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DETECTOR AND RECTIFIER CIRCUITS

by Thomas M. Adams

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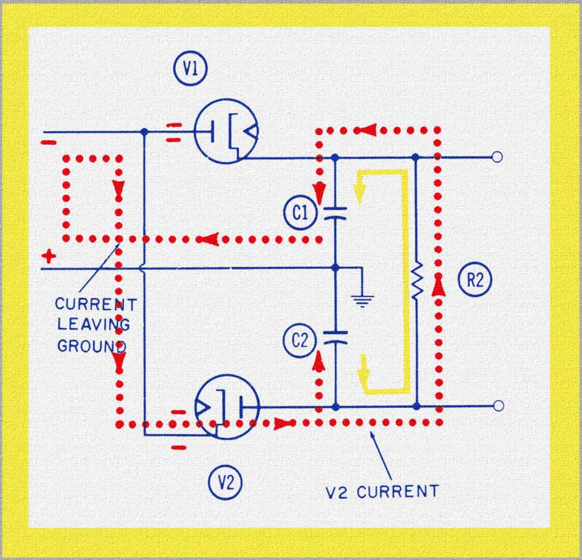

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Basic Electronics Series

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Captain, United States Navy

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PREFACE

There is an interesting parallel between learning electronics and learning a foreign language. Even if a person never goes to school a day in his life, he usually learns to say enough words to get by. Contrast this with a diligent, intelligent high school student studying a foreign language. After two or three years of learning the rules of grammar, declension, spelling, etc., he may be capable of ordering an omelet in his newly acquired tongue—unless the waiter asks: "Chicken or duck?" At this point, the whole communications process may break down, simply because the fundamentals were neglected somewhere along the line.

In the study of electronics (or a foreign language), it is difficult to define "fundamental." This volume, like the previous two on oscillator and amplifier circuits, does not attempt to settle the question. Instead, the text has been written with a single objective in mind—teaching or explaining how circuits operate. At the same time, certain theories such as Kirchhoff's, Ohm's, and Coulomb's are also explained, wherever they apply.

None of the volumes is considered more elementary or advanced than the others. Hence, any volume may be read in any order. In fact, it is hoped that almost any chapter of any book can be read without reference to previous chapters. This volume, like the previous two, presupposes only an understanding of the electron current theory.

Almost all electronic-circuit actions fall into one of five categories, in which electron current flows:

1. Through a pure resistance.
2. Through a pure inductance.
3. In and out of a capacitor.
4. In a resistor-capacitor (RC) combination.
5. In an inductor-capacitor (LC) combination.

These five basic circuit actions appear over and over in electronic-circuit operations. All volumes in this series have this one objective in mind—to explain such basic actions so that, by the end of the chapter, the reader will be able to understand how that circuit operates—*no matter where it is encountered.* After finishing this volume, he should intuitively understand how all detectors and rectifiers work and also the five actions listed above, on which all circuit theory and operation are based.

As before, the diagrams are of circuit *actions* rather than *connections*. The material is neither too advanced for the high school and technical institute level, nor too elementary for colleges. An understanding of circuit actions is the first step. If they can be visualized in the mind's eye, any circuit diagram can be easily interpreted, circuit troubles can be diagnosed and corrected, and a solid groundwork laid for those interested in more advanced theory.

The ability to visualize circuit actions should precede any attempt to learn the rigorous mathematical laws which describe them. This parallels our way of learning, where we first learn to describe before we infer, and then to infer highly concrete and hence obviously valid statements before tackling the more abstract ones.

The philosophy of this and other volumes is oriented around the movements of electrons—which, by definition, are electron currents. All statements about the function of an electronic circuit are in reality statements about electron currents; that is, functions are performed by currents—no currents, no functions. Once the reader understands current movements, the more abstract terminology built up around the circuit functions will become clear to him.

The author is indebted to those persons named in the preface to the oscillator volume for taking the time to review the drawings and proffer helpful suggestions. Additionally, a debt of gratitude is owed to Commander David O. Mann, U.S. Navy, for his many penetrating technical discussions, particularly on resonant circuits.

THOMAS M. ADAMS

August, 1961

Chapter 1

INTRODUCTION

It is frequently said of rectifier power supplies and detector circuits that their functions are based on the peculiar ability of the vacuum tube to permit "unidirectional current flow"—in other words, the flow of electron current through a vacuum tube in only one direction. While this statement is intrinsically true, it requires considerable qualification, *since all other vacuum-tube circuits* also depend directly on this same tube characteristic. For instance, all tube circuits in the other volumes of this series also depend for their operation on the fact that electron current will flow in only one direction through the tube.

RECTIFICATION

The rectifier power supply is probably the simplest application of the fundamental principle of unidirectional current flow through a vacuum tube. For this reason, the first portion of this volume is devoted to rectifier circuits. In order for any type of circuit to find broad usage, there must of course be a need for the function it performs. Rectifier power supplies are widely used and needed to convert alternating current to direct current because of two basic facts:

1. Most of the electric power available throughout the world today, both for home consumption and for industrial and commercial use, is in the form of alternating current.
2. The vast majority of vacuum-tube applications require that the tube be supplied with one or more sources of relatively pure DC (meaning direct current and hence a steady, or direct, voltage).

Alternating current is brought to practically every wall plug in every home, laboratory, and factory in the country. Consequently, every piece of electronic equipment requiring steady, or "DC," voltages for its operation must carry within itself the circuitry required to convert alternating current to direct current, and then be able to adequately filter, or smooth, the output so that it becomes a relatively "pure" DC voltage instead of a pulsating one. Many such circuits will consist of a single vacuum tube with an appropriate combination of the three fundamental components—resistors, capacitors, and inductors—to provide the required filtering action.

The block diagram in Fig. 1-1 shows the basic action of the rectifier circuit, if we can assume the rectifying and filtering functions as separate operations. Of course, in practice both occur together. In fact (as we shall see in later chapters), without filter capacitors, some rectifier circuits would not operate at all. In Fig. 1-1, the alternating AC voltage is applied to the rectifier. This is the 60-cycle AC from the wall plug. Notice that the voltage waveform extends an equal amount above and below the zero line.

The waveform at the rectifier output represents the voltage after rectification but before filtering. Here, the waveform extends only in the positive direction from the zero reference line. It still varies in amplitude, but always above—never below—the line. Likewise, the electron flow through the circuit will always be in the same direction but in varying amounts. Hence, the current and its associated voltage at the rectifier output are known as *pulsating DC.*

The waveform in Fig. 1-1 is for a full-wave rectifier. A half-wave rectifier will not conduct during half-cycles 2, 4, and 6, when the input waveform is negative. Hence, these half-cycles will not be present in the waveform at the rectifier output, and the voltage will be zero during these periods.

The filter circuit follows the rectifier in Fig. 1-1. As we said before, filtering and rectifying occur simultaneously. However, the two are shown in this order so the basic reason for each can be better understood. At the filter output, the waveform shows that the filter circuit has removed all pulsations in the applied

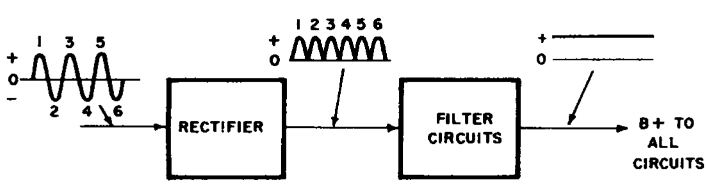


Fig. 1-1. Basic action of a rectifier circuit.

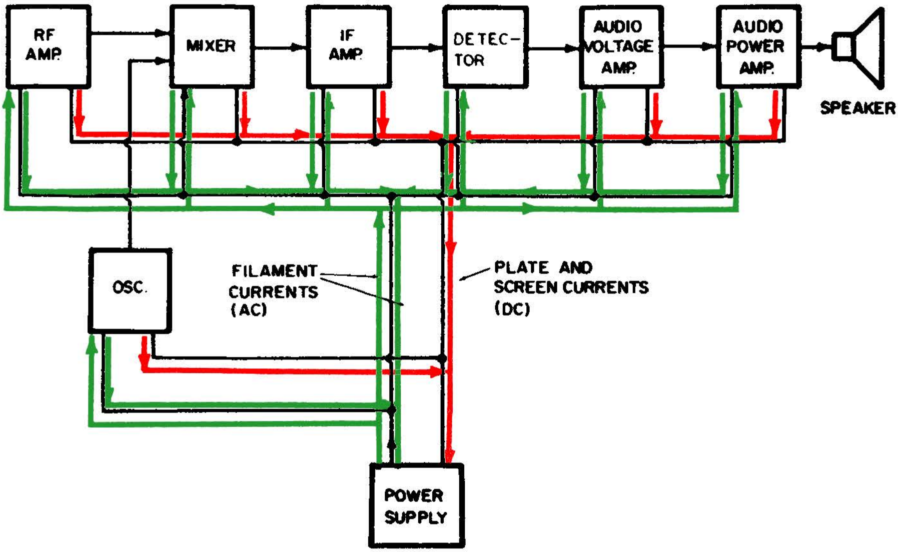


Fig. 1-2. Block diagram of a typical AM superheterodyne receiver, showing plate and filament currents.

waveform. This can be construed as a voltage of a constant positive amplitude, or as a direct current of constant magnitude.

Some ripple will always be present in the output waveform of a rectifier. For all practical purposes, however, the waveform can be considered a steady one, as shown in Fig. 1-1.

Fig. 1-2 shows a block diagram of a superheterodyne AM radio receiver. Each functional block designates a particular type of circuit necessary for complete operation of the receiver. The blocks labeled "detector" and "power supply" are the subject of this book. Because of certain operating similarities, these two circuits can be studied together. As indicated by Fig. 1-2, however, they perform quite different functions.

A detector, for instance, receives an input signal from the final RF or IF amplifier and delivers an output signal to the audio amplifiers. In doing so, the detector has detected (demodulated) the signal carrier. More about the detector circuit later; now we will limit our discussion to the power supply.

The power supply provides an essential service function to *all* circuits in the receiver. This is indicated by the lines which connect the power supply to each of the other fuctional lines in Fig. 1-2. As a general rule, every oscillator, converter or mixer, and amplifier circuit will require at least two separate services from the power-supply circuit, as follows:

1. A high positive voltage for application to the plates and screen grids of the amplifier and oscillator tubes.
2. A low alternating voltage for heating the filaments and/or cathodes, a process which is mandatory in order for electron emission to occur.

A detector circuit does not require the positive plate or screen voltages, but it does require the filament heating voltage.

Fig 2-1 has been color-coded to show the flow of currents between these functional blocks and the power supply. The red lines might be called the B+ current, which flows *from* the plates and screen grids of all amplifier, converter, and oscillator tubes *toward* the high positive-voltage source in the power supply. The various rectifier circuits discussed later make clear why these B+ currents, being made up of electrons, must always flow toward the power supply—never away from it.

The green lines represent the filament heating currents required by the vast majority of vacuum tubes. These are alternating currents, as indicated by the fact that the arrows point in both directions. Sometimes these currents are obtained from a separate winding, of relatively few turns, on the power transformer. Often referred to as the tertiary winding, it supplies the necessary low voltage (usually 6.3 volts) to the filaments. The circuit diagrams for the full-wave rectifier power supply, and the associated text material (Chapter 3), constitute a full qualitative discussion of the operation of a typical low-voltage filament winding. In the vast majority of radio receivers and in many other pieces of electronic equipment, however, the teritary winding is not used. Instead, all filaments are connected in series; that is, the filament current must flow through each tube in succession before reaching the common ground point. The tubes are connected directly across the power line. Filament voltage values are selected so that the total voltage developed across all tubes in series is equal to the power line voltage. Of course, if the filament of one of the tubes in the series string should open, no filament current will flow through any of the tubes.

The plate and filament voltages are applied to the various stages through completely separate wiring; therefore, Fig. 1-2 indicates separate paths for the two types of currents associated with the two voltages. It has been emphasized repeatedly throughout this series that voltages do not *flow* between any two points. When it is desired to apply any particular voltage to a remote point, the natural action or mechanism by which this is accomplished is for an appropriate electron current to flow between the two points.

DETECTION

The term "detection" comes from the early days of radio, when circuits were devised to detect, or discover, the presence of a radio signal from a distant transmitting antenna. From these humble beginnings, the usage of the term "detector" has been broadened so that it is used almost interchangeably with "demodulator." Today the function of detection is almost indistinguishable from the function of demodulating a modulated signal.

The *need* for circuits to detect or demodulate the signal can be seen from Fig. 1-3. Two signals are shown at the transmitter input. The RF carrier is a signal of constant amplitude and frequency. (For the broadcast band, the frequency will be from 540 to 1,600 kilocycles per second.) Before this signal can be used, it must be modulated with the particular intelligence it is to carry. The term "modulate" in this sense means to change some characteristic of the RF carrier so that it will convey the intelligence (music, speech, etc.) to be broadcast. In Fig. 1-3, this intelligence is the audio signal shown entering the transmitter.

Fig. 1-3 shows the carrier being amplitude-modulated and the signal leaving the transmitter antenna. Notice that this signal still varies at the same rate as the RF carrier, but that the amplitude of each cycle varies. If the audio signal at the input were superimposed on either the upper or the lower tips of the mod-

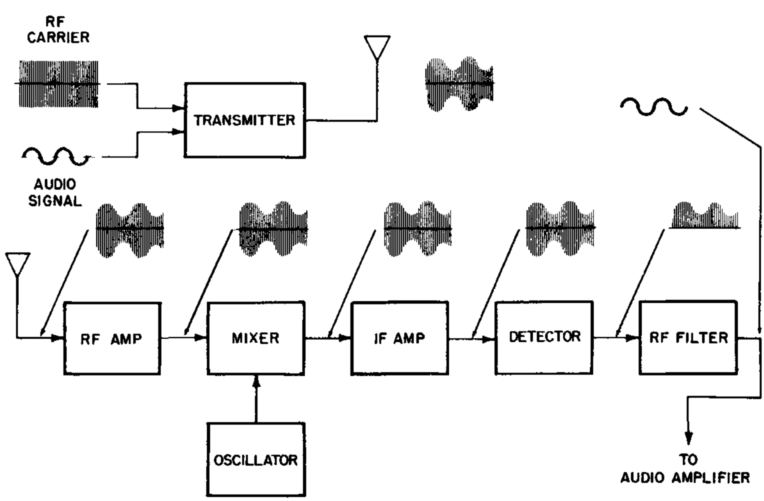


Fig. 1-3. The signal, from modulation at the transmitter to demodulation at the receiver.

ulated carrier, the variations in the modulated carrier would exactly match those of the audio signal. That is, whenever the audio signal went positive, the amplitude of the modulated signal would increase. Likewise, the amplitude would decrease whenever the audio signals were negative.

The modulated RF carrier is picked up by the receiver antenna and amplified by the RF amplifier. Next it is normally converted to a lower frequency (the IF) by the mixer-oscillator circuit. The IF signal, usually 455 kilocycles, is then further amplified by the IF amplifier. Except for its frequency and strength, the signal at the IF-amplifier output is the same as the transmitted signal—the modulations have been faithfully retained.

Now the signal is applied to the detector, which "separates" the audio signal from the RF (IF) carrier. Again, the detecting (rectifying) and filtering actions are shown separately, even though they occur together. The detector performs a function similar to that of the rectifier discussed previously. Notice that the signal at the detector input is still varying at the RF rate, but that only the positive half-cycles of voltage are shown. Thus, this signal is the same as the one applied to the detector, except that the bottom (negative) half has been removed. In other words we have a pulsating DC voltage like we had at the rectifier output. Only now, the pulsations are occurring at the IF rate, and their amplitude varies at the same rate as the original audio signal instead of remaining constant as in the rectifier.

The filter circuit removes the IF pulses, leaving a DC voltage the amplitude of which varies in accordance with the original audio signal. As we shall see in later chapters, this DC subsequently changed to AC before it is further amplified by the receiver.

The foregoing discussion assumed the RF carrier was amplitude-modulated. In addition to amplitude modulation, detectors for demodulating frequency-modulated (FM) signals are analyzed in this volume. With FM modulation, the amplitude of the transmitted RF carrier is held constant and the frequency is varied. This necessitates an entirely different method of detection than described in the foregoing. (FM detection is discussed in Chapters 7 and 8.) The basic purpose of the detector—that of extracting the audio signal from the carrier—remains the same, however—whether the modulation is AM or FM.

There are many additional methods of modulating a carrier wave, such as phase modulation, pulse modulation, frequency-shift keying, etc. In an elementary work like this, however, attention must be directed only to those circuits which have the widest application. Besides, the various types of modulation which have important special application in advanced circuitry will all prove to be *special cases* of either amplitude or frequency modulation. Consequently, a working knowledge of the detectors presented in this volume lay valuable groundwork for anyone pursuing advanced applications of modulation and demodulation.

Almost all detectors and rectifier circuits in this volume depend for proper operation on the principle of the "long time-constant" combination of a resistor and a capacitor. This is undoubtedly the most widely used combination of circuit components in the electronics field. For this reason, it is advisable to understand thoroughly how such a combination works, and how the particular values of components chosen are related to the frequency of the current under consideration. The physical actions in the various R-C combinations of this volume are fully explained as they are encountered in each chapter. Consequently, they will not be reviewed here.

Chapter 2

HALF-WAVE RECTIFIER CIRCUITS

Half-wave rectifier circuits are very common in power supplies of electronic equipment. This is especially true where low cost and high output voltage are essential. In this chapter, the following circuits will be discussed:

Half-wave transformerless rectifier.
Half-wave voltage-doubler rectifier.
Half-wave rectifier with transformer.

TRANSFORMERLESS HALF-WAVE RECTIFIER

Fig. 2-1 and 2-2 show two successive half-cycles in the operation of a transformerless half-wave rectifier power supply. This type of power supply may be plugged directly into either an alternating- or direct-current power line. Because of this feature, the power supply is known as an AC-DC supply. (Obviously, when the unit is operated from a DC line, there will be no such thing as an alternating half-cycle.)

The essential components of this power supply are:

R1—Filter resistor.
R2—Voltage-divider resistor for taking ouput voltages.
C1—First filter capacitor.
C2—Second filter capacitor.
C3—Isolating capacitor.
V1—Half-wave rectifier tube.

Only two main types of currents are at work in this circuit. They are:

1. Main rectifier current (red).
2. Filter currents (green).

When the applied power-line voltage makes the plate of the rectifier tube more positive than the cathode, the tube will conduct electrons from cathode to plate. Their path starts at the other side of the power line. These electrons flow upward through voltage-divider resistor R2, and then to the left through filter resistor R1, enroute to the cathode.

