi fC} = 1.73R$$

Rearranging for f:

$$f = \frac{1}{2\pi \times C \times 1.73 \times R}$$

Substituting the known values and solving:

$$f = \frac{1}{6.28 \times 10^{-8} \times 1.73 \times 10^{4}}$$

$$= \frac{1}{6.28 \times 1.73 \times 10^{-4}}$$

$$= \frac{1}{10.86 \times 10^{-4}}$$

$$= 920 \text{ cycles.}$$

If each of the three R-C combinations could be considered separately, a frequency of 920 cycles per second would satisfy the requirement that the reactive voltage lead the resistive voltage by 60°. This is another way of saying that the capacitor current should lead the resistor current by 60°, since the current through a resistor is always in phase with the voltage developed across the resistor. The three R-C combinations would then cause a 180° phase shift between the input current and feedback voltage.

This solution is not 100% correct because all the current driven through capacitor C3 does not flow downward through R3, but divides between C4 and R3 in proportion to the impedance offered by each path. Likewise, when there is a negative-voltage peak at point *A*, the current it drives into C4 does not all flow downward through R4 (the current shown by the dotted blue line), but again divides between R4 and C5 in proportion to the impedance offered by each path.

The significance of these multiple-current paths is that the amplitudes and phase shifts of the voltages achieved at points *A*, *B*, and *C* cannot be calculated separately as was done earlier. Also, these amplitudes and phase shifts will be modified by the type of circuit which follows.

## Summary

1. Current must first flow into or out of a capacitor before the voltage across it can be changed. Therefore, the current leads the voltage in a capacitor.
2. In an R-C combination, maximum current will flow through the capacitor before it will through the resistor.

3. The voltage developed across a resistor by a current flowing through it is in phase with that current. Consequently, the voltage across a resistor lags the capacitor current.
4. A capacitor opposes the flow of electron current, the amount varying inversely with the frequency of the applied current, in accordance with the standard reactance formula.
5. The current in a capacitor leads the resulting voltage and the resistor current by the same number of degrees, which can be calculated by triangulation. The capacitance and resistance are considered two legs of a right triangle. When these two values are known, the third, or phase, angle can then be determined.

## SCREEN-GRID AND FILTER CURRENTS

Little has been said so far about the remaining currents in the circuit. The screen-grid current, shown in solid blue, follows a closed path within the tube, from cathode to screen grid. Here it exits and flows through screen-dropping resistor R2 and the power supply, then through common ground and cathode biasing resistor R1, and back to the cathode.

During the first half-cycle, the control-grid voltage becomes more and more positive, and the plate- and screen-grid currents also steadily increase. This demand is satisfied by the electrons on the upper plate of cathode filter capacitor C1, and their departure from the top plate draws an equal number (labeled "cathode filter current") from ground to the bottom plate.

The increase in screen-grid current during the first half-cycle also drives an excess of electrons onto the upper plate of screen-grid filter capacitor C2. Coincidentally, an equal number of electrons are driven from the lower plate to ground. This is the screen-grid filter current, also shown in solid blue.

In Fig. 7-2 we see that during the second half-cycle, when the control-grid voltage goes negative and reduces the plate and screen currents, both filter currents flow in the opposite direction. The upper plate of C1 becomes positively charged and draws electrons to it through R1, permitting an equal number to flow back to ground from the lower plate. Therefore, the cathode filter current will always have the same frequency as the basic oscillator frequency. The cathode filter capacitor acts as a "shock absorber"—it keeps the voltage at the cathode from changing as the tube current changes.

The reduction in screen current during the second half-cycle permits the excess of electrons on the upper plate of C2 to be drawn off through R2 and the power supply. An equal number will then be drawn upward from ground to the lower plate of C2. Thus this capacitor also acts as a shock absorber by keeping the screen-grid voltage from changing. It does this by maintaining the flow of electrons constant through R2 so that the voltage drop (or rise) across it will likewise be steady. Thus, the screen-grid filter current will also remain at the basic oscillator frequency.

## Chapter 8

# BLOCKING OSCILLATORS

The blocking oscillator is one of the most widely used relaxation oscillators. It is often employed in the vertical section of a television receiver, as well as in the timing circuit of many radar sets, oscilloscopes, and similar electronic equipment. A typical blocking-oscillator circuit, along with the current flows during each part of the cycle, is given in Figs. 8-1 through 8-3. The circuit components and their functions are:

T1—Pulse transformer, which operates within a specific range of pulse-repetition frequencies (PRF's).
V1—Triode amplifier tube.
C1—Input and blocking capacitor.
R1 and R2—Grid-leak bias and grid-drive resistors (R2 is a potentiometer used for varying the basic repetition frequency).
C2—Output capacitor.
R3—Plate-load and isolating resistor.
M1—Power supply providing a fairly high positive voltage to the plate of V1.

## CIRCUIT OPERATION

You will recall from Chapter 1 that feedback in the normal sense is not required to sustain oscillations in a relaxation circuit. Let us consider that a cycle of operation begins when the grid voltage first permits plate-current electrons to pass through the tube.

This plate current, shown in red on the circuit diagrams, flows through the primary winding of transformer T1 and induces a current of equal value but opposite polarity in the secondary winding.

The polarity of the two windings is such that the induced current in the secondary makes the grid voltage more and more positive as the plate current increases in the primary. These are the conditions depicted in Fig. 8-1. In fact, the effect is cumulative—as soon as the slightest amount of plate current flows into the primary winding, transformer action responds to the changing current and begins to drive the grid positive. As the grid becomes more positive, more plate current flows, causing another positive rise in the grid voltage and a still larger plate current. Soon, maximum plate current is flowing, and any rise in plate voltage will no longer increase the current. When this happens, the tube is said to be saturated.

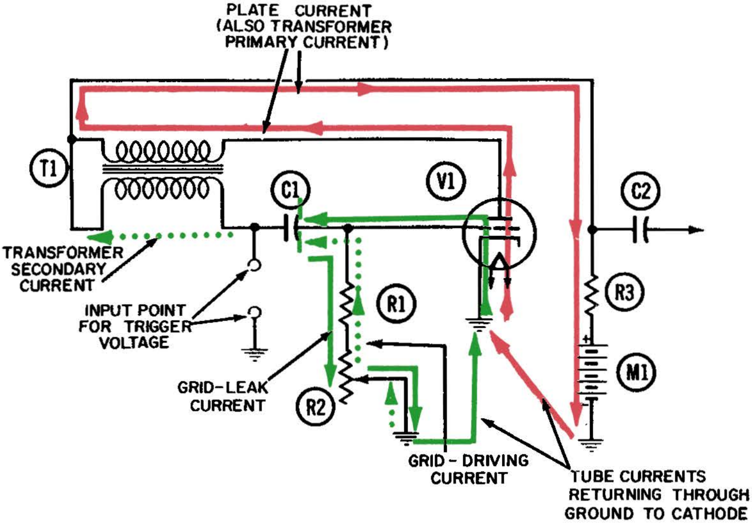


**Fig. 8-1. Operation of the blocking oscillator—first part of conduction period.**

When saturation occurs, the primary current remains steady; therefore, transformer action between the primary and the secondary (which is dependent on a changing current) ceases. There is a temporary stoppage of the secondary current, and also of the grid-driving current flowing upward through R1 and R2. Both currents are shown in dotted green lines, since they are so directly related to each other.