Resistor R1 and capacitor C1 form a long time-constant filter of the type discussed in the introductory chapter to the oscillator volume in this series. Resistor R2 and capacitor C2 form another long time-constant filter combination. These two RC combinations provide adequate filtering and consequently adequate reduction in ripple voltage.

When the circuit is turned off and is at rest, zero output voltage will be measured at either output point. However, as soon as power is applied, electrons will leave the cathode during each positive half-cycle and cross to the plate of the rectifier tube. This action leaves the cathode with a *deficiency* of electrons and consequently with a positive voltage. The upper plate of capacitor C1 immediately assumes this value of positive voltage.

The only way this positive voltage can be reduced to zero is by drawing electrons up from the other side of the line, through the two resistors. (This current is shown in red.) Because these are long time-constant filters, the positive cathode voltage undergoes only insignificant reduction before the next positive half-cycle of power-line voltage is applied. Each positive half-cycle draws more electrons across the tube. During negative half-cycles like those represented in Fig. 2-2, no electrons cross the tube. However, the upward flow of electrons through the resistor path continues throughout the entire cycle.

Ohm's law tells us that the voltage across a resistor is proportionate to the current through it. This is written symbolically as:

$$E = I \times R$$

where,

E is the voltage in volts,
I is the current in amperes,
R is the resistance in ohms.

Coulomb's law tells us that the amount of voltage across a charged capacitor is proportionate to the quantity of electrons (or positive ions) stored there. This is written symbolically as:

$$Q = C \times E$$

where,

Q is the number of coulombs of charge stored (1 coulomb $= 6.25 \times 10^{18}$ electrons),
C is the size of the capacitor in farads,
E is the voltage across the capacitor in volts.

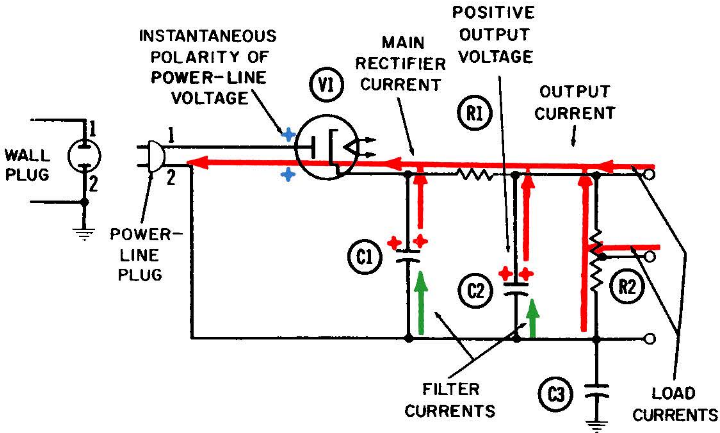


Fig. 2-1. Operation of the transformerless half-wave rectifier—conducting half-cycle.

This formula can be rewritten as:

$$E = \frac{Q}{C}$$

Since the voltage across capacitor C2 is identical to the output voltage across R2, we can make these voltage equations equal to each other and say:

$$\frac{Q}{C2} = I \times R2$$

where,

Q is the quanity of positive ions stored on the upper plate of C2,

I is the main rectifier current (in red) flowing upward through R2.

The positive voltage on the upper plate of C1 draws electrons to the left, through resistor R1. The deficiency of electrons created on the upper plate of C2 becomes the output voltage. It is this positive voltage that draws electron current upward through voltage-divider resistor R2. Any fraction of the total output voltage can be obtained by placing an appropriate tap on the voltage divider.

Filter Currents

The RC filtering used in this power supply is identical in principle to the cathode filtering discussed in the oscillator and am-

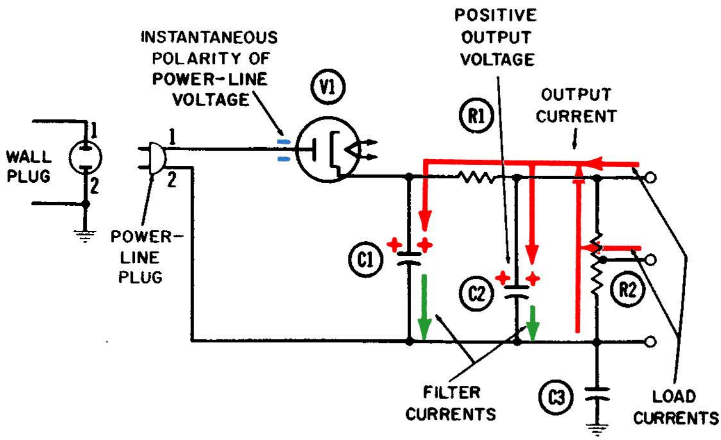


Fig. 2-2. Operation of the transformerless half-wave rectifier—nonconducting half-cycle.

plifier volumes of this series. As electrons are drawn into the rectifier tube, they can come from one of two places—either directly through the high-impedance path composed of R1 and R2, or from the upper plate of C1 (which offers a much lower impedance). Naturally, most of the tube-current electrons come from the top of capacitor C1. In order for this to happen, an equal number must be able to flow *onto* the capacitor's lower plate. These are the electrons, shown in green, flowing upward into C1 during the first half-cycle (Fig. 2-1).

On the negative half-cycle such as are shown in Fig. 2-2, these electrons flow back down to the other side of the line. These two movements constitute the filter action of the capacitor.

A similar filter current flows between the lower plate of C2 and the neutral side of the line. This filter current is much smaller because C1 has already filtered out most of the fluctuation in the main rectifier current.

Capacitor C3 isolates the equipment from ground to eliminate the danger of shock. As shown in Figs. 2-1 and 2-2, the two leads on the left connect to the two prongs of an ordinary electric plug. One of the two wires leading to the wall outlet in the home is normally grounded and the other is "hot." Capacitor C3 could be omitted and the lower end of R2 grounded directly, provided one could always be sure prong 2 would be plugged into the ground side of the power line and prong number 1 into the "hot" side. However, since the plug can be inserted either way, the user runs the risk of connecting the "hot" side of the line directly to the receiver ground, which is usually the chassis. This could result in a dangerous shock, so C3 is added between the line and the receiver chassis as a safeguard.

TRANSFORMER INPUT HALF-WAVE RECTIFIER

Figs. 2-3 and 2-4 show two successive half-cycles in the operation of a half-wave rectifier power supply using a step-up input power transformer. The filter circuit used for converting the resultant pulsating DC into pure DC is similar to the previous circuit used with the transformerless power supply. Both use a resistor (R1) instead of the bulkier and more costly filter choke. Another disadvantage of a filter choke is that the continual passage of current in a single direction through the winding establishes a permanent magnetic field. This feature can be seen more clearly in the next chapter, where the full-wave rectifier is discussed. However, using a resistor in lieu of a filter choke is not without its disadvantage. There is a definite voltage drop and power loss, occasioned by the flow of all the rectified current through the resistor. This loss in voltage and power is in addition to the power consumed by the rectifier current flowing upward through output resistor R2.

Circuit Components

This circuit is made up of the following components:

R1—Filter resistor.
R2—Output resistor, suitably tapped to provide any desired partial voltages.
C1—Input filter capacitor.
C2—Output filter capacitor.
T1—Power transformer.
V1—Diode tube.

Identification of Currents

The following currents are at work in this type of circuit:

1. Power-transformer primary current (solid blue).
2. Power-transformer secondary current (also in solid blue).
3. Diode tube current (red).
4. Cathode heating current (dotted blue).
5. 60-cycle filter currents (green).

Fig. 2-3 shows the half-cycle when the power transformer makes the diode plate positive, so that electrons can cross the tube. An attempt has been made to depict this transformer action just as it actually occurs in these figures. The current in the primary, which is the driving current, can be considered to flow downward through the primary in the first half-cycle, in response to an applied negative voltage. This applied polarity has been indicated by the minus sign at the top of the primary winding.

This primary current *induces* a voltage in the secondary winding which is in opposition to the applied voltage. The polarity of this "back emf" has been indicated by the plus sign at the top of the secondary current associated with this induced voltage, and its flow direction is indicated as upward during the first half-cycle.

This induced voltage and current will have their greatest values twice during each cycle, when the primary inducing current is *changing* at the maximum rate. While the primary inducing current has its greatest value, the secondary induced current and voltage will be zero. These moments also occur twice during each cycle—midway in each half-cycle.

Heating Current

The power transformer used here and in most power-supply applications has a third, or tertiary, winding which delivers a large flow of current to heat the filament or cathode, in order that emission may occur. This current, shown in dotted blue, follows the closed path through the winding and through the filament or cathode. The example used here is a directly heated cathode which requires no additional filament.. This heating current flows at the same frequency as the power current, which is 60 cycles per second in most parts of the United States. It is shown flowing clockwise during the first half-cycle and counterclockwise during the second. The wire connecting the filter network to the cathode is usually brought to the center tap of this winding. In this way, a minimum of 60-cycle ripple (due to the heating operation) will be coupled into the filter system.

During that portion of the first half-cycle while tube current is flowing, it enters the cathode network through this center tap and flows through *both* sides of the line to the cathode before entering the tube. Neither of these two currents in the tertiary winding and in the cathode "disturbs" the other one in any sense.

The tertiary winding constitutes a voltage step-down and current step-up device. Tube cathodes and heating filaments are designed for a certain applied voltage, which varies in size depending on the application. Common values are 5, 6.3, and 12.6 volts. However, 25- and even 35-volt heaters are used.

The *amount* of current is of course regulated by the amount of resistance in the winding and that portion of the cathode or fil-

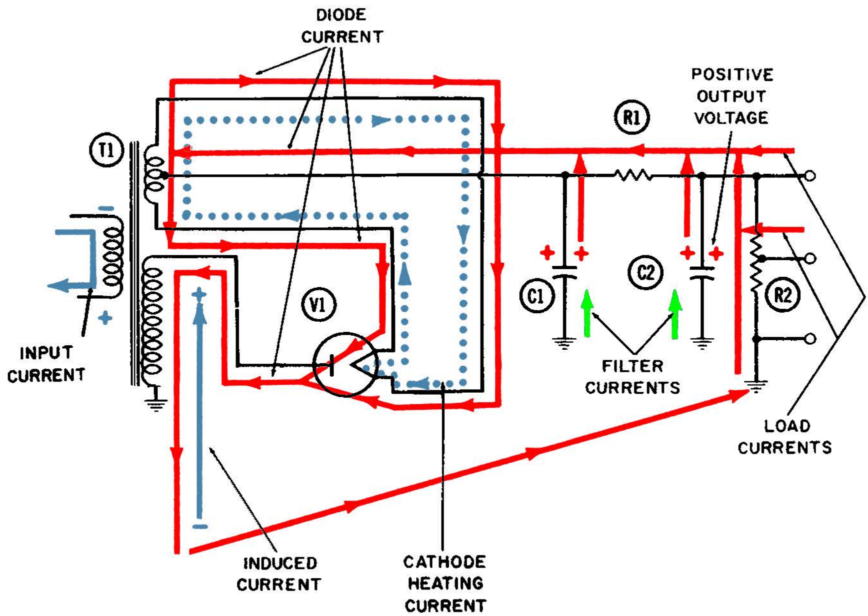


Fig. 2-3. The transformer input half-wave rectifier—first half-cycle.

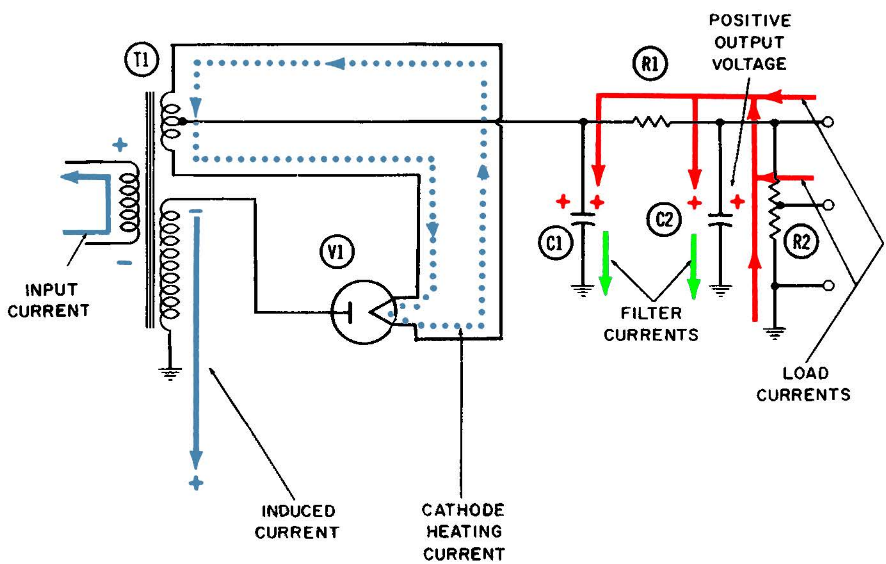


Fig. 2-4. The transformer input half-wave rectifier—second half-cycle.

ament through which the heating current must flow. The tube is designed so that its current heats the cathode sufficiently to emit electrons without burning up the tube.

Sometimes the lead from the filter circuit is connected directly to one side of the filament. Operation is the same, except the diode current flows from the filter circuit directly to the filament, and through the tube to the transformer. In other versions, a tube with an indirectly heated cathode is employed. Then the filter circuit is connected to the cathode and the heater is entirely independent.

Filter Currents

The filter network here operates on the same principle described for the preceding transformerless power supply. As the electron current leaves the cathode and flows across the tube, these filter currents (in green) flow upward from ground into filter capacitors C1 and C2. When the electron flow across the tube stops during the second half-cycle, these filter currents flow downward to ground.

VOLTAGE DOUBLER

Figs. 2-5 and 2-6 show two successive half-cycles in the operation of a dual-diode rectifier system being used as a voltage doubler. This particular circuit includes a step-up input transformer. However, it is even more common for the voltage-doubling principle to be used with a transformerless input. The output voltage would then be limited to about 2.8 times the *peak* value of the alternating supply voltage. With a step-up transformer, the maximum output voltage attainable will equal this figure, multiplied by the turns ratio of the transformer.

As an example, if the input voltage is the standard 110 volts (effective value), its peak value will be 1.4 times as great, or about 155 volts. When doubled, this would come to 310 volts; this is the maximum attainable in a transformerless circuit. In the circuit shown in Figs. 2-5 and 2-6, if the transformer turns ratio were 2-to-1, then the maximum attainable output voltage would be twice as much, or 620 volts.

The following circuit components make up this voltage-doubling circuit:

R2—Output resistor.
C1—Output capacitor.
C2—Output capacitor.
T1—Power transformer.
V1 and V2—Diode tubes.

Identification of Currents

The following electron currents are at work in a circuit of this type:

1. Input power current (blue).
2. Current through V1 (solid red).
3. Current through V2 (dotted red).

Details of Operation

The plate of diode V1 and the cathode of diode V2 are connected directly together and also to the top of the transformer secondary winding. In the first half-cycle shown in Fig. 2-5, transformer action makes the top of this winding positive. V1 conducts from cathode to plate. V2 is of course unable to conduct, since its cathode is more positive than its plate.

The flow of electrons from cathode to plate of V1 charges the upper plate of capacitor C1 to a positive voltage which is almost equal to the peak transformer secondary voltage. The reason is that the capacitor gives up electrons to provide the necessary tube current; the resultant electron deficiency constitutes a positive voltage. As a result of this current flow through the diode and the positively charged capacitor, electron current is drawn upward through resistor R2. This is part of the output current of the rectifier, and it has been shown in solid red lines. The voltage it will develop across R2 will always be proportionate to the amount of current flowing, in accordance with Ohm's law, and will always be *exactly equal* to the voltage across capacitor C1.

After passing from cathode to plate, these electrons head downward through the transformer secondary winding and enter the neutral, or ground, point between the two capacitors.

During the second half-cycle, shown in Fig. 2-6, transformer action causes the top of the secondary winding to assume a negative voltage. This negative voltage appears at the plate of V1 and prevents any electron curent from flowing through this tube. However, the same negative voltage at the cathode of V2 causes a full flow of electrons across this tube. These electrons originate at the ground point between the two capacitors and flow upward through the secondary winding, then downward to the cathode of V2 and through the tube to the lower plate of capacitor C2. Here they accumulate, forming a negative voltage almost equal in value to the negative peak value of the induced voltage across the secondary winding. This negative charge on the lower plate of C2 drives a continuous electron current upward through resistor R2. This current, shown in dotted red lines, is also part of the rectifier output current. It develops a voltage across R2 that will at all times be exactly equal to the negative voltage existing across capacitor C2.

Consequently, these two currents flowing upward simultaneously through R2 will develop a voltage across it which is approximately twice as great as either current could develop alone. The total voltage across R2 is of course equal to the sum of the two capacitor voltages, and almost equal to twice the peak secondary voltage. Because of this feature, the circuit is referred to as a voltage-doubler circuit.

ADVANTAGE OF HALF-WAVE OPERATION

The principal advantage of using a half- rather than full-wave power supply (discussed in the next chapter) is that a power transformer is unnecessary. However, when a power transformer is used, a higher output voltage can be obtained for a given *size and weight of transformer.* A higher voltage can be obtained with half-wave operation because the entire amount of secondary voltage is applied to the plate of the rectifier tube. The DC voltage developed at the cathode can never exceed this peak secondary voltage, although the two will usually be very close in value.

If the secondary of this transformer were center tapped, with the two ends of the winding going to the plates of two rectifier tubes or a twin diode tube (as it is in the full-wave rectifier), then only half the available voltage swing would be applied to each plate, and only half as much output voltage would be available across the output resistor. This point can be clarified by comparing the circuit of Figs. 2-3 and 2-4 with those of the next chapter.

Let us assume the transformers used in two circuits are identical in construction, turns ratio, size, weight, etc., except that one has a center-tapped secondary to allow for full-wave operation. Let us also assume that turns ratio is 1-to-3 and that the *peak* voltage swing of the primary power is about 150 volts, which is reasonably close to home supply conditions (110 volts effective value equals 155 volts peak). Under these conditions, the peak secondary voltage will be 450 volts. In the half-wave rectifier of this chapter, all this voltage will be applied to the diode plate. The resultant cathode voltage will be close to this value, perhaps 420 volts. (The output voltage across R2 will be somewhat less because of the voltage dropped or lost as the rectifier current passes through R1.)