Meanwhile, early in the conduction cycle, the grid is actually driven slightly positive and attracts a substantial number of electrons from the plate-current stream. These grid-leak elec-

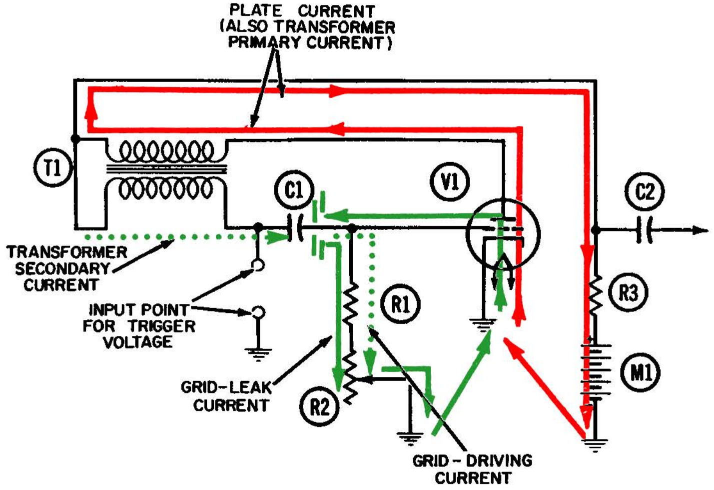


Fig. 8-2. Operation of the blocking oscillator—second part of conduction period.

trons, as they are called, leave the tube via the grid and accumulate on the right plate of capacitor C1. (This flow is shown by the solid green line in Fig. 8-1.) Because of them, the grid is prevented from rising to its full positive voltage during the transformer action. The dotted lines in Fig. 8-4 show how positive

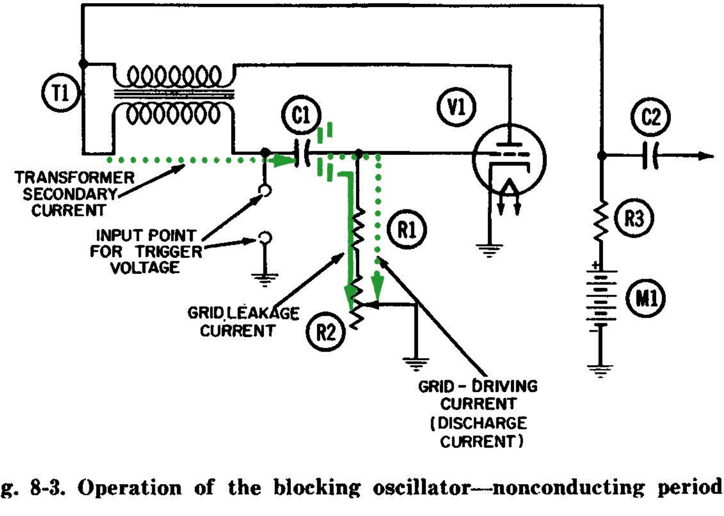


Fig. 8-3. Operation of the blocking oscillator—nonconducting period.

the grid would be driven, were it not for this accumulation of grid-leak electrons.

As soon as plate-current saturation stops the transformer action, the negative voltage represented by these grid-leak electrons "takes over" and begins to reduce the flow of plate current through the primary winding. This leads us into Fig. 8-2, the second part of the conduction period. Now the transformer action is reversed—the secondary current flows in the opposite direction and makes the grid voltage *more negative.*

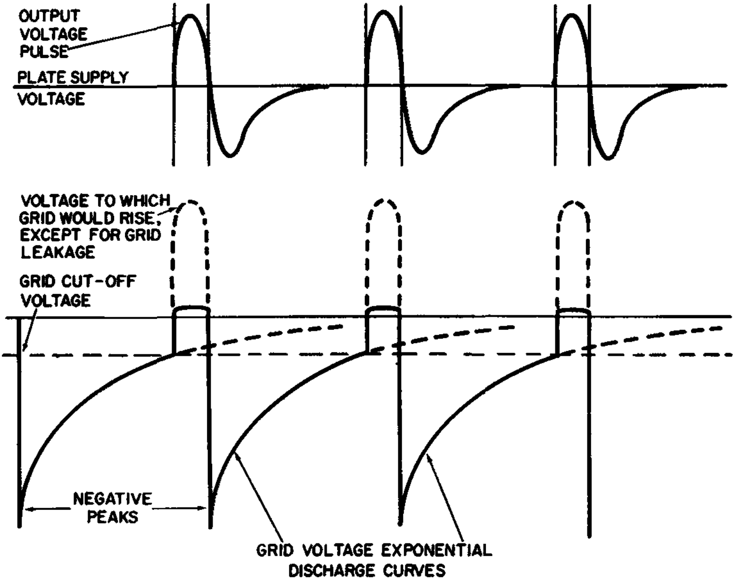


**Fig. 8-4. Plate and grid waveforms during free-running operation of the blocking oscillator.**

These two events are also cumulative—less plate current leads to a more negative grid voltage, which reduces the plate current still more, and so on. The net result is that the plate current through the tube is cut off almost instantaneously. There is nothing to prevent the grid from being driven very negative by the transformer action, as it is by the negative peaks in Fig. 8-4.

During the much longer nonconduction period (Fig. 8-3), there are two currents flowing in the grid circuit. Both of them—the grid-leakage and the grid-driving current—discharge through the grid resistors.

The discharge of grid-driving electrons, which accounts for the sudden negative peak in the grid voltage at the start of each nonconducting period, is completed almost instantaneously.

The flow, or "discharge," of grid-leakage electrons through the grid resistors occurs at an exponential rate which is governed by the time constant of the R-C circuit formed by capacitor C1 and resistors R1 and R2.

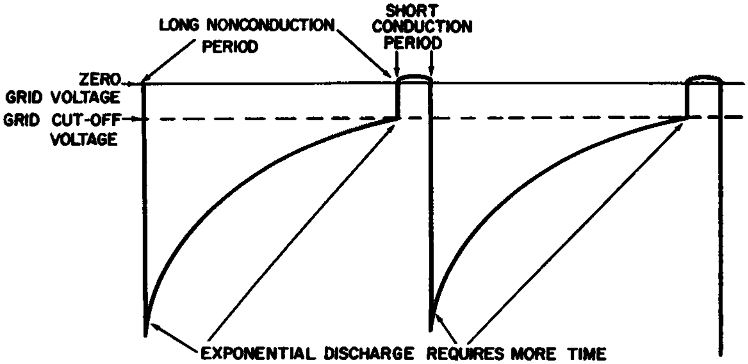


**Fig. 8-5. Blocking-oscillator grid waveform, showing decrease in pulse frequency when grid resistance is increased.**

The exponential curve of the grid voltage during the nonconduction periods in Fig. 8-4 represents the voltage at the grid as the leakage-current electrons discharge to ground. This grid voltage rises towards zero until it reaches the cutoff value (the point where the grid voltage is no longer negative enough to keep the plate current from flowing). With a 6SN7 tube and a plate-supply voltage of about 250 volts, the grid-cutoff voltage will be in the region of −10 volts. The cumulative effects associated with Fig. 8-1 then begin, and a new cycle of oscillation is underway.