In the full-wave rectifier, with the center-tap winding connected to ground each plate would be driven alternately between

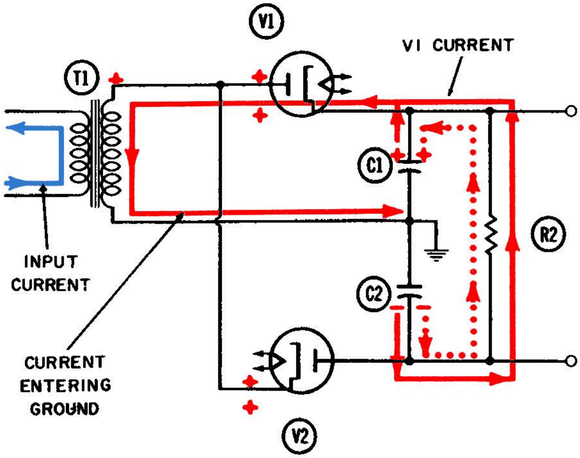


Fig. 2-5. The voltage-doubler rectifier—positive half-cycle.

plus and minus 225 volts. The maximum attainable output voltage would thus be limited to 200 volts or so.

Since a transformer is bulky and heavy, there are many applications where its elimination is desirable. For example, most table-model radios use the circuit of Figs. 2-1 and 2-2 and many television receivers employ the voltage-doubler circuit in Figs. 2-5 and 2-6. At other times the circuit of Figs. 2-3 and 2-4 is selected because the advantage of higher output voltage without transformer size or bulk has overriding attractions. An obvious disadvantage which must be accepted in choosing half-wave over full-wave operation is the probability of somewhat poorer *voltage regulation.*

VOLTAGE REGULATION

Voltage regulation is defined as the percentage variation in output voltage of a power supply in going from no load to full load. It may be expressed by this formula:

$$\text{Voltage regulation} = \frac{E_2 - E_1}{E_1} \times 100$$

where,

E2 is the output voltage at no load,

E1 is the output voltage at full load.

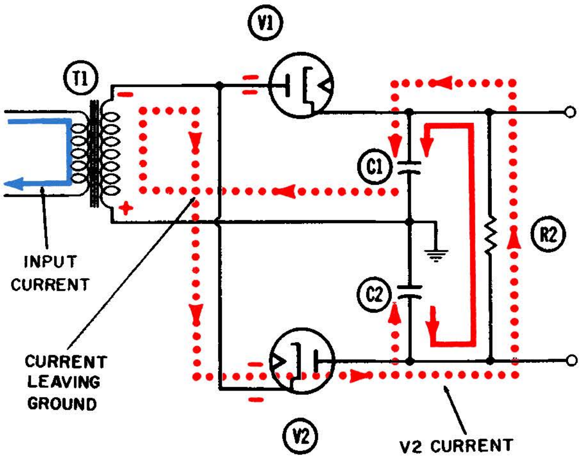


Fig. 2-6. The voltage-doubler rectifier—negative half-cycle.

The no-load condition with a power supply means it is not delivering current to any external circuits. Figs. 2-1 through 2-4 show some load current being drawn toward the rectifier tube from the right side of the diagrams. The electrons which make up this load current are being drawn from all tube circuits supported by this power supply. The power supply delivers current to these load circuits by providing a high positive voltage which draws electrons through them. These electrons are mostly in the form of plate and screen-grid currents of vacuum tubes.

The *total current* a rectifier tube will draw is determined by its construction and by the applied voltage from the transformer secondary. When little or no load current is flowing, the rectifier will draw all its required current up from ground through resistor R2. The output voltage is then equal to the voltage developed across R2 by this current, in accordance with Ohm's law.

When substantial load current is drawn, however, the amount of current drawn through R2 will be decreased equally, and the voltage developed across R2 will also be decreased proportionately. This amounts to a reduction in the output voltage under full-load conditions.

Obviously, a voltage regulation of zero per cent is unattainable in power supplies of this type. In order for the regulation to equal this ideal, the output voltage under full-load conditions would have to *equal* the output voltage under no-load conditions—an impossible situation.

In this type of circuit and using RC filters as described, fairly high values of regulation (meaning *poor* voltage regulation) will be obtained. Values of 30% or 40% are not uncommon.

Chapter 3

FULL-WAVE RECTIFIER CIRCUITS

In this chapter, three versions of the full-wave rectifier circuit will be discussed. Half-wave rectifiers, discussed in the previous chapter, utilize only one half-cycle of the applied alternating voltage. Full-wave rectifiers, on the other hand, use both half-cycles. This results in a ripple frequency twice that of the half-wave rectifier. In other words, using half-wave rectification the rectifier will conduct for a portion of one half cycle; then, during the next half-cycle, the tube does not conduct. This results in a pulse, then a long period of no voltage, followed by another pulse. Of course, the filter circuit "fills in" between pulses so we have a DC voltage at the output. With the full-wave rectifier, conduction occurs on both half-cycles; hence the output contains twice as many pulses of DC, witn no long periods between them. All that is required of the filter circuit is to smooth out the output. Thus, smaller filter capacitors can be employed.

CONVENTIONAL FULL-WAVE RECTIFIER

The first full-wave rectifier circuit to be discussed might be called the "conventional" circuit, which is widely used in power supplies for radios, television sets, etc. It employs a center-tapped transformer, a tube with two diode plates, and a common directly-heated cathode. Figs. 3-1 through 3-4 show the four quarter-cycles of operation for the circuit. The components, and their functional titles are:

R1—Load resistor.
C1—First filter capacitor.
C2—Second filter capacitor.
L4—Filter choke.
T1—Power transformer.
V1—Full-wave rectifier tube.

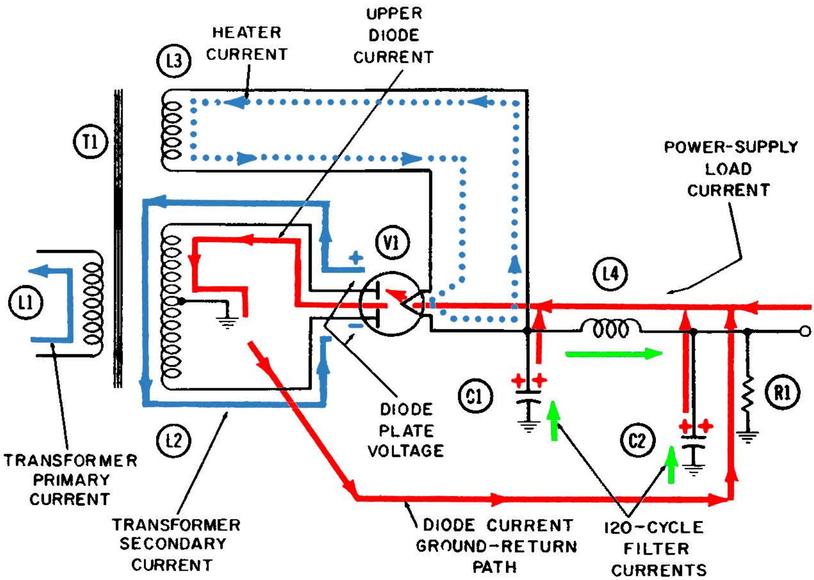


Fig. 3-1. The full-wave rectifier—first quarter-cycle.

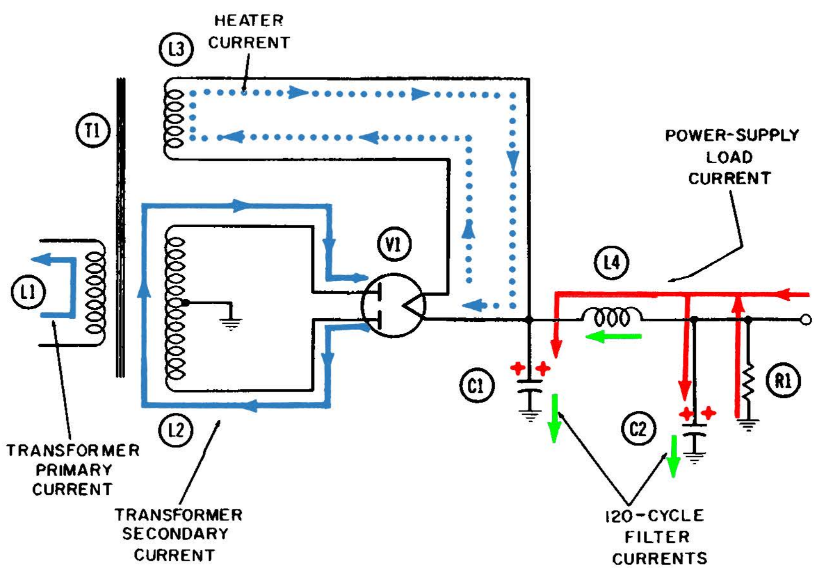


Fig. 3-2. The full-wave rectifier—second quarter-cycle.

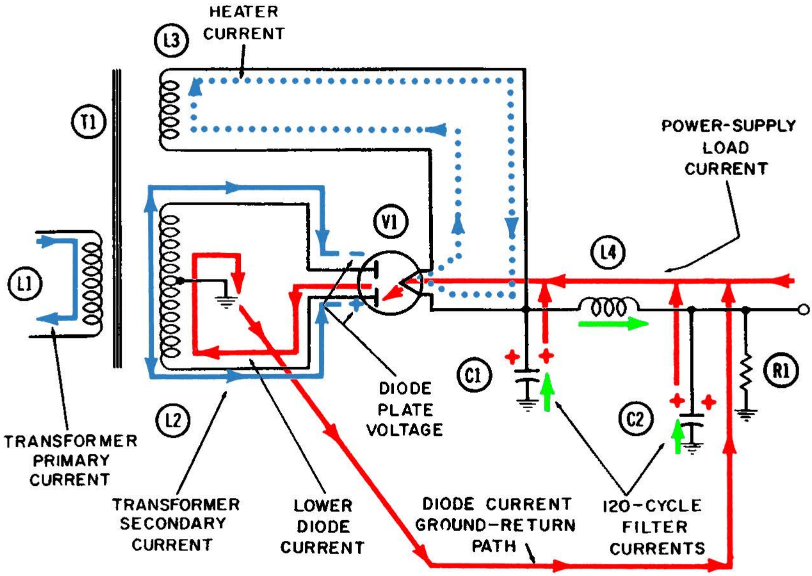


Fig. 3-3. The full-wave rectifier—third quarter-cycle.

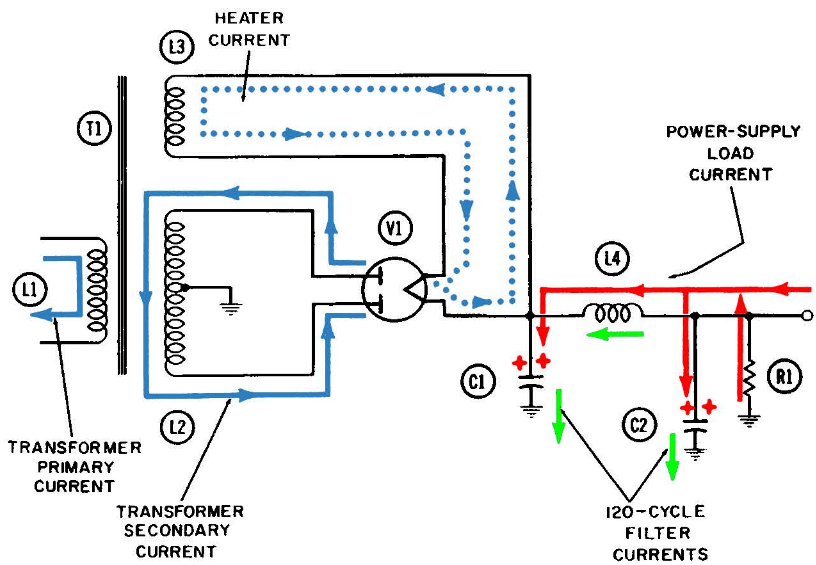


Fig. 3-4. The full-wave rectifier—fourth quarter-cycle.

Fig. 3-5 shows the phase relationships between the transformer secondary current, the upper-diode plate voltage, the upper- and lower-diode currents respectively, and finally the output-voltage waveform. (The ripple component of this output voltage has been exaggerated somewhat for easy identification.)

No waveform is shown for the lower-diode plate voltage. However, such a waveform would be exactly 180°, or half a cycle, out of phase with the upper-diode plate voltage shown in line 2.

It can be seen from these waveforms that each diode conducts once during each cycle and raises the output voltage slightly each time. As a result, the ripple-voltage frequency is twice the basic power frequency. The output-voltage waveform also reveals the fairly abrupt rise in voltage when the diode conducts, as opposed to the much more gradual decay between conduction. This slow decay results from the filtering provided by C1, C2, and L4. This action is explained more fully later in the discussions of the circuit-operation diagrams.

Three separate "families" of currents are shown in Figs. 3-1 through 3-4. The first such family might be called the *power* group, because all currents are driven from the primary power source such as an AC supply line. There are three currents in this group—transformer primary, transformer secondary, and filament heating.

The second family, or group, of currents is the "rectified," or unidirectional, currents; after being filtered, they enable this circuit to provide the stable DC voltage output necessary for the operation of many electronic systems.

The third family is the *filtering* current which "smooths" out the pulsations in the rectified current.

Each of these currents is shown in the following colors in Figs. 3-1 through 3-4:

1. Transformer primary current (solid blue).
2. Transformer secondary current (also in solid blue).
3. Tube-filament heating current (dotted blue).
4. Rectified or unidirectional current (red).
5. Filter current (green).

The Power Currents

The first current of this group flows in the primary winding of the power transformer and is indicated in solid blue. In the average household this is a 60-cycle current, and its associated driving voltage is the standard 110 volts. The first quarter-cycle diagram (Fig. 3-1) shows a single quarter-cycle of this driving current as it flows upward through the primary winding. The essential property of a transformer (or any other inductance) is that it will resist any *change* in the amount of current flowing at any given moment. During an entire half-cycle (such as the one represented by Figs. 3-1 and 3-2), this primary-winding current undergoes an entire series of changes. Starting from zero, it rises to maximum and falls to zero again, always in the upward direction.

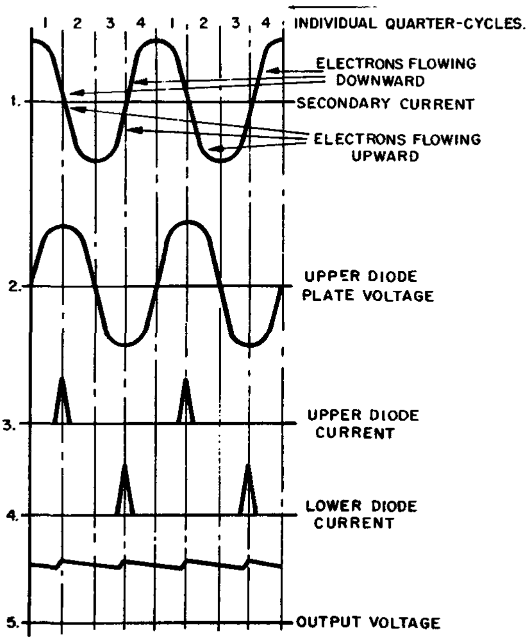


Fig. 3-5. Full-wave rectifier waveforms.

Any changes in direction or amount of this current will cause current movements in other parts of the transformer. The large secondary winding carries a current, also shown in solid blue, whose movements are associated with the voltage changes on the plates of the twin-diode rectifier tube. All currents are electrons in motion. Hence, an electron current flowing in one direction will ultimately deliver a certain quantity of electrons to one end of the current path and will leave a scarcity of them at the other end. A concentration of free electrons is by definition a negative voltage. By the same token, a scarcity (deficiency) of electrons results in a concentration of positive ions, which is by definition a positive voltage.

During the entire first quarter-cycle, this current moves *downward* in the transformer secondary. At the end of the quarter-cycle, the lower end of the transformer has achieved its maximum negative voltage, as depicted by the blue minus sign at the lower plate of the rectifier tube. At the same time, a deficiency of electrons will exist at the upper end of the transformer secondary. This is shown by the blue plus sign at the plate of the upper rectifier tube.

The upper diode will conduct the maximum amount of rectified (red) current at the same instant this diode plate reaches its maximum positive voltage. The first quarter-cycle diagrams (Figs. 3-1 and 3-5) depict this instant.

The third and final current in this group of power currents flows in the tertiary winding of the transformer. Its purpose is to heat the cathode of the twin-diode rectifier tube. This winding consists of a relatively few turns of wire. Thus it is a low-voltage winding which delivers high current. The current in the primary winding drives this cathode heating current at the same 60-cycle frequency. To clarify the transformer action, this current is shown flowing in opposite phase to its driving current—in other words, downward during the first quarter-cycle and upward during the second and third. During the fourth quarter-cycle, it again flows downward.

This current follows the closed path which includes only the tertiary winding and the direct-heated cathode. In the four diagrams depicting circuit operation (Figs. 3-1 through 3-4), this heating current is shown in dotted blue.

The Rectified Currents

The rectified currents, in red, eventually flow through the rectifier tubes, from the common cathode to either plate. At the end of the first quarter-cycle, as shown in Figs. 3-1 and 3-5, this current flows from the cathode to the upper plate of the two diodes. (The current-voltage action in the transformer secondary makes the upper-diode plate positive. This accounts for the electron flow across the tube to the upper-diode plate. Whenever either diode plate is more positive than the cathode, electrons will leave the cathode and cross the open space to that plate.)

Any electrons leaving the cathode must be provided with a return path to the cathode. This is a fundamental requirement of vacuum-tube operation. The return path in the circuit of Fig. 3-1 is from the upper plate of the diode to the top of the transformer secondary, then through its upper half to the center tap. Here the current enters a common ground and returns to the bottom of R1, which serves as both a bleeder and a load.

The current then continues upward through R1, then to the left through the filtering inductance, to the cathode.

The diagrams for the third quarter-cycle (Figs. 3-3 and 3-5) show electron current flowing from the cathode to the *lower* plate of the diode. Current flows in this direction through the tube because the secondary current in the transformer has made the lower-diode plate positive. This is indicated by the blue plus sign on the lower plate of the twin-diode tube.

After crossing the lower diode, the rectified current (still shown in red) goes to ground through the lower half of the transformer secondary, then through ground and back to the load resistor. It returns to the cathode by flowing upward through this resistor, and to the left through the filtering inductance L4.

Another component of rectified current is shown entering the filtering inductance from the right. This portion does not pass through the load resistor. Instead, it comes from those vacuum-tube circuits which receive their DC power from this rectifier circuit. Once it enters the rectifier, this current follows the same paths as the other through the diodes and transformer secondary to the common ground. From here, it then has a free return path to the cathodes of the other tubes.

An important measure of any rectifier's performance is its capability for voltage regulation—that is, the stability of its output voltage under varying loads. The output voltage of this rectifier is the positive voltage on the upper plate of capacitor C2, and consequently at the output terminal. This voltage, represented by red plus signs, should be as steady as possible under all circumstances from no load to full load—in other words, it should be "regulated," or have "regulation."

In any charged capacitor (such as C2), there is a definite relationship between the amount of charge (electrons or positive ions) stored there and the amount of negative or positive voltage produced. Coulomb's law states this relationship as a formula:

$$Q = C \times E$$

where,

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

Since one coulomb of charge is always equal to a precise number of negative electrons or positive ions (6.25×10^{18}, to be exact), the voltage across a charged capacitor is always *directly proportionate* to the quantity of electrons or ions stored in the capacitor.

The Filtering Currents

In addition to good regulation under varying load conditions, it is desirable that the output voltage on the charged capacitor, C2, have a minimum ripple component. Inadequate filtering of the power supply causes this ripple voltage. Fig. 3-1 shows the rectified currents (red) flowing through the upper diode during that portion of the first quarter-cycle when the transformer current-voltage actions (shown in solid blue) makes the upper-diode plate more positive than the cathode. As electrons leave the cathode, others are drawn to it from the filter of the power supply. Thus, current flows *upward* from both capacitor plates at this instant.

A component of filtering current is shown in green beneath each capacitor. As electrons move *away* from the top plates of each capacitor and head toward the cathode, the same amount of filtering current (number of electrons) flows upward from ground. It is the essence of capacitor action that the same amount of current flows onto (or away from) one plate as flows away from (or onto) the other.

Figs. 3-2 depicts the operation during the second quarter-cycle. It is inserted here to show the completion of one cycle of filtering. The filtering currents, shown in green, are flowing in the opposite direction, back into ground. The electrons in these currents were drawn upward by the other electrons leaving the upper plates. However, with nothing to hold them on the bottom plate, they quickly fall back to a point of neutral voltage (in other words, ground). At the same time, the rectified currents are shown *entering* rather than leaving the upper plates of these two filter capacitors.

Thus, during a single half-cycle of the primary power current, one complete filtering cycle has occurred. Also, during the same period, rectifier current flows off the upper plates of the filter capacitors, and then back onto them. When the primary power frequency is 60 cycles per second (the standard household supply throughout most of the United States), this filtering action will occur twice as fast, or 120 times per second.

Two things determine the amount of voltage across filter capacitor C2—its size, and the number of positive ions stored on its upper plate. This voltage is also the output of the whole rectifier circuit. Near the end of the first quarter-cycle, as shown by Fig. 3-5, electrons are leaving this plate and passing through the tube. Hence the output voltage, being already positive, will tend to become even more so. The *inflow* of electrons a moment later, when the plate current stops flowing, will tend to reduce this output voltage. These undesirable fluctuations are termed the ripple voltage. They will occur at twice the input frequency, since two complete fluctuations will occur for each cycle of input frequency.

One obvious means of reducing the ripple voltage is to use a larger output capacitor C2. Then, a greater *quantity* of positive ions, in comparison with the number of electrons coming in or going out during each quarter-cycle of the filtering action, will be stored on the capacitor. If the capacitor is made large enough, the number of electrons becomes insignificantly small in relation to the number of ions, and the output voltage may be considered steady.

The first and third quarter-cycle diagrams show the components of rectifier current flowing *away* from the upper capacitor plates. In turn, compensating filtering currents flow upward from ground, toward each of the lower capacitor plates. The second and fourth quarter-cycles show currents flowing *onto* the upper capacitor plates, with compensating currents flowing back into ground from the lower plates.

Capacitor action can be clarified by remembering that the quantity of current (or electrons) flowing into one side of a capacitor is always equal to the quantity flowing away from the other side. If the flow of either current is impeded, its counter-part on the other side will also be reduced and by the same amount. Thus, if the connection between either lower plate and ground becomes broken, or "open," the component of filtering current shown in green will be unable to flow. The capacitor will then cease to act as a filter, or "shock absorber." Now, when rectified current passes through either diode, the surge of electron current which *would have been* drawn from the upper capacitor plate must be drawn from other parts of the circuit.

Specifically, if this trouble occurred to capacitor C2, the surge of electrons being drawn into the filter choke from C2 would have to come instead from the external circuit or load resistor, or both. The momentary increase in electron current through the resistor would momentarily raise the voltage at the output point. This voltage rise would be repeated each time electrons flow through either diode, or 120 times a second. The resultant fluctuation in output voltage would constitute an unacceptable component of ripple voltage.

The action of choke coil L4 in contributing to the total filtering function is rather crudely portrayed by green current lines flowing back and forth in the coil. At any given instant, these currents flow in such a direction that they oppose any *change* in the amount of rectified current being drawn through the coil. In the first quarter-cycle, the upper diode requires a surge of electrons. They are drawn from both the upper plate of capacitor C1 and the left end of the choke coil. Any inductance will oppose any *change* in the amount of current flowing through it. This opposition takes the form of a voltage opposite in polarity to the imposed voltage and is called the "counter emf" or "back emf." As the imposed voltage draws the excessive current through the coil to the cathode, the counter emf generates a "counter current," shown in green. The latter flows in the opposite direction to the normal current, and the two currents therefore will tend to cancel each other. Practically speaking, the "counter current" can never be as large as the normal current. Also, since the counter current depends on changes in the normal current, it dies out quickly as soon as the normal current ceases to change and approaches a steady value.

The second quarter-cycle shows the current in green as having reversed itself so that it is now flowing *toward* the cathode. The rectified current through the diode is decreasing at this time; thus, the current in green tends to keep the total current through the coil from changing.

Fig. 3-3 represents the third quarter-cycle of operation. Here current is flowing through the lower diode. This demand for additional electrons must again be supplied from the upper plate of capacitor C1 and from the rectified current flowing through choke coil L4. As before, the existence of inductor (choke) action is shown by the momentary current, in green, flowing in the opposite direction through the coil. This current momentarily opposes the change in total current through the coil.

The fourth quarter-cycle (Fig. 3-4) shows this hypothetical current flowing *toward* the cathode again. This time it opposes the decay (decrease) in rectified current which will occur as the lower diode ceases to conduct and before the upper diode starts. Each diode conducts for only a relatively small portion of a quarter-cycle. This occurs when the current-voltage relationship in the transformer secondary winding makes the plate of each diode more positive than the voltage on the upper plate of capacitor C1.

Likewise, the filtering currents in the inductor coil do not flow continuously for each full quarter-cycle before reversing direction. Their basic frequency will of course be 120 cycles per second.

Because of this additional filtering in the choke coil, the output voltage at the right end of the coil will be steadier than the voltage at the left end. In other words, the ripple voltage has been reduced by this additional filtering. As more and more coils and capacitors are added to the filter, the output voltage will become freer and freer from ripple.

If C1 and C2 have the same capacitance, then the positive voltages on their two upper plates will represent equal amounts of positive ions in storage, since the voltages are assumed to be equal. However, since one of these two voltages fluctuates more widely, different amounts of electron current must flow in and out during each cycle. The voltage on C2 is steadier than on C1. Consequently, *fewer* electrons *leave* the upper plate of C2 during each conduction period than leave C1.

Also, the filtering current (green) flowing between C2 and ground will consist of fewer electrons than are in the filtering current between C1 and ground. Each current is driven by the arrival and departure of electrons at or from the upper plates of the respective capacitors. To repeat, the *same quantity of electrons* must always be in movement on both sides of any capacitor.

FULL-WAVE BRIDGE RECTIFIER CIRCUIT

Figs. 3-6 and 3-7 show two successive half-cycles in the operation of a full-wave bridge rectifier circuit. The symbols used here are for solid-state rectifiers such as selenium, silicon, germanium, etc. However, the circuit would function equally well using conventional tubes. A solid-state rectifier functions like a diode—electron current flows essentially in only one direction through it. Electron flow through a solid-state rectifier is in the direction opposite the arrowhead indication. When the flat end of the rectifier (we call this end the cathode) is made more negative than the triangular end, electron current will be drawn across the junction with relative ease. However, when the rectifier anode (triangular end) is made more negative, practically no electron current flows in the reverse direction.

The components of this circuit include:

R1—Output resistor.
C1—Output filter capacitor.
T1—Input power transformer.
M1 through M4—Solid-state rectifiers.

Identification of Currents

Four separate electron currents perform key functions in this circuit. They are:

1. Transformer primary current (blue).
2. Secondary induced current (also in blue).
3. Current through rectifiers M2 and M3 (solid red).
4. Current through rectifiers M1 and M4 (dotted red).

Details of Operation

The phase and amplitude relationships between the primary and secondary currents and their associated voltages were discussed earlier. Hence, they will not be repeated here. Input transformer T1 will probably be of the voltage step-up variety. Thus, the amplitude of the voltage induced across the secondary winding will be N times the amplitude of the primary input voltage (where N is the ratio between the number of turns of wire in the primary and in the secondary).

In the first half-cycle, represented by Fig. 3-6, the polarity of this secondary induced voltage has been indicated by a blue plus sign at the top of the winding and a blue minus sign at the bottom. Since this positive polarity is applied to the junction of rectifiers M1 and M2, it will draw electron current through M2. Simultaneously, application of a negative voltage to the junction of rectifiers M3 and M4 will in effect "push" electrons through rectifier M3.

The paths for both electron currents are identical—in fact, they are the same current. Shown in solid red, it flows only during this half-cycle, through rectifier M2, downward through the transformer secondary, through rectifier M3, and to the common-ground return line. From here it enters output resistor R1 and flows upward through it to re-enter rectifier M2.

During the second half-cycle, in Fig. 3-7, the polarities of the induced voltages are reversed. Now the top of the secondary winding is negative and the bottom is positive. The negative polarity at the junction of rectifiers M1 and M2 in effect "pushes" electrons through rectifier M1, in the direction shown. Simultaneously, the positive voltage at the junction of rectifiers M3 and M4 draws electrons through M4. These two currents also have identical paths—*upward* through the transformer secondary winding and then through rectifier M1 to ground. From ground, the path is through output resistor R1 and rectifier M4 to the bottom of the transformer secondary.

The presence of capacitor C1 serves as a symbol of the filtering action needed to convert the pulsating voltage output across R1 to a pure DC voltage or one having a low ripple content. Without adequate filtering, the current through R1 would consist of a series of half sine waves. Moreover, this current would momentarily cease to flow twice during each cycle, as the current switches from one set of diodes to the other.

Such a single R-C combination would of course be entirely inadequate for filtering the output of a power supply. A much more elaborate system, like the one discussed in connection with the power supply in Figs. 3-1 through 3-4, would be required instead. The capacitor was used here for one reason only—to demonstrate the principle of preserving a steady DC voltage at the output point, even while the current is switching from one set of diodes to the other end and, consequently, not flowing through either set. The presence of this output voltage is indicated by the red plus signs on the upper plate of C1.

Since the anodes of M1 and M3 are connected to a common ground point, the two rectifiers cannot conduct electrons unless their cathodes are *more negative* than the ground voltage. Likewise, the cathodes of rectifiers M2 and M4 are connected to the output point, which is maintained at a fairly high positive voltage. Hence, they cannot conduct electrons either, unless their anodes are more positive than this output voltage.

FULL-WAVE VOLTAGE DOUBLER

Figs. 3-8 and 3-9 show two alternate half-cycles in the operation of a full-wave voltage-doubler power supply with transformer input. The transformer used here might be identical to the one shown in Figs. 3-1 through 3-4. Because of the different circuit construction, however, the output voltage developed across output resistors R1 and R2 will be twice the output voltage developed across R1 in Figs. 3-1 through 3-4. There are two important differences in the construction of the voltage-doubling circuit. First, the lower end of the transformer secondary is connected to ground rather than to the plate of the lower diode, V2. Also, the position of diode V2 is reversed from the previous example; here its cathode is connected directly to the plate of diode V1. In addition the junction of output resistors R1 and R2 is connected to ground; now this circuit will deliver both a negative and a positive output voltage.

Although two separate tubes are shown in Figs. 3-8 and 3-9, two halves of a single tube (with separate cathodes) are often employed. At other times, solid-state rectifiers such as used in Figs. 3-6 and 3-7 are utilized.

The necessary components of this circuit correspond as closely as possible to components doing similar jobs in Fig. 3-1. They include:

R1 and R2—Output resistors.
C1—Output filter capacitor.
C2—Output filter capacitor.
T1—Power transformer.
V1—Upper-diode rectifier tube.
V2—Lower-diode rectifier tube.

For simplicity, the choke coil in Fig. 3-1 has been omitted from this circuit, and also the tertiary winding for heating the filaments. Likewise, the filament heating current, shown in dotted blue in Fig. 3-1, does not appear in Figs. 3-9 and 3-10.

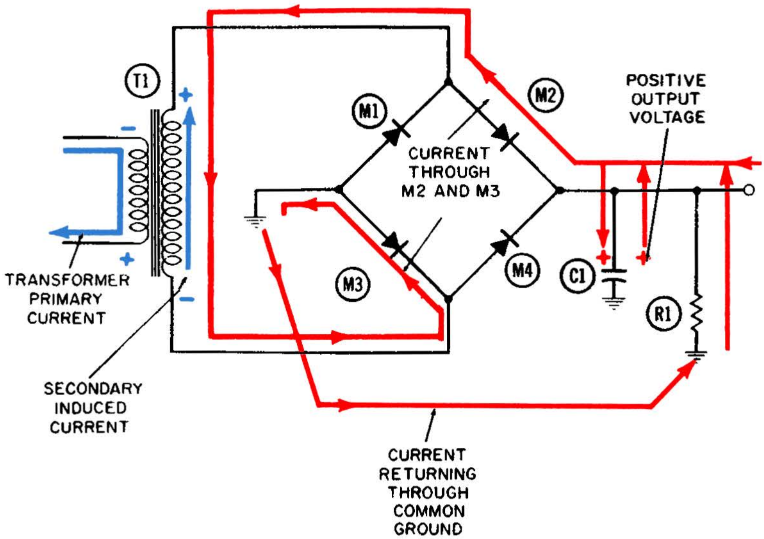


Fig. 3-6. The full-wave bridge rectifier—first half-cycle.

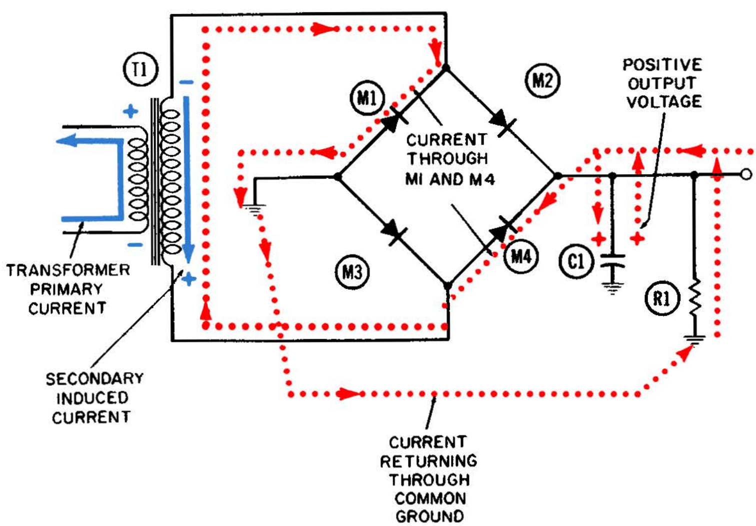


Fig. 3-7. The full-wave bridge rectifier—second half-cycle.

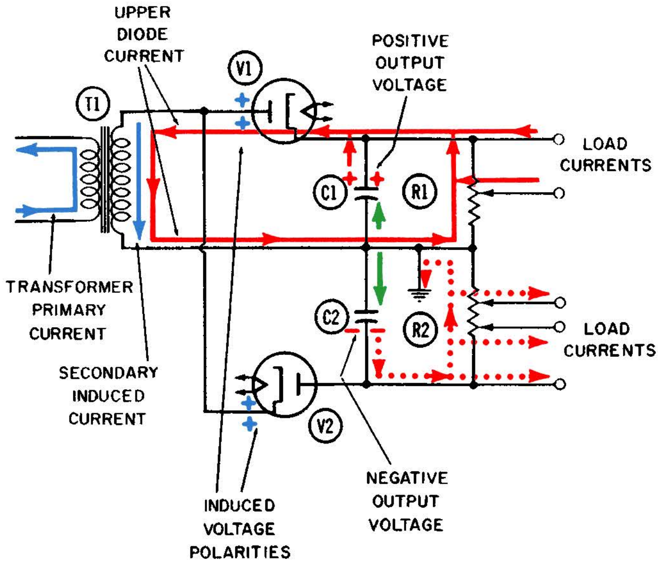


Fig. 3-8. The full-wave doubler rectifier—positive half-cycle.

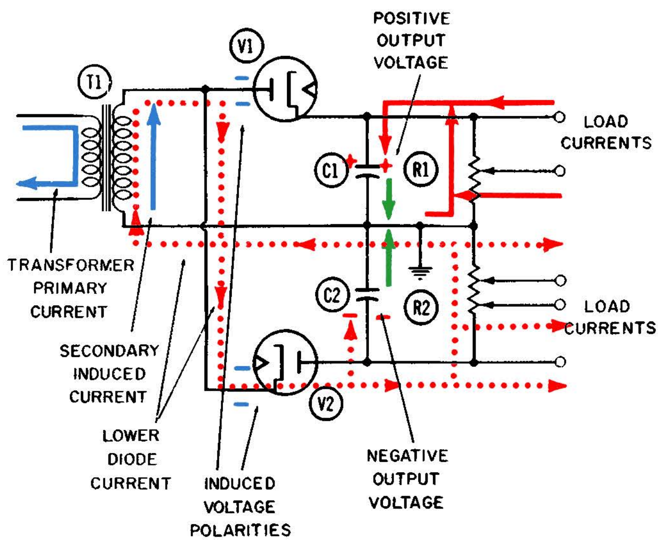


Fig. 3-9. The full-wave doubler rectifier—negative half-cycle.