As long as the values of C1, R1, and R2 do not change, the oscillation frequency of a blocking oscillator should be fairly stable. However, the number of electrons coming out of the tube and onto the grid capacitor may vary from cycle to cycle because of slight changes in plate voltage, heater voltage or temperature, etc. Consequently, each discharge period may have a slightly different negative voltage than its predecessor, and will thus require more or less time to reach the cutoff voltage and start a new cycle. When a blocking oscillator is running unsynchronized in this manner, it is said to be "free-running." Fig. 8-4 shows the grid-voltage waveform in such an oscillator.

The waveform in Fig. 8-5 has a longer discharge time, resulting in a lower pulse-repetition frequency (PRF). This condition is achieved by moving the tap downward on potentiometer R2, so that the discharging grid-leakage electrons will encounter *more* resistance as they flow to ground. In other words, the time constant of the grid circuit is increased.

The opposite effect can be created by moving the potentiometer arm *upward* so that the leakage path contains *less* resistance; this will shorten each cycle and *increase* its PRF.

Thus, potentiometer R2 acts as a frequency control (in a television receiver it is labeled the Vertical or Horizontal Hold control). Its application will be more clearly understood after you have studied the discussion on synchronization of the oscillator.

### Summary

1. The grid voltage reaches cutoff and plate current begins to flow through the primary winding.
2. This increasing current in the primary winding is coupled to the grid circuit by transformer action. The transformer is connected so that this rising current causes the grid voltage to become less and less negative, thereby increasing the plate current even further.
3. The plate current reaches saturation, and can no longer increase.
4. The grid voltage becomes positive, and the grid draws grid-leak current from the tube.
5. The plate current in the transformer primary collapses and, the current induced in the secondary drives the grid highly negative, cutting off the tube.
6. Grid-leakage electrons leak off until the grid voltage is again raised to the cutoff point. Plate current again flows, and the cycle is repeated.

## SYNCHRONIZING A BLOCKING OSCILLATOR

To synchronize a blocking oscillator, positive-going voltage "spikes" from an external source are applied to the grid. Here they add to the existing voltage and raise it enough to trigger the cycle prematurely. Fig. 8-6 shows the sequence. Reading from left to right, you can see that the first cycle of oscillation begins before the trigger or synchronizing spike arrives. In the second and third cycles, the spike is applied to the grid when its voltage is very negative. Notice, however, that the combined voltages still are not sufficient to raise the grid voltage to cutoff. It is evident from Fig. 8-6 that the oscillator is running *faster*, or at a *higher* frequency, than the spike frequency, and cannot be synchronized.

Fig. 8-7 shows the opposite condition. Here the oscillator is running *slower*, or at a *lower* frequency, than that of the synchronizing spikes. This is the desirable condition, because now the oscillator can be synchronized. Positive spikes of trigger voltage are applied to the grid *near the end of each nonconduction period*. Now the spike is sufficient to raise the grid voltage to the cutoff point. Thus, each new cycle starts the instant a trigger spike is applied.

In a television receiver these trigger spikes are known as sync pulses and are part of the received signal. At the transmitter, their frequency is rigidly held to the correct frequency (60-cps for the vertical-sync pulses, and 15,750 cps for the horizontal-sync pulses). At the receiver the pulses are separated from the picture information and amplified to the point where they are able to trigger the blocking oscillator. It in turn generates a much more powerful pulse, at the same frequency, which is further amplified and used to sweep the beam back and forth, and up and down, on the screen.

When horizontal or vertical sync is lost in a television receiver, it is most likely caused by an increase in the natural frequency of the corresponding oscillator. As a result, the picture information does not arrive in step with (is not synchronized with) the beam as it moves across the screen. The remedy is to decrease the natural frequency of the oscillator by lengthening the nonconduction period. This is accomplished by adding resistance to the grid-leak discharge path. In a television receiver, potentiometer R2 would thus be connected directly to an adjusting knob and labeled the Vertical Hold control.

A second (and less likely) reason for loss of horizontal or vertical sync is a *decrease* in oscillator frequency, of such magnitude that the trigger pulses arrive too early during the nonconduction period (too far down on the exponential curve), instead of near the end as they should. This is not too likely to happen, because a much greater deviation in natural frequency is required here before loss of sync occurs. When it does, the remedy of course is to *increase* the natural frequency of the oscillator by *shortening* the nonconduction period. This is accomplished by decreasing the resistance of potentiometer R2 in the grid circuit, in order to speed up the discharge time of the grid-leakage electrons so that the pulses will again trigger the oscillator.

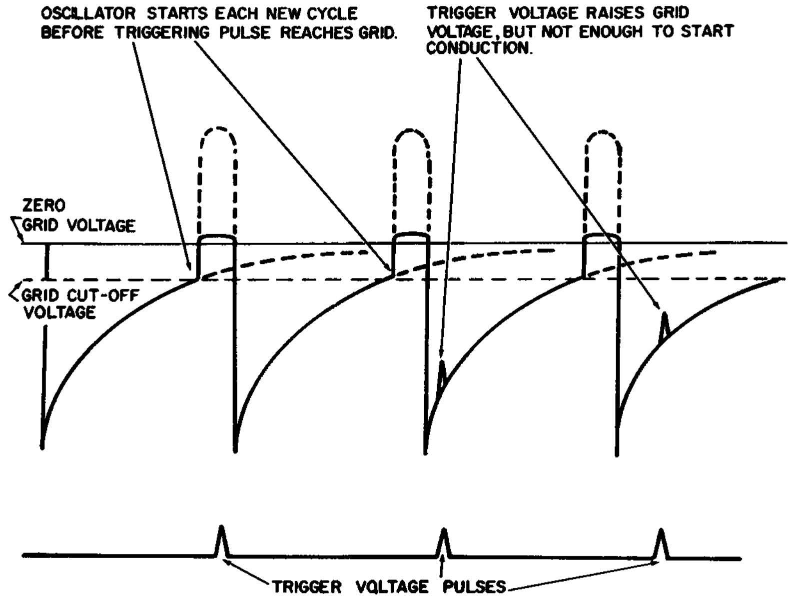


Fig. 8-6. Blocking-oscillator grid waveform when oscillator is running too fast to be synchronized.

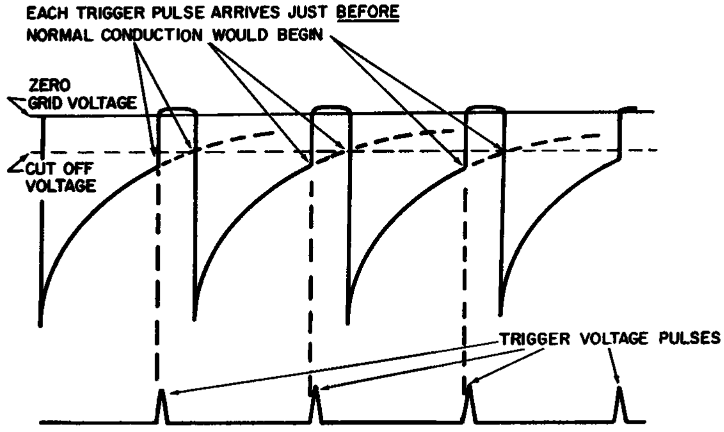


Fig. 8-7. Blocking-oscillator grid waveform when oscillator is being synchronized by applied trigger voltage.