Identification of Currents

Six principal electron currents are at work in this circuit, as follows:

1. Primary current in power transformer (blue).
2. Induced secondary current in power transformer (also in blue).
3. Current through upper diode V1 and its filter network (solid red).
4. Current through lower diode V2 and its filter network (dotted red).
5. Two filter currents between C1 and ground and between C2 and ground (both green).

Details of Operation

Fig. 3-8 has been designated the positive half-cycle of operation, because at this time the inductive action between the primary and secondary winding drives the upper end of the secondary winding positive. This positive voltage is indicated in Fig. 3-8 by the blue plus signs at the plate of diode V1 and also at the cathode of diode V2.

Diode V1 will conduct electrons, now that its plate is more positive than its cathode. This is the current shown in solid red, and its complete path is from cathode to plate within the tube, then downward through the secondary winding and to the right. Here it enters resistor R1, flows upward through R1, and returns to the cathode. Almost the full peak voltage which is developed across the transformer secondary winding is also developed across R1, since the lower end of it and the secondary winding are both connected to a common ground.

Electrons flow through diode V1 during only a small portion of the first half-cycle, when the plate reaches its peak positive voltage. During the remainder of this so-called positive half-cycle, the cathode of V1 will be more positive than the plate. This is due to the integrating action of the filter system represented by R1 and C1. During that short period when electrons are being drawn across diode V1, this excess demand is provided from the upper plate of capacitor C1. This accounts in Fig. 3-8 for the upward flow of electrons leaving this plate, and also for the continuing positive voltage on it, as indicated by the red plus signs in Figs. 3-8 and 3-9.

During the nonconductive portion of the positive half-cycle, and during the entire negative half-cycle, electrons flow *downward* onto the upper plate of capacitor C1. This direction of flow is indicated in Fig. 3-9 only. The filter current (shown in green in Fig. 3-8) between the lower plate of C1 and ground flows upward when electrons are drawn away from the upper plate of C1 for passage through the tube. During the remainder of each cycle the current flows downward, as indicated in Fig. 3-9.

No current can flow through diode V2 during the first half-cycle of Fig. 3-8 since its cathode is positive and its plate is negative (for reasons we shall discuss later).

The positive voltage created at the upper plate of capacitor C1 is one of the output voltages of the power supply. It serves to draw electron current toward it from any load or loads to which it is connected. Two such load currents are shown in Figs. 3-8 and 3-9. One enters the filter at the main output tap, and the other through a potentiometer tap. Such a potentiometer could be made to provide a positive output voltage with any value between zero (ground) and the full output value.

During the second, or negative, half-cycle depicted by Fig. 3-9, the inductive action across the transformer makes the upper end of the secondary winding negative. This temporary negative voltage is indicated by the minus signs at the plate of V1 and the cathode of V2. At the negative peak of this half-cycle, the cathode of V2 will become more negative than the plate. As a result, this diode will conduct. The complete path of this current (shown in dotted red) is from cathode to plate within the tube, upward through R2, turning left to the lower end of the secondary winding. Then it flows upward through this winding, and downward to the cathode again.

R2 prevents each pulsation of plate current from flowing immediately to ground as it passes through the lower diode. Consequently, these electrons flow onto the lower plate of capacitor C2. A pool of negative electrons is soon created, and consequently a source of negative voltage. This pool of electrons persists during the entire cycle, and it drives a continuous electron current *upward* through resistor R2, toward the ground connection. This current can be seen in Figs. 3-8 and 3-9.

The filter current which flows between capacitor C2 and ground changes its direction in accordance with the main electron current through diode V2. When V2 is conducting, electrons flow onto the lower plate of C2. This action forces the filter current to flow upward from C2, toward ground. When V2 is not conducting, the filter current flows back onto the upper plate of C2 from ground. The latter condition is depicted most clearly in Fig. 3-8.

The three output points on resistor R2 constitute sources of negative rather than positive voltage. Negative voltages are required for various reasons in some types of equipment. A negative voltage source *delivers* electrons *to* a load, rather than drawing them away as a positive voltage source does. For this reason, load currents are shown flowing *away* from the various taps on resistor R2.

Since the full transformer-secondary voltage appears across each resistor separately, and since the two resistors are in series, the input voltage has in effect been doubled. As an example, if the peak primary voltage were 150 volts and the transformer turns ratio were 2-to-1, then the peak secondary voltage would be 300 volts. Thus, the positive output voltage on capacitor C1—measured between the upper plate of C1 and ground—would approach 300 volts, and so would the negative voltage output on capacitor C2, measured between the lower plate of C2 and ground.

A voltage measurement across the entire output-resistor path, consisting of R1 and R2 in series, would indicate a difference of 600 volts. This is twice the peak input voltage across the transformer secondary.

Chapter 4

DIODE-DETECTOR CIRCUITS

The diode detector is one of the simplest and most widely used circuits for detection of a carrier wave. The term "detection" is frequently used synonymously with "demodulation"—particularly whenever some modulation is imposed on the radio-frequency carrier wave at the transmitting source. The detector circuit produces a steady, or DC, voltage which will at all times be proportionate to the strength of the carrier wave. In fact, this voltage depends on the carrier wave for its existence. Consequently, if the carrier signal is turned on and off by keying the transmitter, the detector circuit will provide a means of knowing this at the receiver, and therefore a means of "reading" the keying.

CIRCUIT DESCRIPTION

Figs. 4-1 and 4-2 show the two half-cycles of operation of the diode detector. The circuit components and their functional titles are:

R1—Diode load resistor.
C1—RF tank capacitor.
C2—Coupling capacitor.
T1—Output IF transformer.
V1—Diode tube.

There are only two main families of currents at work in this circuit:

1. Radio-frequency alternating currents (blue).
2. Unidirectional tube current (red).

The radio-frequency tank consists of transformer T1 and capacitor C1. This circuit is resonant at the particular radio frequency being received. An oscillation of electrons will be built up in this tank and be sustained by another RF current which exists at the same frequency in the primary winding of the transformer. Both currents are shown in blue.

RF TANK CURRENT

Fig. 4-3 shows a series of sine waves representing the radio-frequency voltage and current in the tank. Unless otherwise stated, such a voltage sine wave normally applies to the voltage at the *top* of the tank; this is the point of coupling to the plate of the diode detector. The first half-cycle is centered at the instant of maximum negative voltage, as indicated in Fig. 4-1 by the blue minus signs on the top of plate tank capacitor C1. The blue line indicating electron current is shown during this half-cycle as flowing upward through the transformer secondary, thus delivering electrons into C1.

The tank voltage is represented by the plus and minus signs on the upper plate of C1 in Figs. 4-1 and 4-2. It drives an external current (shown in blue) up and down through diode load resistor R1. When this tank voltage is at its maximum negative value midway in the negative half-cycle, the electrons in this external current will be flowing *downward* through R1 at their maximum rate.

By the same token, when the tank voltage is at its maximum positive value midway in the positive half-cycle, the external-current electrons will be flowing *upward* through R1 at their maximum rate. This will cause the top of the resistor to reach its maximum positive voltage, which is just high enough to overcome the negative voltage caused by the accumulation of electrons on the right plate of C2. As a result, the diode can again conduct.

The normal path for this external current driven by the tank current is up and down through diode load resistor R1. There is a simple rule of thumb for determining the instantaneous polarity of a voltage associated with any current flow. Recall that current is nothing more than electrons in motion; also, that all electrons have a negative charge and are therefore repelled by each other and by negative voltages in general. So, in flowing through a conductor, electrons always head *toward* a point of more positive (less negative) voltage than the point *from* which they are leaving. Since the lower end of the resistor is tied to ground, it will always be at zero voltage. Therefore, when electrons flow downward through R1, as they do in Fig. 4-1, the driving voltage at the top of the resistor must be negative. Conversely, when they flow upward as in Fig. 4-2, this driving voltage must be positive.

UNIDIRECTIONAL CURRENT

Diode tubes have one important characteristic—when their plate voltage is more positive than their cathode voltage, electrons will cross the evacuated space from cathode to plate. This condition is fulfilled during a portion of the second half-cycle (but not during all of it), and electron current is shown in red crossing the tube. The complete path for this current is from cathode to plate and downward through diode load resistor R1 to ground, then through ground and back to the cathode. During its journey through the tube and to the top of the resistor, this DC current is pulsating at the basic radio frequency. Because of the delay in entering and passing through the resistor, the electrons from the detector tube accumulate on the right plate of capacitor C2. Here they form a constant negative voltage, as indicated by the red minus signs on the capacitor. Some electrons flow into this pool during each pulsation from the detector, and an equal number flows out during the entire cycle. The latter flow is pure rather than pulsating DC.

CIRCUIT OPERATION

It is important to distinguish between the two different currents which flow through the diode load resistor. The current just discussed, along with its associated negative voltage on the right plate of capacitor C2, applies a fixed negative voltage to the plate of the diode. Before the diode can conduct, the other current (shown in blue) must first overcome the fixed negative voltage. This will occur only during that portion of the positive half-cycle when this current is flowing upward at or near its maximum rate. During these moments, it will exceed the amount of fixed current which regularly flows downward through the resistor each time the diode conducts. The net result of the two opposing voltages is a small, momentary positive voltage at the diode plate, permitting more tube current to flow. These moments occur midway in each positive half-cycle. Fig. 4-3 shows a small amount of plate current flowing whenever the tank and plate voltages reach their positive peaks. It can be seen that the plate voltage in line 3 of Fig. 4-3 is negative most of the time. This is due to the accumulation of electrons on the right plate of C2 as a result of diode conduction, followed by the filtering action of C2 and R1.

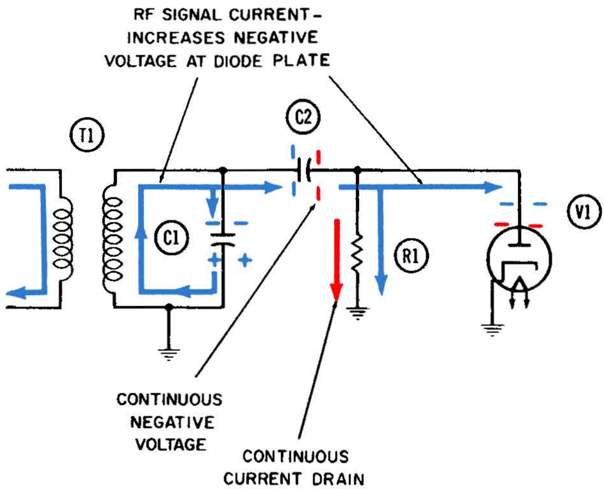


Fig. 4-1. The diode-detector—negative half-cycle.

The action of the tank voltage alternately increases and decreases this negative voltage, so that the plate voltage at any instant is the sum of the two voltages. Only when the diode plate is more positive than the cathode will plate current flow.

Let us look more closely at line 3 of Fig. 4-3, which represents the voltage at the diode plate. This voltage is mostly negative and is caused by the accumulation of electrons on the right plate

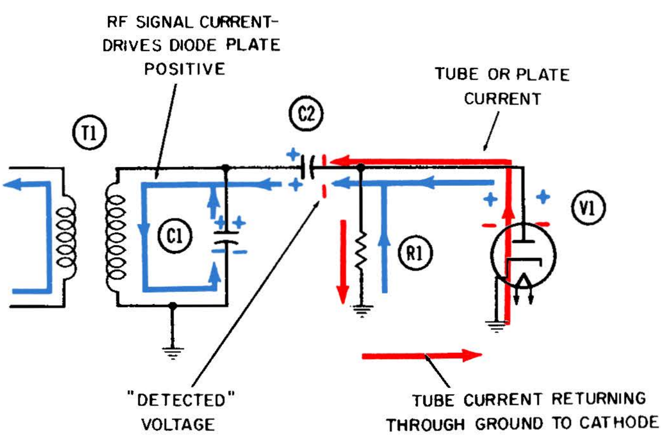
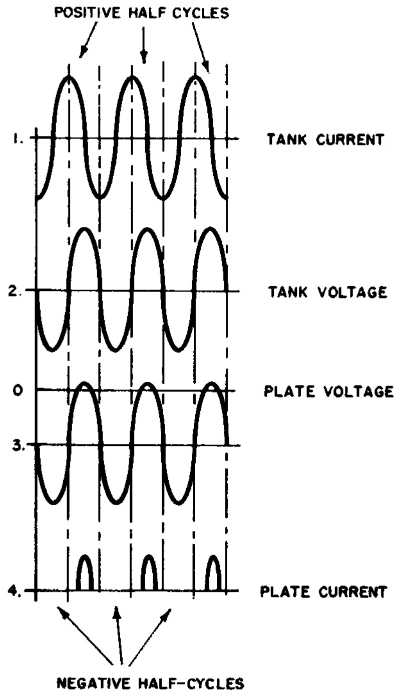


Fig. 4-2. The diode-detector—positive half-cycle.

Fig. 4-3. Tank- and plate-current and -voltage waveforms in the diode detector circuit.



of C2. The *size* of this negative voltage depends on the strength of the radio-frequency current in the tank; and the latter, of course, depends in part on the strength of the received signal. If the carrier signal is cut off at the transmitter, as is done during keyed CW communications, the tank current will die out in a relatively few cycles. The diode will then stop conducting, and the negative voltage on the right plate of capacitor C2 will drop to zero as the electrons stored there drain downward through the diode load resistor to ground.

When the carrier signal is resumed at the transmitter, the tank current comes back into being, the diode conducts, and a negative voltage again builds up at the top of the diode load resistor. Thus, with this circuit, what amounts to a "DC voltage" has been produced; its existence depends on the existence of a carrier signal, and the strength of this voltage will vary in accordance with the amplitude variations (modulation) of the carrier. Hence, we can say the carrier signal has been "demodulated," or "detected."

Chapter 5

DIODE DETECTOR WITH AUTOMATIC VOLUME CONTROL

Most diode detectors also include an automatic volume control (AVC) circuit, along with the basic detector discussed in the previous chapter. Automatic volume control is a fairly elaborate function within radio receivers. Its purpose is to maintain a constant audio output, or volume, in the face of possible changes in signal strength due to abnormal propagation conditions. Signal fades and build-ups are the obvious results of these irregularities in propagation. It would be most disconcerting for the listener to have to continually adjust the volume on his receiver in order to compensate for a program becoming suddenly too loud or faint. Therefore, automatic volume control is added to virtually all radio receivers.

SUMMARY OF ILLUSTRATIONS

A total of eight circuit diagrams and seven waveform diagrams are used to illustrate the various actions in the operation of a diode detector with AVC.

The first two circuit diagrams (Figs. 5-1 and 5-2) show successive negative and positive half-cycles of unmodulated radio-frequency signal current being received and detected by diode detector V1 (this tube is an integral part of the total AVC circuit). Certain DC voltages come into existence when this detection occurs. These are shown as the three detected voltages on the upper plates of capacitors C2, C3, and C4, and also as the AVC voltage on the upper plate of capacitor C5. The electrons which constitute these detected voltages come originally from the plate current of the tube. Consequently they, too, are shown in green. Fig. 5-3 shows negative and positive half-cycles of tank voltage and current, and also of detector plate current and AVC voltage.

The plate current leaves the tube in the form of pulsations at the signal frequency. Filter capacitor C2 bypasses these pulsations to ground. This bypassed, or filtered, RF current is shown in dotted blue.

The next two circuit diagrams (Figs. 5-4 and 5-5) show the actions occurring in the audio half-cycles which precede a modulation trough and peak. Also, Fig. 5-6 shows a modulated waveform for each condition. It also portrays the pulsations in plate current, the negative audio and AVC voltages, and finally, a sine-wave representation of the current which must flow through an AVC resistor (such as R4) when RF signals are being demodulated.

The next two circuit diagrams (Figs. 5-7 and 5-8) show the voltage-current conditions while a carrier signal is fading. The waveform diagrams in Figs. 5-9 and 5-10 show the changes occurring in the carrier signal, the resultant audio voltage, and finally the change in AVC voltage during a carrier fade.

The last two circuit diagrams (Figs. 5-11 and 5-12 show the voltage-current conditions while a carrier signal is building up. The associated waveform diagrams of Figs. 5-13 and 5-14 illustrate the changes occurring in the carrier signal, the audio voltage, and the AVC voltage during a carrier build-up. Fig. 5-15 is a graphical representation of the audio voltage developed across output resistor R2 during a period of carrier fade and a period of carrier build-up.

Some of the important truths the reader should expect to learn from these diagrams and the text include:

1. The changes in audio voltage on capacitors C2, C3, and C4 from modulation peak to trough, and what causes them.
2. Why the AVC voltage on capacitor C5 does not change between modulation troughs and peaks.
3. What causes an audio current to flow up and down in output resistor R2.
4. What causes the AVC current to flow back and forth in AVC resistor R4 at the audio frequency, and why this current flow does not change the amount of AVC voltage stored on capacitor C5.
5. What causes the negative AVC voltage to decrease during a carrier fade and to increase during a build-up.

CIRCUIT DESCRIPTION

The components which make up this circuit, and their functional titles are:

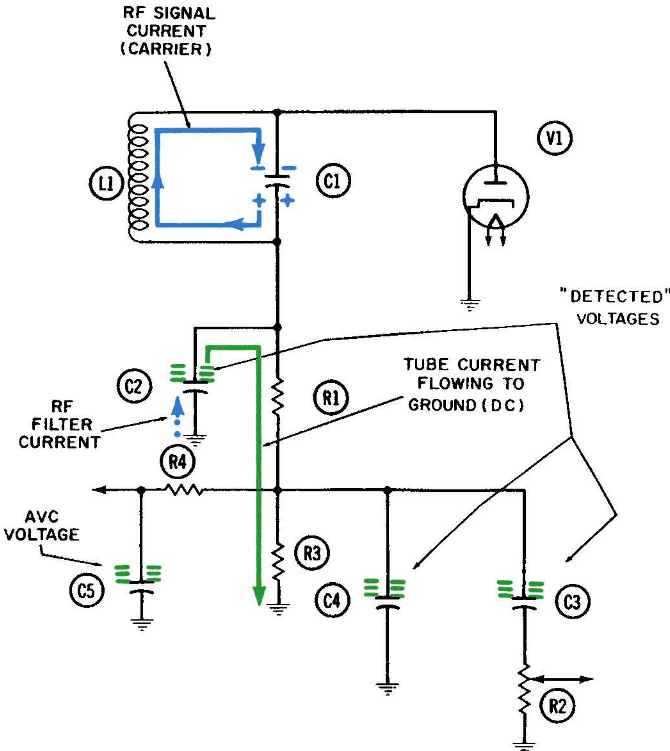


Fig. 5-1. The AVC circuit—negative half-cycle of unmodulated RF.

R1—Filter resistor (works in conjunction with C2).
R2—Audio-output resistor.
R3—Primary load resistor.
R4—AVC resistor.
C1—RF tank capacitor.
C2—RF filter capacitor.
C3—Output coupling capacitor.
C4—Additional RF filter, or bypass, capacitor.
C5—AVC storage capacitor.
L1—RF tank inductor.
V1—Diode tube.

Five electron currents are at work in this over-all circuit. They are:

1. Radio or intermediate-frequency tank current (solid blue).

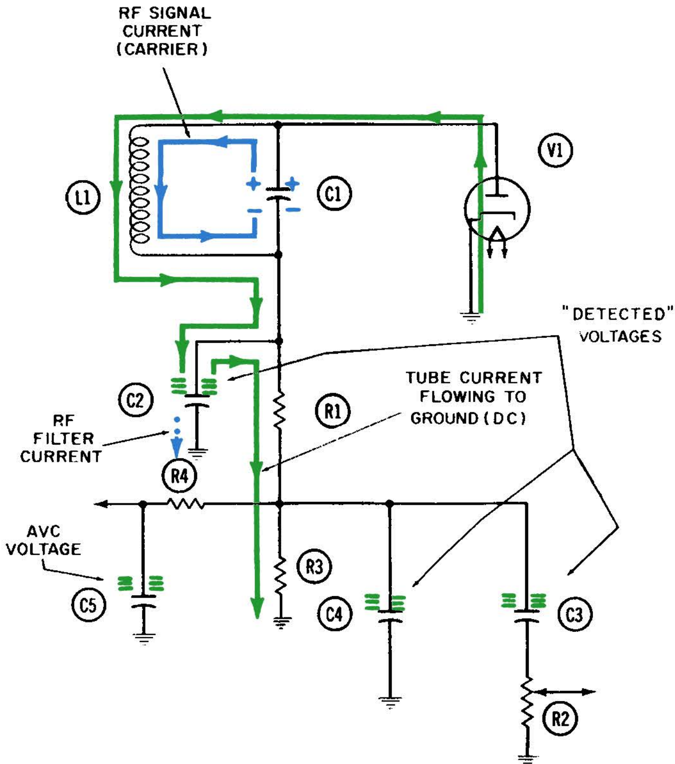


Fig. 5-2. The AVC circuit—positive half-cycle of unmodulated RF.

2. Pulsating radio or intermediate-frequency DC flowing through the detector (green).
3. AVC filter current (also in green).
4. Modulation signal, usually called audio (red).
5. Radio-frequency filter currents (dotted blue).

Voltage levels, both for audio and for automatic volume control, are shown by green minus signs. There are three kinds of time periods, which might be referred to as cycles, that are important in understanding this circuit. These periods are the short time required for one RF or IF cycle, the somewhat longer time for one modulating cycle, and the much, much longer time required for signal fades or build-ups. A typical intermediate frequency (IF) in broadcast receivers is 455 kilocycles per second. Thus the time required for one IF cycle is 1/455,000 second, or slightly more than two microseconds.

If the audio tone being demodulated is middle *C*, then its frequency will be 256 cycles per second. Thus the time for one such audio cycle is 1/256 second, or about four milliseconds. This is 4,000 microseconds—about *two thousand* times longer than the time of one IF cycle.

Even this is short compared with the time required for a signal to completely fade or build up. The latter may take several seconds or even minutes. Thus, many hundreds or even thousands of audio cycles may occur during one fade or build-up.

These relative time values are important to understanding demodulation and the automatic control of volume.

In order to depict one complete audio cycle in the accompanying diagrams, it would be necessary to show the 2,000 IF cycles occurring. This would hardly be practical. Likewise, to show a complete signal fade followed by a build-up, we would have to show several thousand audio cycles—and consequently many millions of IF cycles.

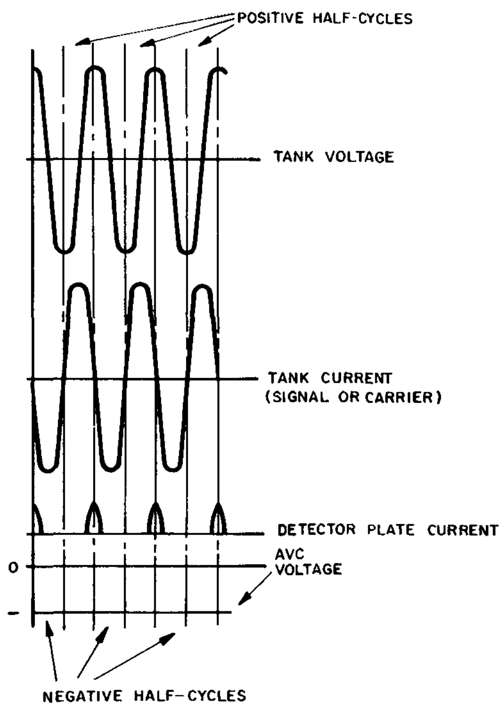


Fig. 5-3. AVC circuit waveforms when unmodulated RF is being received.

As is true with any vacuum tube, a closed path must be available between plate and cathode of the detector diode in order for detector current to flow. This path includes coil L1 and resistors R1 and R3. The green line has been chosen to represent detector current; it completes a path from plate to ground by flowing through L1, R1, and R3.

R1 and C2 together act as a radio-frequency filter. Resistor R3 and capacitor C4 act as an additional RF filter. Resistor R2 and capacitor C3, in conjunction with R3 and C4, develop an audio-voltage output from the detector or demodulator stage.

Resistor R4 and capacitor C5 are the two components which provide the necessary compensation for varying signal strengths. Without them, the remainder of the circuit would continue to function as a fairly elaborate diode demodulator. In order to understand the AVC function, it is necessary to begin with the diode detector and to consider how it operates to detect, or demodulate, an incoming radio-frequency signal.

CIRCUIT OPERATION

In Fig. 5-4 when a modulation trough is occurring, we see two green minus signs on the upper plate of filter capacitor C2. Between the lower plate of this capacitor and ground, the dotted blue arrows indicate current flow in both directions. This current, which is flowing at the basic radio frequency, represents the RF pulsations being filtered out of the detector current before it continues its journey back to the cathode.

Capacitor C2 is of such a size that its reactance at this particular radio frequency will be substantially less than the resistance of the alternate path available to the detector current. This path is through the series combination of R1 and R3 to ground.

Figs. 5-4 and 5-5 each cover a period which includes *many* RF cycles. The reader should recognize that this filtering current flows *downward* when a pulsation of detector current flows onto the top plate of C2, and that it flows *upward* in the interim before the next pulsation occurs.

When a detector pulsation of current is small, as it is near a modulation trough, only a small filtering current must flow. On the other hand, when a pulsation is large, as it is near a modulation peak (Fig. 5-5), a large amount must flow.

Although this filtering current is driven by the pulsations of detector current (shown in green), the filtering current is shown in dotted blue in order to help clarify the actual closed path of detector current from plate to ground. While the energy in the

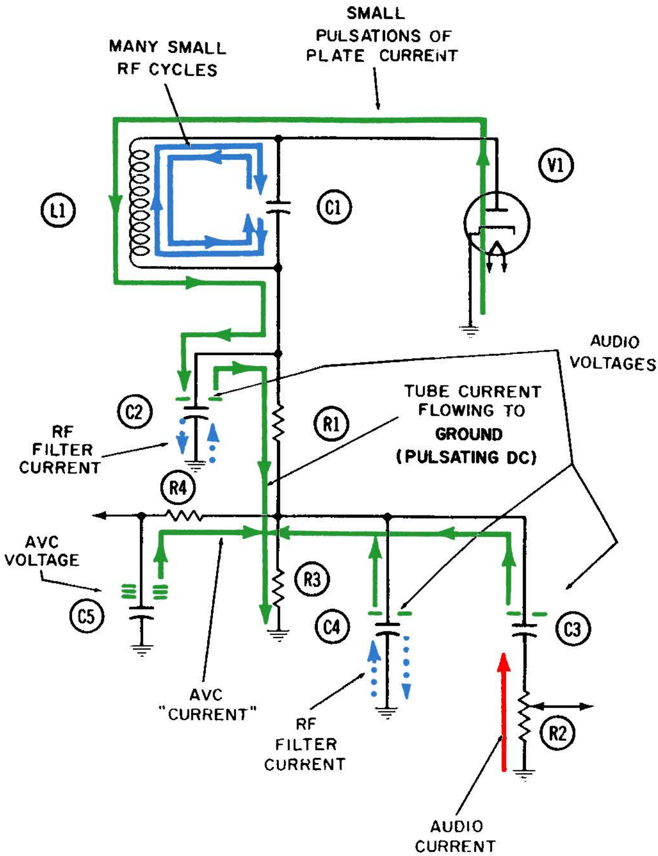


Fig. 5-4. Operation of the AVC circuit—audio half-cycle preceding a modulation trough.

individual pulsations is passed across the capacitor plates, the electrons which compose the detector current form a pool of negative voltage on the upper plate of C2 until they can escape downward through R1 and R3 to ground and the cathode.

This pool of electrons on the upper plate of C2 constitutes the first appearance of the audio voltage in a receiver system. Receivers are customarily analyzed in the order in which a signal progresses through from antenna to speaker. Until this detector stage is reached, no audio voltage has been generated in the system.

In Fig. 5-4, the amount of negative voltage on capacitor C2 is indicated by the two minus signs. In Fig. 5-5 this negative voltage has been greatly increased, as indicated by a total of ten such

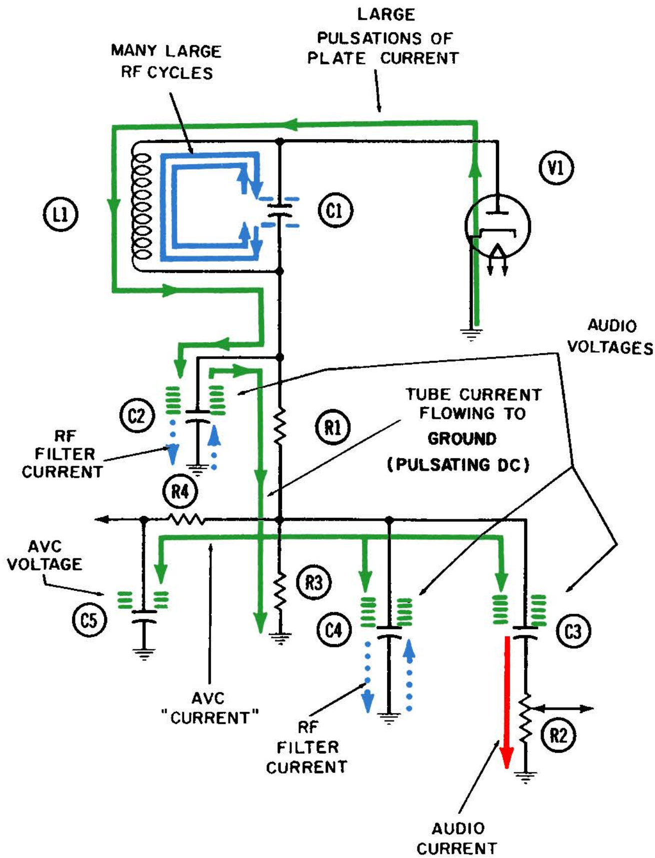


Fig. 5-5. Operation of the AVC circuit—audio half-cycle preceding a modulation peak.

signs. These two figures constitute one whole cycle of the audio, or modulating, voltage. The voltage on this capacitor indicates the rise and fall of the audio voltage in accordance with the peaks and troughs of the modulating envelope. During each half-cycle of the audio voltage, many hundreds or even thousands of pulsations of detector current will be coming into the capacitor.

The waveforms of Fig. 5-6 should be studied in conjunction with Figs. 5-4 and 5-5. Note that the sine wave of audio voltage in Fig. 5-6 is below the reference line of zero voltage at all times. In other words, the audio voltages which appear simultaneously on capacitors C2, C3, and C4 are negative at all times; and they fluctuate from their low negative value at the modulation troughs, to a high negative value at the modulation peaks.

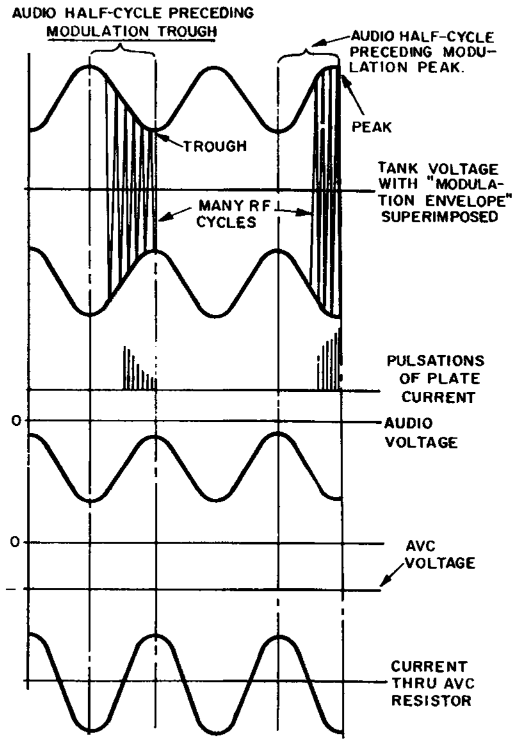


Fig. 5-6. AVC circuit waveforms when modulated RF is being received.

The electron current which flows downward through R1 and R3 is a pulsating unidirectional current, but the pulsations are occurring at the audio frequency. The least current flows when the voltage on C2 is lowest, during the modulation trough. Conversely, the most current flows when the voltage on C2 has its highest value, during the modulation peak.

Since an audio current flows through resistors R1 and R3, an audio voltage is developed across them. This is in accordance with Ohm's law. It is desirable for R3 to be considerably larger than R1, so that *most* of this audio voltage will be developed across R3. The reason for this will be apparent from analysis of the function of resistor R2 and capacitor C3. These two are in series with each other, and the series combination is in parallel with R3. R2 is a variable resistor across which the *output* audio voltage is developed. This potentiometer is commonly used as the volume control in receiver systems.

Capacitor C4 serves primarily as an additional radio-frequency filter, on the likely assumption that the combination of R1 and C2 will not do a thorough job of filtering the RF pulsations out of the detector current and into ground.

The combination of C3 and R2 is critical because the two develop the output audio voltage for the next amplifier stage. The product of these two components must give a short time-constant when compared with the lowest audio frequency being demodulated. When this short time-constant condition has been met, an alternating current at the audio frequencies will flow up and down through resistor R2. This current will be drawn *upward* as electrons flow away from the upper plate of capacitor C3 during the modulation trough, as indicated in Fig. 5-4. Conversely, the current will be driven *downward* through R2 as electrons flow onto the upper plate of C3 during the modulation peak, as indicated in Fig. 5-5.

This two-way current through R2 is the first appearance in the receiver of *alternating* current at the audio frequencies. The audio current which flows through R1 and R3 is unidirectional. In other words, it is DC which pulsates at the audio frequencies. Frequently this current is called pure DC with an alternating component superimposed on it. Both concepts are correct, and the reader should use the one that is clearer to him.

The alternating current through resistor R2 develops an audio voltage across it, in accordance with Ohm's law. This voltage then becomes the output of the detector stage. By moving the arm of the potentiometer to the various points on the resistor, it is possible to apply any given percentage of this output audio voltage to the grid of the first amplifier stage. By this means, the receiver volume can be adjusted to any desired level.

Although the voltage levels on C3 and C4 follow the changes occurring on C2, the two are slightly lower than the voltage on C2. The amount of reduction in audio voltage is an accurate reflection of the relative voltage drops occurring across R1 and R3, respectively. The voltage drop across R1 is a loss, which is made acceptable by the filtering achieved from adding R1 and C2 to this circuit.

Resistor R4 and capacitor C5 form the AVC filter combination. In order to understand how these components perform, it is desirable to visualize the current through R4, the voltage on the upper plate of C5, and their interrelationship with the audio voltage on C4 and C3. Since the voltage level on these capacitors is rising and falling in accordance with the modulation, we can visualize an *average* voltage value for a whole modulating cycle. The detected voltages shown in Figs. 5-1 and 5-2, when the car-

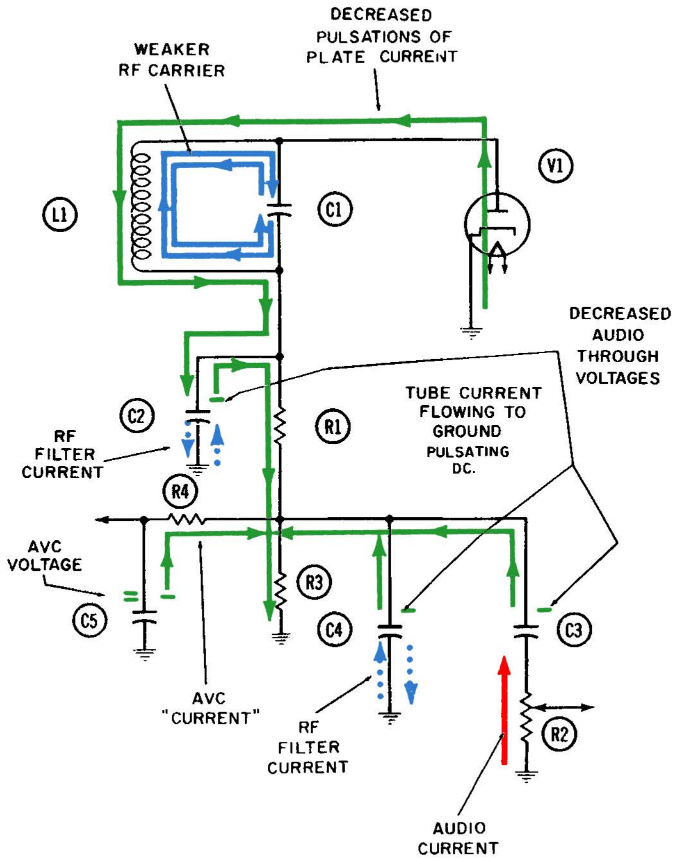


Fig. 5-7. Operation of the AVC circuit—modulation trough during a carrier fade.

rier is unmodulated, are a fair approximation of what this average value would be. During the modulation trough of Fig. 5-4, the voltage level on these capacitors is *below* this average level. Conversely, it is *above* the average value during a modulation peak in Fig. 5-5.