## OUTPUT COUPLING

Output voltage (shown in Fig. 8-4) can be coupled out of the blocking-oscillator circuit via coupling capacitor C2. The output point is connected to the junction of the transformer primary and secondary windings and thus exhibits the voltage at this point. In Fig. 8-1, which shows conditions during the first part of the conduction period, the current flows from right to left in the secondary winding. This can only mean that the secondary voltage is more positive at the left side winding, accounting for the initial rise in output voltage shown by the waveform in Fig. 8-4.

Toward the end of the conduction period, as depicted in Fig. 8-2, the secondary current reverses direction and flows from left to right, in accordance with the concept of counter emf discussed in Chapter 1. Now the voltage at the left side of the winding is negative. Actually, it does not reach its most negative value until shortly after the nonconduction period begins. This accounts for the negative peak in the output waveform of Fig. 8-4.

The positive output pulse can easily have a magnitude of a hundred volts or more. Even without additional amplification, it is thus able to provide a variety of functions in electronic circuits.

## Chapter 9

# MULTIVIBRATORS

The multivibrator circuit is widely used for providing the timing function in television, computers, radar, and many other applications. The basic free-running multivibrator circuit is given in Figs. 9-1 and 9-2. Its components are:

R1—Plate-load resistor (about 20,000 ohms) for V1.
R2—Grid-biasing and -driving resistor (about 2 megohms) for V1.
R3—Plate-load resistor (about 20,000 ohms) for V2.
R4—Grid-biasing and -driving resistor (about 1 megohm) for V2.
C1—Grid coupling and blocking capacitor (800 micromicrofarads) for V1.
C2—Grid coupling and blocking capacitor (also 800 micromicrofarads) for V2.
V1 and V2—Triode amplifier tubes.
M1—Power supply.

There are six currents at work in this circuit, and their movements must be understood in order to comprehend how the circuit operates as a whole. Each of the current paths is shown in a different color in Figs. 9-1 and 9-2. These currents, and the colors representing them, are:

1. Plate current for V1 (solid red).
2. Grid-leak biasing current for V1 (solid green).
3. Grid-driving current for V1 (solid blue).
4. Plate current for V2 (dotted red).
5. Grid-leak biasing current for V2 (dotted green).
6. Grid-driving current for V2 (dotted blue).

The voltage waveforms resulting from the current flow at the plate and grid of each tube are given in Fig. 9-3.

## CIRCUIT DESCRIPTION

As mentioned previously, the circuit in Figs. 9-1 and 9-2 is connected to operate as a free-running multivibrator. Its pulse-repetition frequency is determined by the values of the resistors and capacitors, and by the conduction characteristics of the two vacuum tubes.

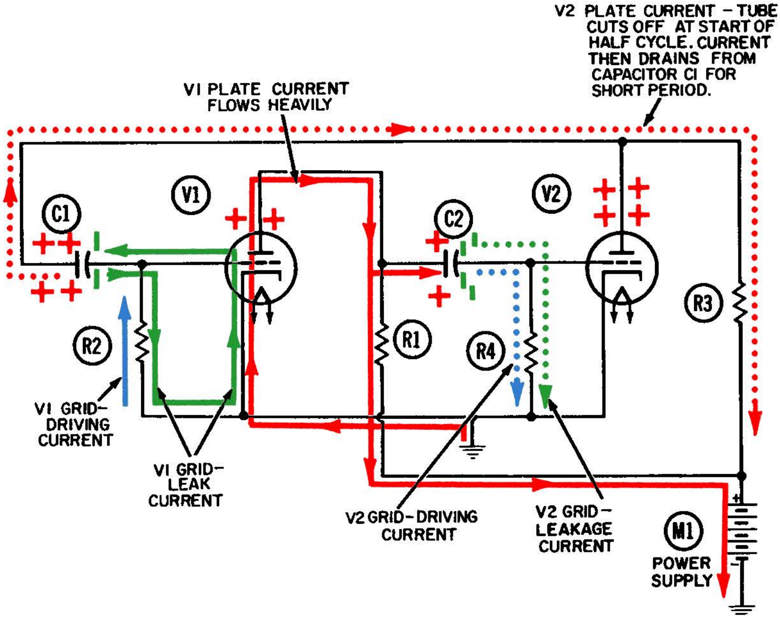


Fig. 9-1. Operation of free-running multivibrator—first half-cycle.

Operation begins when plate voltage is applied to V1 and V2 simultaneously. As each tube conducts electrons from cathode to plate, the voltage at each plate will drop—but not by the same amount. If both tubes conducted exactly the same number of plate-current electrons (which they never do) and if the two plate-load resistors were *exactly* the same value (which they never are), then both would be identical. But such an assumption is purely hypothetical—the two drops will never be the same.

Let us assume that V1 conducts the greater amount of plate current. As a result, its plate voltage will drop to a lower positive value than V2's. Let us also assume that it drops to +100 volts, and that the supply voltage is +250 volts.

It is true to say that capacitors oppose any change in voltage, or another way of saying the same thing: "it is impossible to instantaneously change the voltage across a capacitor." The fundamental meaning of these statements will be made clearer by now observing the action within capacitor C2. Before tube V1 conducts, the voltage on the left plate of C2 (and also on the plate of V1) is the +250 volts from the power supply, while the voltage on the right plate is essentially zero since it is connected to ground through grid resistor R4. Thus, the moment before conduction begins, the voltage *across* the two plates of the capacitor is +250 volts.

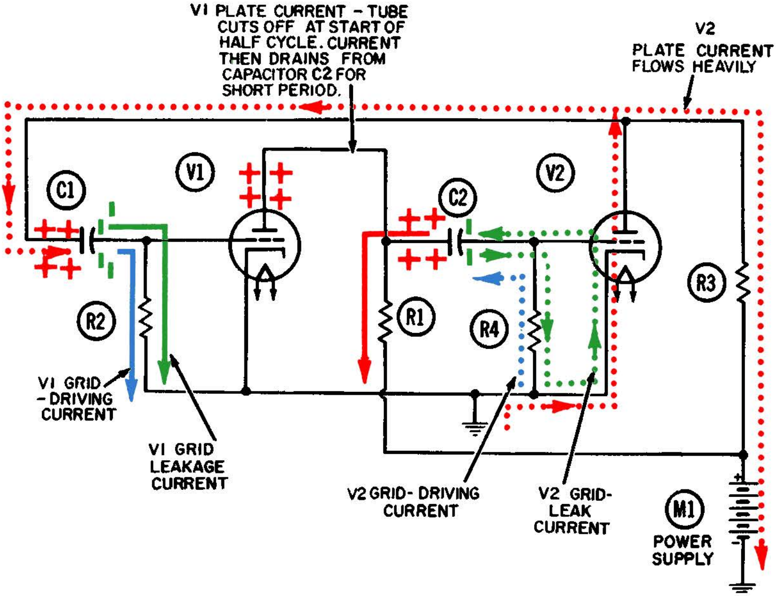


**Fig. 9-2. Operation of free-running multivibrator—second half-cycle.**

We know that the voltage across C2 does not change at the same instant the tube conducts and the plate voltage drops. It will remain at +250 volts momentarily, and then decrease to +100 volts as the electrons flow onto the left plate of C2. As they do, an equal number will flow from the right plate and downward through R4. This grid-driving current, shown in dotted blue in Fig. 9-1, produces a voltage drop across R4. Now the voltage at the junction of R4 and C2 (hence, the grid voltage) is −150 volts. Line 4 of Fig. 9-3 shows the voltage waveform at the grid of tube V2. At the start of the first half-cycle this voltage suddenly goes from zero to −150 volts, and then returns toward zero at an exponential rate determined by a corresponding exponential decay in the grid-leak current (shown in dotted green) flowing downward through R4 to ground.