Even with changes in percentage of modulation, this average voltage level on the capacitors will not change, although the amounts of voltage above and below the average will. For instance, with a very low percentage of modulation impressed on the carrier wave, the capacitor voltage during the modulation trough will be only slightly below average. On the other hand, during a modulation peak it will be an equal percentage above the average level.

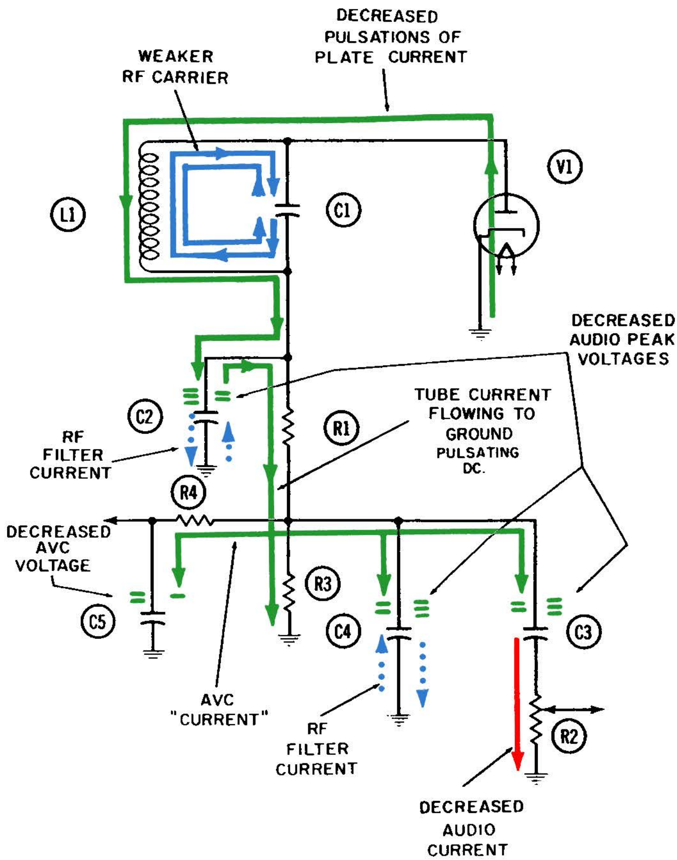


Fig. 5-8. Operation of the AVC circuit—modulation peak during a carrier fade.

Let us consider how capacitor C5 acquires its charge of negative voltage, as indicated by the series of green minus signs. If there were no modulation at all on the carrier signal, then the average voltage levels on C3 and C4 would be quickly achieved and maintained because of continued detection of the unmodulated carrier. Under this condition, electron current would flow from the upper plates of C3 and C4, through resistor R4, to the upper plate of C5. Eventually C5 would become charged to the same average value of negative voltage. This leads us to an important point in the operation of AVC circuits(and in understanding them)—namely, *the AVC capacitor will charge to the average value of the audio voltage.*

Once the reader visualizes that this can and does happen to an unmodulated carrier, only one more step is required to demonstrate that this principle still holds where there is some modulating voltage on the carrier signal. Figs. 5-4 and 5-5 are useful for demonstrating this point. During the modulation trough depicted by Fig. 5-4, electron current (shown in green) will flow *out* of AVC capacitor C5 and toward those points of lesser negative voltage on C3 and C4. During the modulation peak depicted by Fig. 5-5, a greater negative voltage exists on C3 and C4. Now electron current flows *away* from these capacitors, toward the AVC capacitor. The voltage on this capacitor has remained substantially unchanged during the entire cycle.

The reason the voltage level on the AVC capacitor does not change during an individual cycle of audio voltage can best be understood by calling on the time-constant concept. When a resistance in ohms is multiplied by a capacitance in farads, the resultant product has the dimensions of time and is measured in seconds. In a long time-constant RC combination, its product is

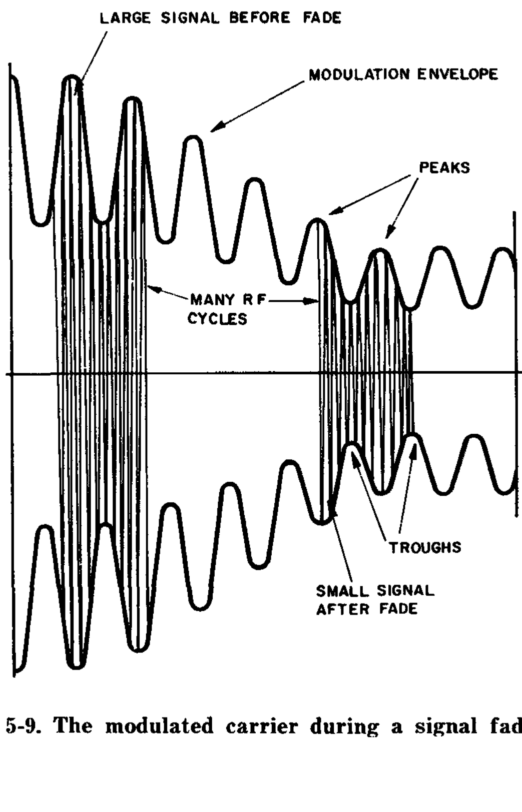


Fig. 5-9. The modulated carrier during a signal fade.

a long time, in comparison with the duration of one cycle of the frequency under consideration. The lowest frequency of audio voltage in a normal receiver might be in the neighborhood of 100 cycles per second, so that the time for one cycle is .01 second. (Time for one cycle is always the reciprocal of the frequency, or $T = 1/f$.)

AVC resistors and capacitors are very large components. Typical values for R4 and C5 would be 2 megohms and .05 microfarad, for example.

Calculating the time constant of this combination, we find that:

$$\begin{aligned} T &= R \times C \\ &= (2 \times 10^{6}) \times 5 \times 10^{-8} \\ &= 0.1 \text{ second} \end{aligned}$$

One-tenth of a second is certainly a long time, in comparison with the one-hundredth of a second of the longest audio cycle considered above.

The AVC capacitor is much larger than C3 (which is much larger than C4). Hence, *many more electrons* are required to charge the AVC capacitor to the average voltage level than are required by C3 and C4. Because the AVC resistor also is large, only a minute amount of electrons will be driven back and forth

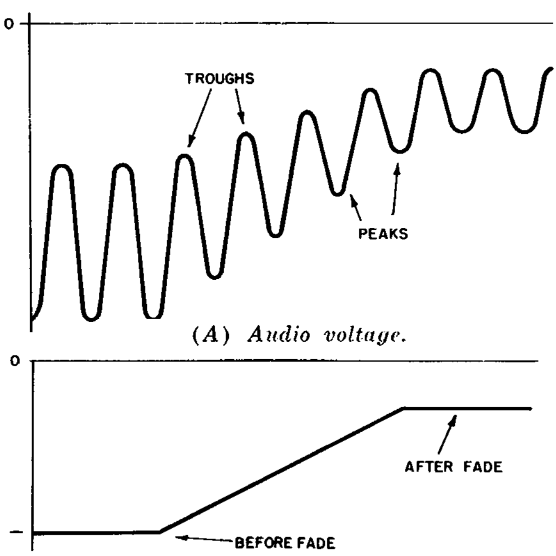


Fig. 5-10. The audio and AVC voltage changes during a signal fade.

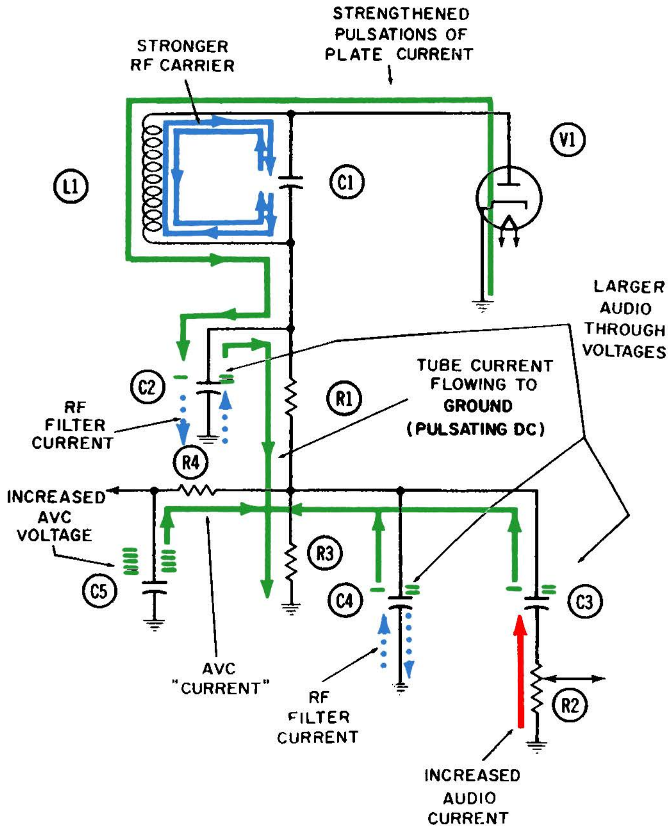


Fig. 5-11. Operation of the AVC circuit—modulation trough during a carrier build-up.

through it as the voltage levels on C3 and C4 change in accordance with the modulation peaks and troughs. This small amount of electron traffic in and out of C5 will be insignificant *in comparison with the electrons stored there.* Consequently, the AVC voltage—which is the negative voltage stored on the upper plate of AVC capacitor C5—*does not change with the audio or modulating voltage.* This is an important point in understanding automatic volume control.

The AVC line connected to the junction of R4 and C5 leads directly to the control grids of one or more RF amplifier tubes. The carrier signal must be processed through these tubes before it reaches tuned tank L1-C1. Hence, this increased negative voltage shows up as a larger negative bias on the grids of these tubes

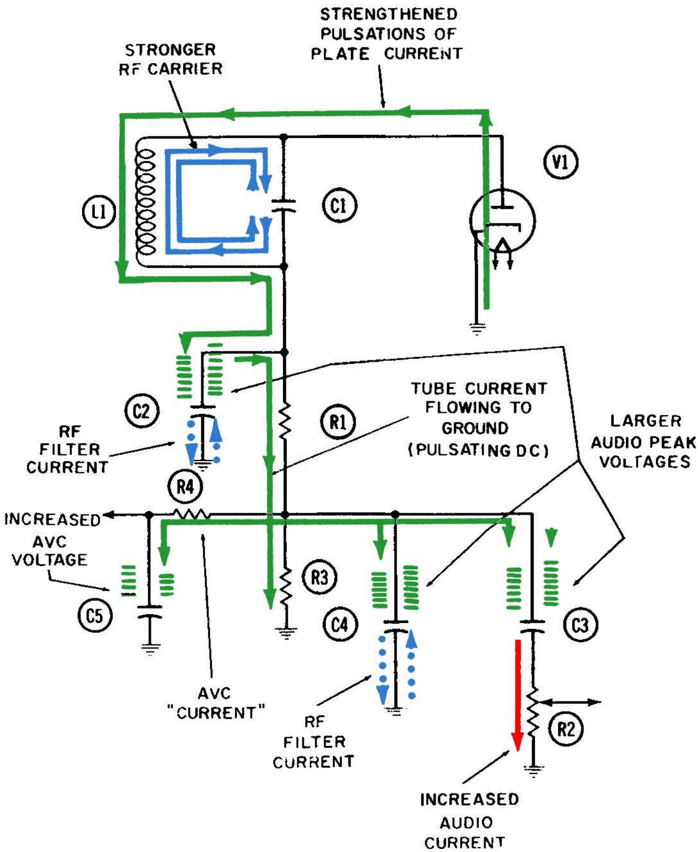


Fig. 5-12. Operation of the AVC circuit—modulation peak during a carrier build-up.

and reduces their amplification, to compensate for the stronger signal.

A signal fade or build-up may take place over a period of several seconds. During this time, many hundreds of cycles of audio voltage will probably occur. The audio current (shown in red) which flows back and forth through R2 will of course continue to do so during this time. However, the voltage on C5 can only be changed by the current through resistor R4. This resistor, along with R3, provides the only path to ground for the electrons which make up the AVC voltage on C5. The only way this voltage can be decreased or increased is for electrons to empty out through R4, or for more electrons to come in through that path.

In the example shown, when a signal build-up occurs more electrons must flow into C5 during the modulation peaks than flow out during the modulation troughs. This flow continues until the AVC voltage has become stabilized at the new average audio voltage. During this interim, the current flowing through R4—to the left in Fig. 5-12—will exceed the current flowing to the right in Fig. 5-11. Thus, although two-way current continues to flow through the AVC resistor at the audio frequencies, its amount varies between individual half-cycles. In this way, the AVC voltage is automatically kept at the average value of audio voltage coming from the detector.

CIRCUIT ACTIONS DURING A CARRIER FADE

Fig. 5-9 is a simplified representation of a modulated carrier signal undergoing a fade, or reduction in signal strength, because of abnormal propagation or atmospheric conditions. Fig. 5-10 shows the resultant reduction in audio voltage after detection or

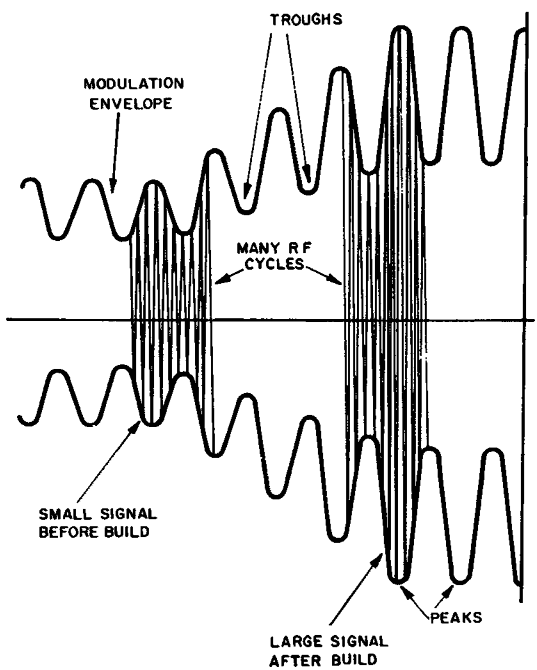
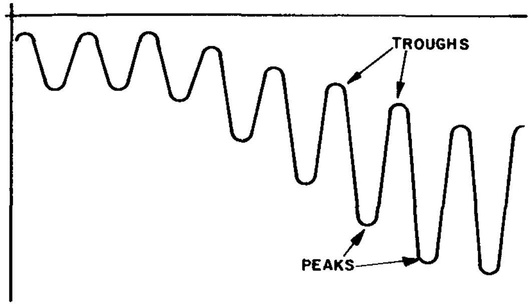
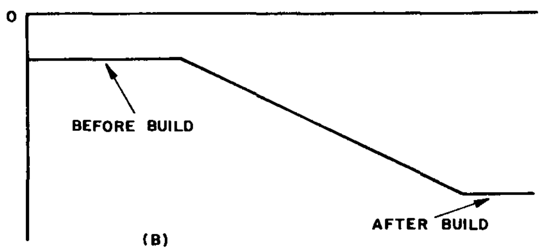


Fig. 5-13. The modulated carrier during a period of signal build-up.

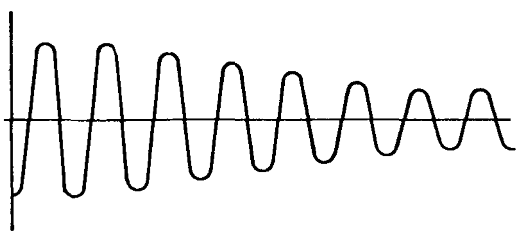


(*A*) *Audio voltage after demodulation.*

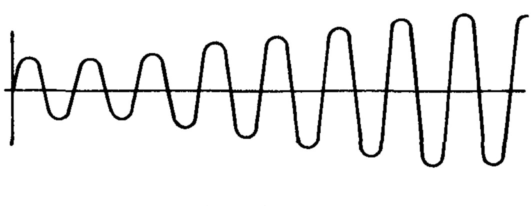


(*B*) *AVC voltage.*

Fig. 5-14. The audio and AVC changes occurring during a period of signal build-up.



(*A*) *During signal fade.*



(*B*) *During signal build-up.*

Fig. 5-15. The audio output voltage during a signal fade and a signal build-up.

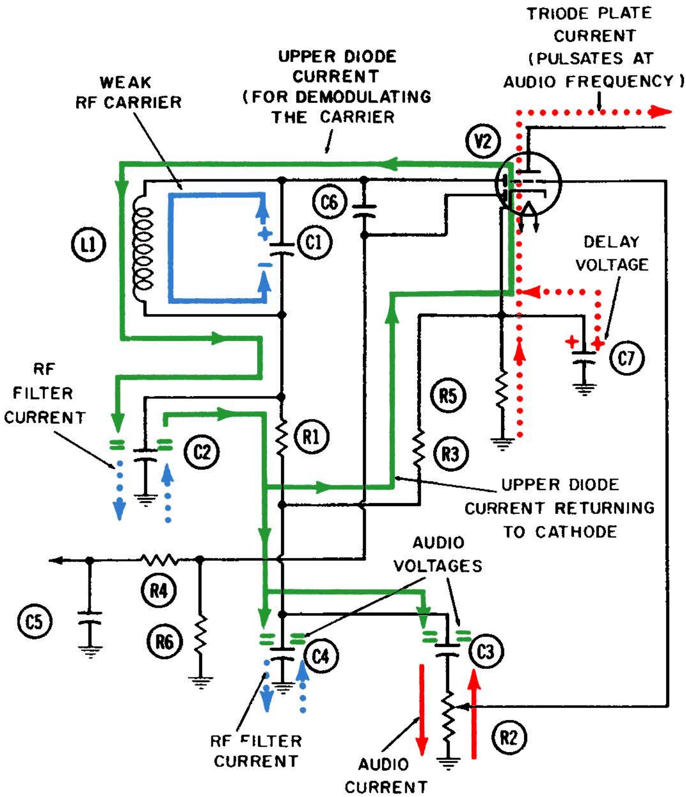


Fig. 5-16. The delayed AVC circuit—weak-signal operation.

demodulation. It is important to note that individual audio cycles are larger before the fade. Also note the more obvious fact that the *average value* of the audio voltage decreases from a high to a low negative value during the fade. The AVC voltage line in this figure represents the negative voltage stored on capacitor C5 in Figs. 5-7 and 5-8. This line faithfully reflects the average value of audio voltage.