The sudden drop immediately cuts off the plate current through V2 and thus allows its plate voltage to rise toward the value of the supply voltage. It will stay at 250 volts until the grid voltage has gone from −150 volts to the cutoff value of −10 volts. The first half-cycle has now ended.

The second half-cycle begins when the rise in plate current through tube V2 causes a drop in its plate voltage, similar to the action in tube V1. Since plate-load resistors R1 and R3 are both equal in value, the voltage at the plate of V2 drops from +250 to +100 volts, just as the plate of V1 did.

Capacitor C1 starts this second half-cycle with 250 volts across it, since its one plate is connected to the plate of tube V2 and its other plate is connected to ground through grid resistor R2. C1 will also oppose any change in voltage across its plates. The voltage on the right plate, which is also the voltage applied to the grid of tube V1, immediately goes from zero to −150 volts as current flows downward through grid resistor R2. This current decays exponentially to zero, and the resultant voltage across it (which is also the voltage applied to the grid of tube V1) will likewise decay toward zero at the same exponential rate, as shown in Fig. 9-3.

It is important to note why the second half-cycle is so much longer than the first. You will recall that C1 and C2 have equal values of 800 micromicrofarads; but R2 is 2 megohms, or twice the value of R4. Using the formula ($T = R \times C$) explained earlier, we can calculate the time constant for the C1-R2 combination as follows:

We know:

$$R = 2 \text{ megohms} = 2 \times 10^{6} \text{ ohms},$$

$$C = 800 \text{ micromicrofarads} = 800 \times 10^{-12} \text{ farads},$$

$$T = R \times C.$$

Therefore,

$$\begin{aligned} T &= 2 \times 10^{6} \times 800 \times 10^{-12} \\ &= 2 \times 800 \times 10^{-6} \\ &= 1{,}600 \times 10^{-6} \text{ seconds} \\ &= 1{,}600 \text{ microseconds} \end{aligned}$$

Similarly for C2-R4, where the only new value is R4 which is 1 megohm ($1 \times 10^6$ ohms), the time constant is:

$$
\begin{aligned}
T &= 1 \times 10^6 \times 800 \times 10^{-12} \\
&= 800 \times 10^{-6} \text{ seconds} \\
&= 800 \text{ microseconds}
\end{aligned}
$$

Thus, the time constant of C1-R2 in the grid circuit of V1 is twice as long as the one for C2-R4 in the grid circuit of V2.

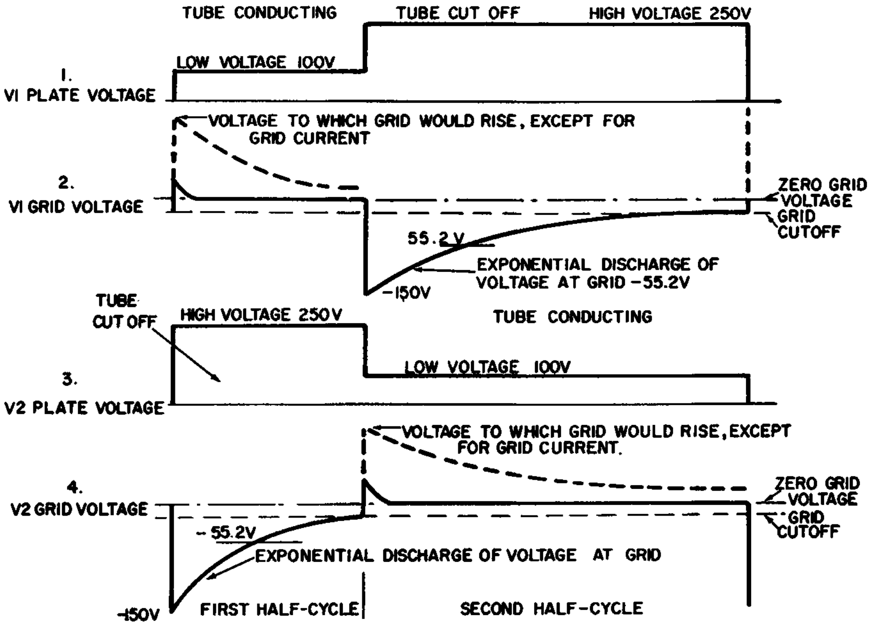


**Fig. 9-3. Grid- and plate-voltage waveforms for free-running multivibrator.**

Remember that the time constant of an R-C circuit is the length of time it will take the capacitor to discharge to 63.2% of its original value. Therefore, during the first 800 microseconds after the first half-cycle starts, the grid voltage on V2 will discharge to about −55.2 volts, or 36.8% of its original −150 volts. This is shown in line 4 of Fig. 9-3.

After three time periods of 800 microseconds each, the grid of V2 will have discharged to about −7.5 volts. Since its cutoff value is −10 volts, V2 will start conducting before the third time period is completed, ending the first half-cycle and starting the second one.

Now the grid of V1 will also discharge to −7.5 volts after three time periods of 1,600 microseconds each. Slightly before the end of the third time period, V1 begins conducting and the first half-cycle starts all over.

Thus, we see that the first half-cycle is slightly less than 3 × 800 microseconds, or 2,400 microseconds; and that the second half-cycle is twice as long, or not quite 4,800 microseconds.

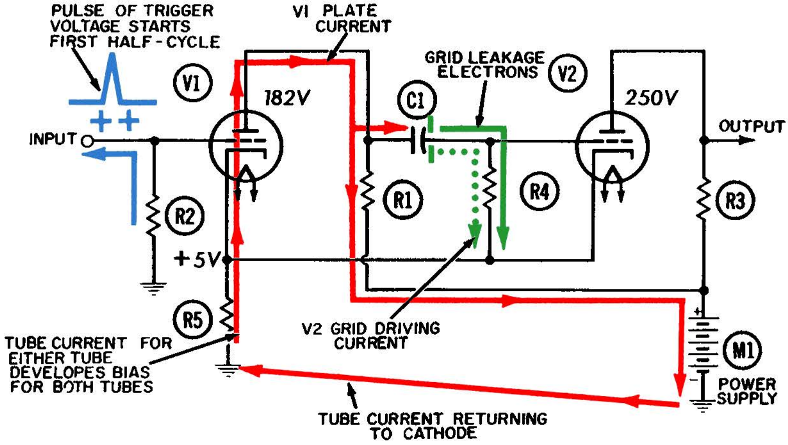


**Fig. 9-4. Operation of a modified Eccles-Jordan multivibrator—first half-cycle.**

The waveforms at the plates of V1 and V2 will be rectangular, as shown by lines 1 and 3 of Fig. 9-3, because of the unequal half-cycles. If the two half-cycles were equal—that is, if R2 and R4 had identical resistances—the waveforms would be square, and the multivibrator could then be considered a crude form of square-wave generator. (Actually, they would only be approximations of square waves. However, the term *square wave* is adequate for conveying a general understanding of how the circuit operates.)

Note in lines 2 and 4 of Fig. 9-3 that the grid voltage rises exponentially until it reaches −10 volts (its cutoff value). At this point, it almost immediately jumps to a slightly positive value, then drops back to the zero-voltage line and hovers there during the remainder of the half-cycle that the tube is conducting.

What prevented the grid from being driven positive instead of remaining at (or near) zero? Whenever the control grid is driven positive (as it was here), it will attract electrons from the plate current. These grid-leak electrons, sometimes more loosely described as "grid current," collect on the control grid and drive the positive-going grid voltage back to zero.

The dotted portions of lines 2 and 4 in Fig. 9-3 show how high the grid voltage would rise, were it not for the grid-leak current. At the start of the first half-cycle (Fig. 9-1), for example, the current through V2 is suddenly cut off, and the voltage at the plate rockets from +100 volts toward the supply voltage of +250 volts. Capacitor C1, connected to the plate of V2, opposes this sudden change in voltage across *its* plates—it tries to drag the V1 grid 150 volts in the positive direction, from −10 volts to +140 volts, but is prevented from doing so by the grid-leak current flowing out of V1 and onto the left plate.

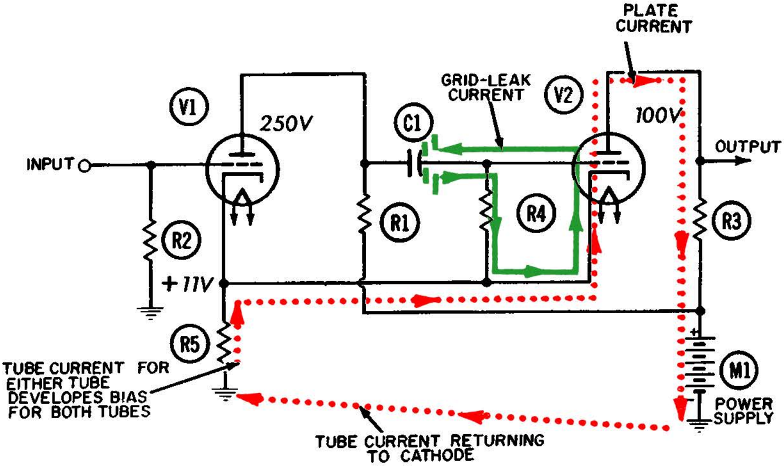


**Fig. 9-5. Operation of a modified Eccles-Jordan multivibrator—second half-cycle.**

A series of similar events also occurs at the start of the second half-cycle (Fig. 9-2) and prevents the V2 grid voltage from rising any further after it passes the zero-voltage point.

During the first half-cycle, the grid-leak and -driving currents flowing through R2 travel in opposite directions. The driving current predominates and "triggers" V1 to start the first half cycle. Through R4, however, the two currents flow in the same direction. (Remember that grid-leakage electrons always flow downward, in an attempt to discharge from their storage points on the grid sides of the grid capacitors.)

In Fig. 9-2 the situation has been reversed—the currents flow in the same direction through R2, but in opposite directions through R4. The driving current is more temporary than the leakage current, since it flows only while the plate voltage in the other tube is rising or falling.

### Summary

Both multivibrator tubes will begin to conduct plate current when the supply voltage is applied. One of the tubes inevitably will conduct slightly more current, even though the two circuits are identical. When this happens, its plate voltage will fall and, by capacitive coupling, reduce the voltage at the grid of *the second tube.*

The lower voltage will reduce the current through the second tube and raise its plate voltage. This rise is capacitively coupled to the grid of the first tube, increasing the plate current and reducing the plate voltage of the first tube still further. The effects are cumulative, so that the first tube conducts more and more heavily until it cuts off the second tube.

The grid voltage of the second tube will have been driven considerably below cutoff during this sequence; and because of the grid-leakage electrons it has accumulated, the second tube requires considerable time to discharge this negative voltage to ground before it can conduct again.

When this does happen, the earlier sequence is repeated, only this time in reverse. The plate voltage of the second tube begins to drop because of the rising plate current. Since the plate is capacitively coupled to the grid of the first tube, its voltage drops accordingly, reducing the plate current and raising the plate voltage of the first tube. By capacitive coupling the grid voltage of the second tube is raised still higher, and so on, in another cumulative series of events. The first tube will soon be cut off, and will remain off until its negative grid voltage can again discharge to the cutoff value.

Shifting conduction from one tube to the other in this manner, the multivibrator circuit will oscillate indefinitely. For this reason it has been aptly named a "flip-flop" circuit.

## THE ECCLES-JORDAN MULTIVIBRATOR

The modified Eccles-Jordan multivibrator (Figs. 9-4 and 9-5) is also known as a "one-shot" or "trigger" multivibrator. Unlike in the free-running multivibrator described previously, only one of the tubes has its plate coupled back to the grid of the other. This feature prevents the circuit from cycling repeatedly. Also, both tubes use a common cathode-biasing resistor to drive the voltage at both cathodes in the positive direction, in a manner which will be explained later. The grid of V1 is returned to ground, whereas in V2 it is returned to the cathode. Since ground is at a lower voltage than the cathodes, normally V1 remains cut off and V2 conducts.

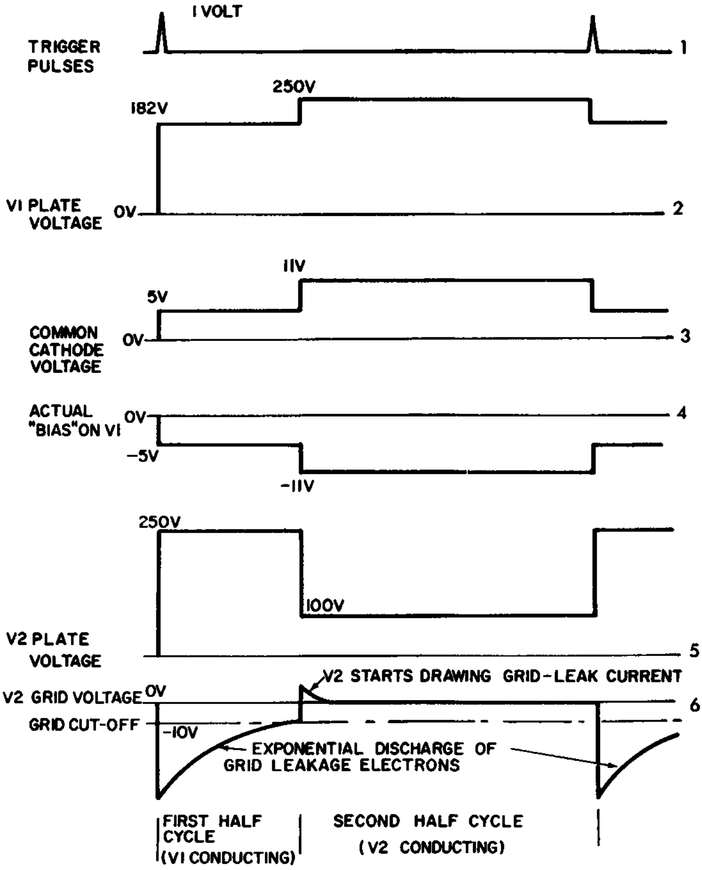


Fig. 9-6. Voltage waveforms during one cycle of operation of the Eccles-Jordan multivibrator.

The components of this circuit include:

R1—Plate-load resistor (about 20,000 ohms) for V1.
R2—Grid driving resistor for V1.
R3—Plate-load resistor (about 20,000 ohms) for V2.

R4—Grid blocking and driving resistor (about 1 megohm) for V2.

R5—Common cathode-biasing resistor (about 1,000 ohms) for V1 and V2.

C1—Grid coupling and blocking capacitor (about 800 micromicrofarads) for V2.

V1 and V2—Triode amplifier tubes.

The currents at work in this circuit appear in the following colors in Figs. 9-4 and 9-5:

1. Grid driving current for V1 (blue, in Fig. 9-4.)
2. Plate current for V1 (solid red, Fig. 9-4).
3. Grid driving current for V2 (dotted green, in Fig. 9-4).
4. Plate current for V2 (dotted red, in Fig. 9-5).
5. Grid-leak current (solid green, in Figs. 9-4 and 9-5).

The first half-cycle begins with the arrival of a positive triggering pulse at the control grid of V1. This pulse, shown in blue in Fig. 9-4, draws a small electron current upward through grid resistor R2 and into whatever coupling device is at the left of V1.

V1 is normally cut off (nonconducting) because its grid is connected to ground and thus is at zero voltage, whereas its cathode is at the positive voltage produced by the current flowing upward through cathode biasing resistor R5. On the other hand, V2 normally conducts a substantial amount of plate current.

Plate current for either tube will flow upward through resistor R5. Since both tube cathodes are connected to the top of R5, the two will always have the same positive voltage on the cathode, irrespective of which tube is conducting. Let us assume it is +11 volts.

Tube V1 is normally cut off because its control grid is connected to ground, or zero voltage, through resistor R2. Hence, the grid is at zero volts also, and we said earlier that the cathodes are at +11 volts. This leads us into *bias*, an often misused term.

Bias, in the correct sense, refers to the *difference* in voltage between the grid and cathode. In this circuit we would normally say the cathode is 11 volts more positive than the grid. But it would be just as correct to say the grid is 11 volts more negative than the cathode. This 11-volt difference in voltage between the grid and cathode is the bias. (If the cathode were at zero volts instead and the grid were at −11 volts, the bias would still be the same −11 volts.)

If we assume that the grid cutoff voltage is −10 volts, V1 will remain cut off as long as its bias is −11 volts. Nothing happens until a trigger pulse exceeding +1 volt arrives at the grid and raises its voltage above the cutoff value. When the pulse arrives, plate current begins to flow through V1, marking the beginning of the first half-cycle (Fig. 9-4).

Now the V1 plate voltage begins to fall. This drop in voltage is coupled from the plate of V1, via C1, to the grid of V2. The flow of plate current through V2 is cut off, causing the plate voltage to rise rapidly toward the value of the supply voltage.

Unlike in the free-running multivibrator discussed previously, this rise in plate voltage is not coupled back to the grid of V2. Consequently, the grid voltage of V1 will not rise as high, and V1 will conduct less plate current, than it would if connected as a free-running multivibrator.

This reduction in plate current through V1 (compared with that which would flow in the free-running multivibrator) has two important effects. First, the plate voltage of V1—and hence the voltage at the grid of V2—will not be reduced to as low a value. Secondly, the cathode-bias voltage developed across R5 will be lower during the first half-cycle. Line 3 of Fig. 9-6 shows this reduction in cathode voltage.

Let us assume the cathode voltage across R5 drops from +11 volts during the second half-cycle to +5 volts during the first one. This has the effect of reducing the total grid bias from −11 to −5 volts.

Line 4 of Fig. 9-6 is essentially an inversion of Line 3; it shows the actual bias on V1. Once the trigger voltage has started this tube conducting, the grid returns fairly quickly to zero volts and the bias stabilizes at −5 volts—enough to permit a reasonable amount of plate current to flow.

Line 5 of Fig. 9-6 shows the plate-voltage waveform for tube V2. At the start of the first half-cycle when the plate current is cut off, the plate voltage rises to the value of the supply voltage, and remains there until the plate current is turned on again at the start of the second half-cycle.

Line 6 of Fig. 9-6 is quite similar to the grid-voltage discharge curves shown in Fig. 9-3 for the free-running multivibrator, and will therefore not be reanalyzed in detail here. Tube V2 will remain cut off as long as the difference in voltage between its grid and cathode is greater than the cutoff value of −10 volts. The discharging of capacitor C1 consists of grid-leakage electrons flowing downward through grid resistor R4. The rate of flow, which decreases exponentially, determines the voltage developed across R4.

The first half-cycle ends when V2 begins to conduct. This cuts off the flow of plate current through V1, but in a different manner than in the free-running multivibrator. The increase in total current through cathode resistor R5 raises the voltage at both cathodes, immediately restricting the flow of plate current through V1. As a result, the plate voltage of V1 begins to rise. This increase is coupled via C1 to the grid of V2, raising the grid voltage and hence the plate current of this tube still further. This increase in V2 plate current, flowing through common-cathode resistor R5, further reduces the plate current through V1, cutting the tube off very quickly.

The second half-cycle, once begun, will continue indefinitely unless retriggered by an outside voltage source. Thus, it will usually last longer than the first half-cycle. The grid voltage of V2 will rise momentarily to a slightly more positive value than the cathode, but will then begin to acquire some grid-leak electrons from the tube, preventing it from rising any further. Throughout the second half-cycle, the two voltages will remain close to the same value.

The different amount of plate current through each tube is reflected by the waveform voltages at the two plates. When not conducting, each tube plate will rise to the +250-volt supply voltage. However, since V2 conducts more than twice as much current as V1, and since R1 and R3 are equal in value, it follows from Ohm's law that the resulting voltage drop across R3 will be more than twice the one across R1. Consequently, approximately 182 volts has been indicated at the plate of V1 during the first half-cycle, as opposed to 100 volts for V2 during the second half-cycle.

## Chapter 10

# THYRATRON SAWTOOTH GENERATORS

A thyratron differs from a vacuum triode in that it is filled with an easily-ionized gas, rather than being evacuated. Under certain conditions the gas will become ionized, when grid and plate voltages are applied, and permit a very heavy electron current to flow between cathode and plate.

An important characteristic of the thyratron is the inability of its control grid to cut off the plate current—once a thyratron begins to conduct, the only way it can be cut off is for the plate voltage to be lowered almost to zero—15 or 20 volts is not abnormally low.

The schematic symbol is the same for a vacuum tube or thyratron except for a dot within the tube envelope, as shown for the thyratron in Figs. 10-1 and 10-2.

Thyratrons are capable of generating sawtooth-voltage waveforms (so named because of their shape) which are used for sweeping the electron beam across the face of a cathode-ray tube in an oscilloscope, radar set, or other application where it is desired to gradually move the beam across the face of the tube and then quickly return it to the starting point. Fig. 10-3 shows the waveform generated at the plate.

The only significant current in this circuit crosses from cathode to plate and could perhaps be called "plate current." However, its movement during the conducting and nonconducting period of each cycle is quite different from the plate-current flow in a vacuum tube. Let us start at the beginning, when the power supply is turned on and applies a positive voltage to the plate.

In order for the plate voltage to rise from zero to the power-supply voltage, free electrons must be drawn away from the plate of the tube, the upper plate of capacitor C1, and from any component connected to the output. This is the charging process and the amount of time it takes depends on the values of plate-load resistor R1 and capacitor C1 in Fig. 10-1. R1 is very large, several hundred thousand ohms; and C1 is 1,000 micromicrofarads or so. The plate-voltage curve begins at zero and rises exponentially toward the power-supply voltage, as shown in Fig. 10-3. (An exponential curve is one which does not rise or fall at the same rate from left to right.) The dashed-line portions of the curves in Fig. 10-3 represent the voltage which would exist at the plate if the charging process were completed.

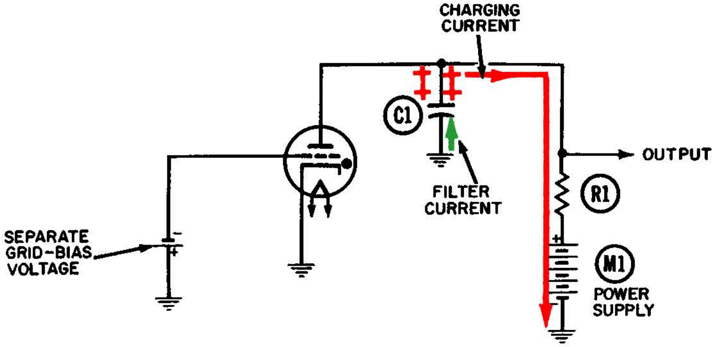


**Fig. 10-1. Operation of the thyratron sawtooth-voltage generator—charging half-cycle.**

In a thyratron tube, the value of plate voltage at which the gas "breaks down" or becomes ionized is called the *firing voltage.* When this happens, the molecules of gas becomes ionized and release their free electrons, and the interior of the tube becomes filled with both positive ions and negative electrons. Attracted by the positive voltage at the plate, the negative electrons flow there in a steady stream and are replaced by other free electrons emitted by the heated cathode.

The value of the firing voltage depends partly on the applied grid-bias voltage, shown as a separate battery in Figs. 10-1 and 10-2. In a typical thyratron tube, this grid bias is on the order of −5 volts, and the firing voltage at the plate is 75 to 100 volts.

Once the tube begins to conduct, it delivers electrons to the plate much faster than high-value plate-load resistor R1 can pass them. The electrons accumulate on the upper plate of capacitor C1 and reduce its charge to a very low positive voltage, as depicted in Fig. 10-2. The charged capacitor is now said to be "discharging through the tube." Strictly speaking, the capacitor is not discharging through the tube, but its positive *voltage* is being discharged because the tube supplies a large number of free electrons (in the form of plate current) to the capacitor. This discharging process occurs in only a tiny fraction of the time required for the charging process, as shown by Fig. 10-3.

Once the gas has been ionized, the grid can no longer control the flow of current. Now it can only be stopped by reducing the *plate* voltage to a very low value—on the order of 15 or 20 volts. This might be called the "cutoff" voltage for a thyratron.

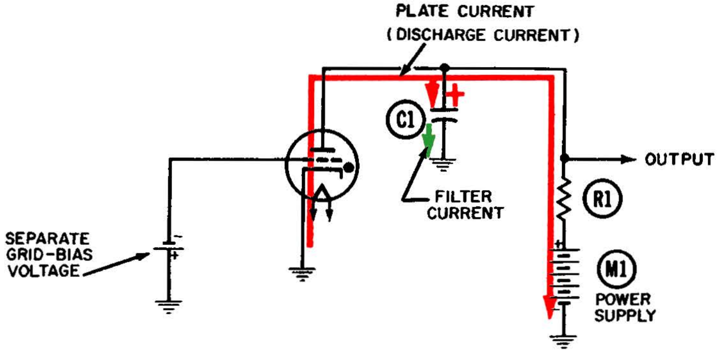


**Fig. 10-2. Operation of the thyratron sawtooth-voltage generator—discharging half-cycle.**

The exponential charging curve is almost a straight line in the low plate-voltage regions, between the cutoff and firing voltages. This area, referred to as the linear portion of the curve, is where the sawtooth voltage is generated.

As in any tube, the current must have a closed path leading back to the cathode. In Figs. 10-1 and 10-2, the complete path is from cathode to plate, through the load resistor and power supply to ground, and back to the cathode.

The much shorter discharge half-cycle makes the thyratron an ideal sweep generator. After the beam has been swept across the face of the screen, it must be retraced as quickly as possible or the viewer will see a flickering picture. The short discharge period is normally used for retrace, so that the beam will be out of action as briefly as possible.

A filter current, shown in green, flows between the lower plate of capacitor C1 and ground. In Fig. 10-1 the current flows upward because of normal capacitor response to the voltage changes at

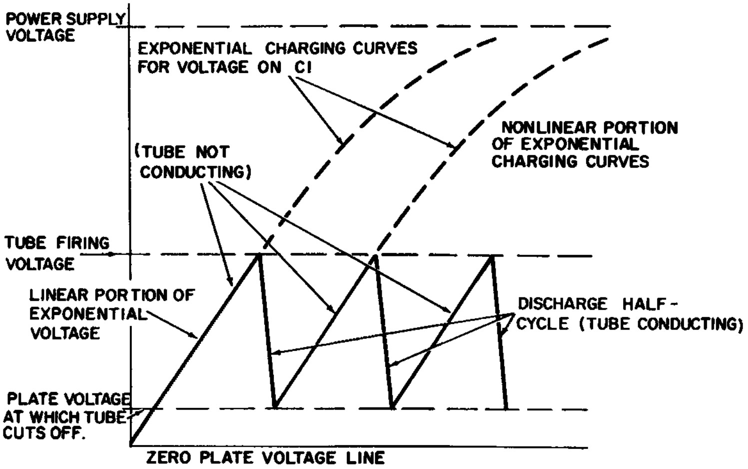


**Fig. 10-3. Sawtooth output voltage generated at plate of thyratron generator.**

the plate of the tube, but is driven downward in Fig. 10-2 by the plate-current electrons flowing onto the upper plate.

Obviously, a high positive value of plate-supply voltage contributes to greater linearity of the charging half-cycle, whereas a lowered value would lead to greater curvature in the discharge curve.

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