Fig. 5-7 shows the relative sizes of the audio and AVC voltages at the moment of a modulation trough, after the carrier has faded. Fig. 5-8 shows the same voltages at the moment of a modulation peak. Compare these voltages with those that existed at the same points before the carrier faded (Figs. 5-4 and 5-5). You will see that the audio and AVC voltages are both lower. However, the amounts of AVC voltages indicated in Figs. 5-7 and 5-8 are intended to be equal, because the AVC voltage does not change

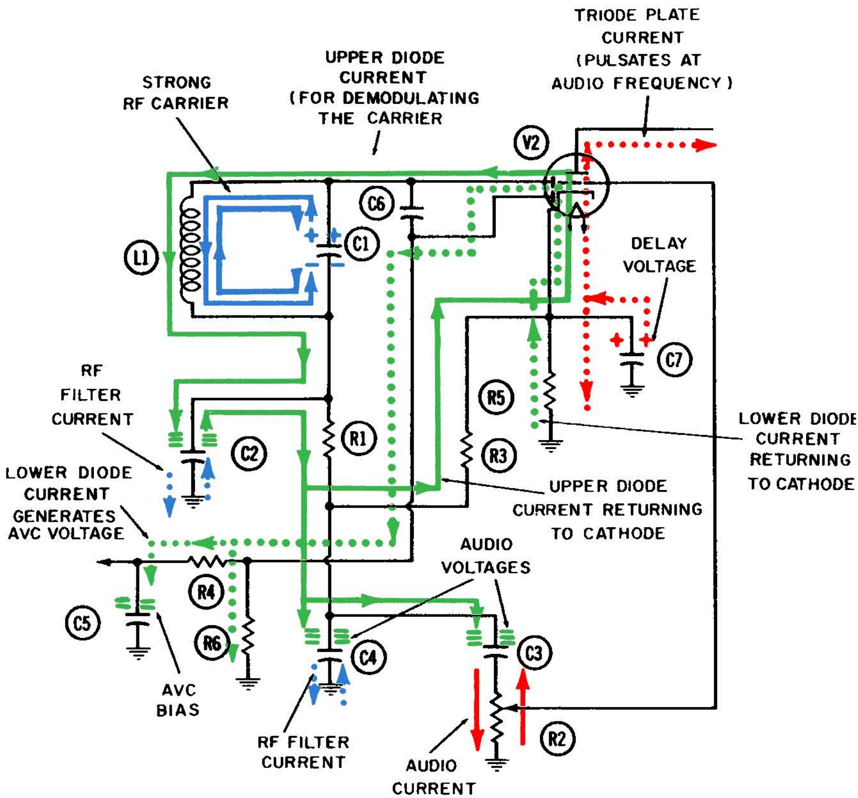


Fig. 5-17. The delayed AVC circuit—strong-signal operation.

from modulation trough to peak. This is due to the long time-constant nature of the R4-C5 filter combination, as previously discussed.

During a carrier fade, the AVC current which flows through resistor R4 reduces the number of electrons stored on capacitor C5. This is normally a minute two-way current that flows at the audio frequency. During a modulation trough this current flows to the right, as shown in Figs. 5-4, 5-7, and 5-11, because the momentary audio voltage at the right end of the resistor is more negative than the stored AVC voltage at the left. Electrons will always flow from an area of higher to one of lower negative voltage as long as a conducting path is provided. During a modulation peak this current flows to the left, as shown in Figs. 5-5, 5-8, and 5-12.

Under normal conditions, the amount of AVC current which flows to the right during a modulation trough will just equal the amount which flows to the left during a modulation peak. However, when a carrier fade is occurring, these two components of current are no longer equal. More current flows to the right during the trough half-cycle than flows to the left during the peak half-cycle. This inequality will continue until the fade has been completed, and in this way the AVC voltage will "discharge" electrons until it again equals the average value of the audio voltage.

CIRCUIT ACTIONS DURING A CARRIER BUILD-UP

Fig. 5-13 shows a simplified representation of a modulated carrier signal undergoing a build-up, or increase, in signal strength. Fig. 5-14 shows the resultant increase in audio voltage after demodulation, and also the increase in negative AVC voltage as a result of this build-up in signal strength. As in the case of the fading signal, the AVC voltage accurately reflects the *average* value of the audio voltage.

Fig. 5-11 shows the audio and AVC voltage during a modulation trough, after a carrier build-up. By comparing these voltage pictures with the same voltages in Fig. 5-4, you can see that the build-up in carrier strength has caused the audio and AVC voltages to go more negative.

Fig. 5-12 shows these voltages to be larger than their counterparts in Fig. 5-5 before the carrier build-up. Between the modulation trough of Fig. 5-11 and the peak of Fig. 5-12, however, the AVC voltage itself does not change. The AVC current flowing through resistor R4 again provides the mechanism by which the AVC voltage becomes stabilized at the average value of audio voltage.

AUDIO-OUTPUT VOLTAGE

Fig. 5-15 shows the audio-output voltage developed across potentiometer R2 as the audio current (shown in red) is driven up and down through R2. As indicated in Figs. 5-4, 5-7, and 5-11, this current flows upward during modulation troughs. During modulation peaks, it goes downward, as shown in Figs. 5-5, 5-8, and 5-12. Excess electrons from the detector tube flow onto the upper plate of capacitor C3 during modulation peaks, driving an equal number away from the lower plate and down through the resistor. (This is the basic capacitor action.) As these excess electrons flow away from the upper plate of C3 during a modulation trough and discharge to ground through R3, an equal number will be drawn upward through R2 to the lower plate of C3.

During a carrier fade, less audio current will flow and therefore less output voltage will be developed across resistor R2, as indicated in Fig. 5-15A. The resultant reduction in volume would be undesirable to the listener. However, if we connect the grid of a previous RF amplifier tube to the AVC voltage point on capacitor C5, the lower AVC voltage will *reduce* the negative grid bias on the RF amplifier tube. This will increase the amplification of the signal and thus largely nullify the effects of the fading signal.

Likewise, during a carrier build-up the spread between peak and trough voltages on capacitor C3 is greater and more audio current will flow in output resistor R2. According to Ohm's law, the voltage developed *across* a resistor is proportionate at all times to the current flowing through the resistor. Thus, the audio-output voltage increases as the carrier strength builds up. This higher voltage, shown by Fig. 5-15B, may increase the loudness to the point where it is most unpleasant to the listener.

When the higher negative AVC voltage on capacitor C5 is connected to the control-grid circuit of a previous amplifier tube, the negative grid bias of the tube will be increased and its amplifying properties reduced. This reduces the total amplification of the signal and largely nullifies the undesirable effects which would otherwise result from the stronger signal.

DELAYED AVC

Figs 5-16 and 5-17 show two modes in the operation of a circuit designed to provide delayed automatic volume control. There are considerable similarities between this circuit and the one shown previously. To accentuate these similarities, individual components having identical functions in the two circuits have been assigned the same names. The component names and functions are:

R1—Filter resistor.
R2—Audio-output resistor.
R3—Primary load resistor.
R4—AVC resistor.
C1—RF tank capacitor.
C2—RF filter capacitor.
C3—Output coupling capacitor.
C4—Additional RF filter capacitor.
C5—AVC storage capacitor.
L1—RF tank inductor.

Additional components in the delayed AVC circuit, which were not present in the previous AVC circuit, are:

R5—Cathode filter capacitor.

R6—AVC return resistor.

C6—Isolating and coupling capacitor between the two diode plates.

C7—Cathode filter capacitor.

V2—Dual-diode/triode tube.

Principles of Operation

Delayed AVC allows us to eliminate the AVC on weak signals, but to enjoy its benefits when the incoming signal level reaches a predetermined strength. These objectives are accomplished by using separate diodes for signal demodulation and for automatic volume control. Recall that the electron current through the single diode in the preceding example was eventually used to provide an audio-output voltage as well as an AVC bias voltage.

Each diode plate in tube V2 operates independently from the other, and also independently from the triode operation within the same envelope. The fundamental principle of diode operation prevails in either case—that whenever a diode plate is more positive than the cathode, electrons will be drawn across the open space between the two electrodes.

Both diode plates are driven by the same alternating tank voltage. The tank current associated with this tank voltage is shown circulating between the inductance and capacitor within the tank. The half-cycle in Fig. 5-16 represents operation during a weak signal. At the moment shown, the tank current is flowing downward through L1 and thus delivering electrons to the lower plate of capacitor C1, making it negative and the upper plate positive.

This positive voltage is coupled directly to the upper diode plate and capacitively (by means of C6) to the lower diode plate. Even with a weak RF or IF signal applied from the tank, the upper diode plate will draw some electron current on the positive half-cycles. This diode current, shown by the solid green lines, follows a similar path as the diode current in the previous example, with one important difference. After flowing through resistor R3, it goes directly to the cathode rather than ground.

This manner of connecting R3 to the cathode assures that the signal will be detected, even with weak signals. Since the multiple tube has a common cathode and since cathode biasing is used in connection with the amplifying function of the tube, the cathode is necessarily placed at a positive voltage. This voltage persists as long as electron current flows through the tube.

Depending on the requirements of the particular circuit, this positive cathode voltage might have any reasonable value—but for convenience, let us assume it is +3 volts. *This becomes the amount of delayed AVC the circuit is using.* The lower diode plate is returned to ground through resistor R6. So this diode plate will assume a reference voltage of zero. The alternating voltage resulting from the IF oscillations in the tuned tank is coupled to this diode plate by capacitor C6. As a result, the diode plate voltage will vary in either direction from this zero reference value.

In the weak-signal example shown in Fig. 5-16, the IF oscillations are considered small enough that they never raise the lower diode plate any higher than +3 volts. Consequently, no electron current can flow between the cathode and this plate, and no automatic-volume-control voltage will be developed.

In the strong-signal example of Fig. 5-17, the IF oscillations are large enough that they raise the lower diode plate well above +3 volts on each positive peak. Fig. 5-17 depicts one such positive peak occurring. As a result, the lower diode plate is now more positive than the cathode, and conduction occurs. The complete path of this electron current, shown in dotted green, is from cathode to lower diode plate within the tube, then downward to the junction of the two AVC resistors R4 and R6. The ultimate destination is of course back to the chassis and then to the cathode. However, resistor R6 is made large enough to impede this flow and divert some of the electrons into resistor R4. Eventually a pool of electrons collects on the upper plate of capacitor C5. These accumulated electrons become the AVC voltage, which is applied to one or more control grids of the preceding RF (or IF) amplifier tubes.

This negative AVC voltage increases as the signal becomes stronger and vice versa, in the same manner shown in earlier figures of this chapter. Because of the similarity in function between these two circuits, a detailed analysis of AVC will not be repeated here.

Chapter 6

GRID-LEAK DETECTOR CIRCUITS

Grid-leak detection combines the functions of detection and amplification into one triode vacuum tube. As we said before, the primary purpose of detection is to demodulate a carrier current, or carrier wave, which has been modulated (i.e., changed) by the audio-frequency current representing the intelligence being conveyed. Like the diode detector discussed in the two previous chapters, the grid-leak detector is useful only for amplitude-modulated carrier currents.

CIRCUIT DESCRIPTION

Figs 6-1 through 6-4 represent successive half-cycles of operation during a modulation trough and a modulation peak. Since the peak is separated from the trough by many hundreds or even thousands of radio-frequency cycles, the operating conditions depicted by Fig. 6-3 do not immediately follow those of Fig. 6-2.

The circuit components in Figs. 6-1, 6-2, 6-3, and 6-4 and their functional titles are as follows:

R1—Grid biasing resistor.
R2—Load resistor.
C1—RF tank capacitor.
C2—Grid leak capacitor.
C3—RF filter capacitor.
C4—Coupling and DC blocking capacitor to the headphones.
L1—RF choke.
T1—RF transformer.
V1—Triode tube.

The tank (consisting of C1 and the secondary winding of T1) is adjusted, or tuned, to resonance at the basic carrier frequency being transmitted. After being received and amplified by the receiver, the amplified signal will then be delivered to the grid-leak detector circuit for demodulation.

A total of four different groups, or families, of currents are at work in this circuit. These currents, and the colors they are shown in, are as follows:

1. Radio-frequency alternating currents (blue).
2. Radio-frequency unidirectional currents (solid red).
3. Audio-frequency unidirectional currents (green).
4. Audio-frequency alternating currents (dotted red).

The order in which these currents are listed follows closely the one in which they are normally considered in a circuit. This conforms with the idea that the "input"—i.e., control-grid portion—of a circuit must normally be understood before the "output," or plate portion, is discussed.

The four colors chosen do not follow exactly this breakdown of currents into four families. However, this was not done to confuse the reader! One of the most important points to be understood about any current is its complete path through a circuit. This essential information can frequently be made clearer in this series by using different colors than by some other means. Consequently, the reader should not try to match colors faithfully with these current families.

RADIO-FREQUENCY ALTERNATING CURRENTS

The current shown in blue in the grid tank circuit is the final amplified version of the modulated carrier wave. This oscillatory current is sustained by a similar current (also in blue) which flows in the transformer primary. In Fig. 6-1, the tank current is shown moving *upward* through the transformer secondary. Since a current is made up of electrons in motion, electrons are withdrawn from the lower plate of tank capacitor C1, making the plate positive as indicated by the blue plus sign. These electrons are then delivered to the upper plate of C1, making the plate negative as indicated by the blue minus sign. This negative voltage in turn delivers electrons to the left plate of grid capacitor C2, but they cannot flow onto the plate unless an equal number flow away from the right plate. The latter component of current, also shown in blue, leaves the grid capacitor and moves toward the grid, making it momentarily negative and thus restricting the flow of electron current through the tube (but not cutting it off entirely). The red line, which follows the con-

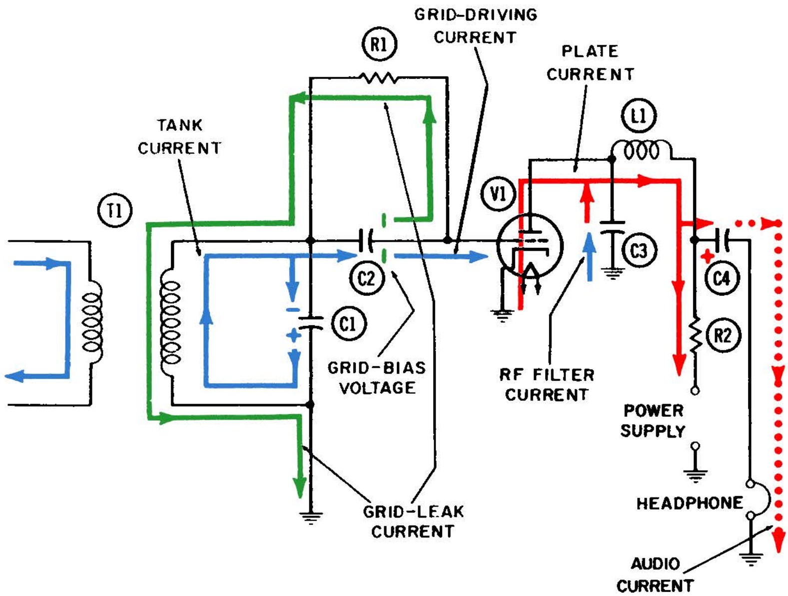


Fig. 6-1. Operation of the grid-leak detector—negative half-cycle of RF during modulation trough.

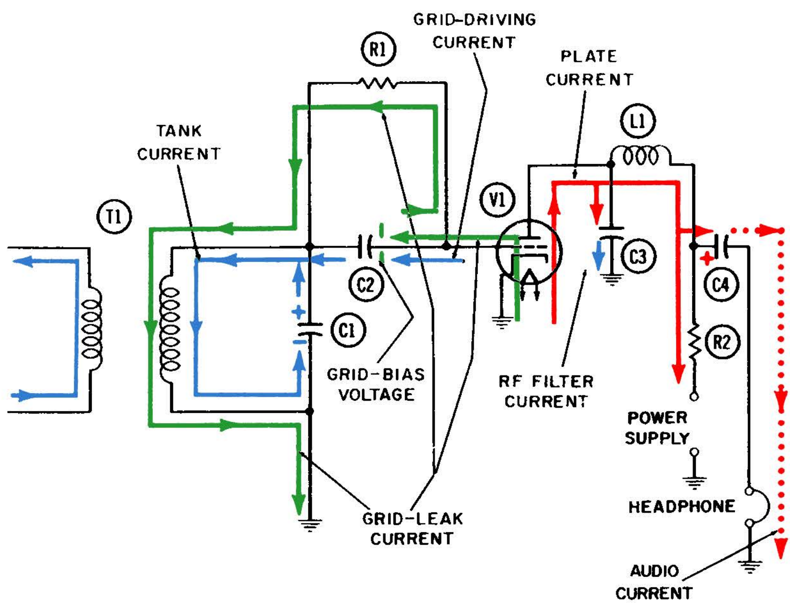


Fig. 6-2. Operation of the grid-leak detector—positive half-cycle of RF during modulation trough.

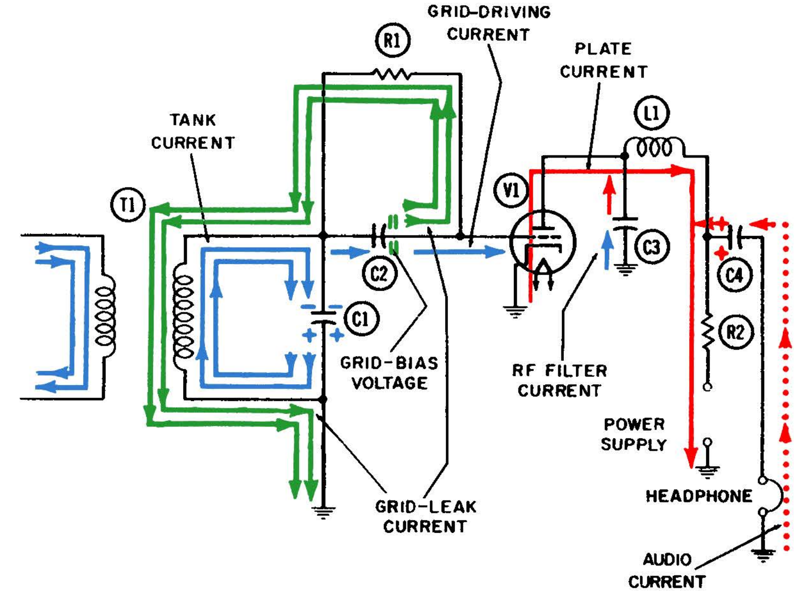


Fig. 6-3. Operation of the grid-leak detector—negative half-cycle of RF during modulation peak.

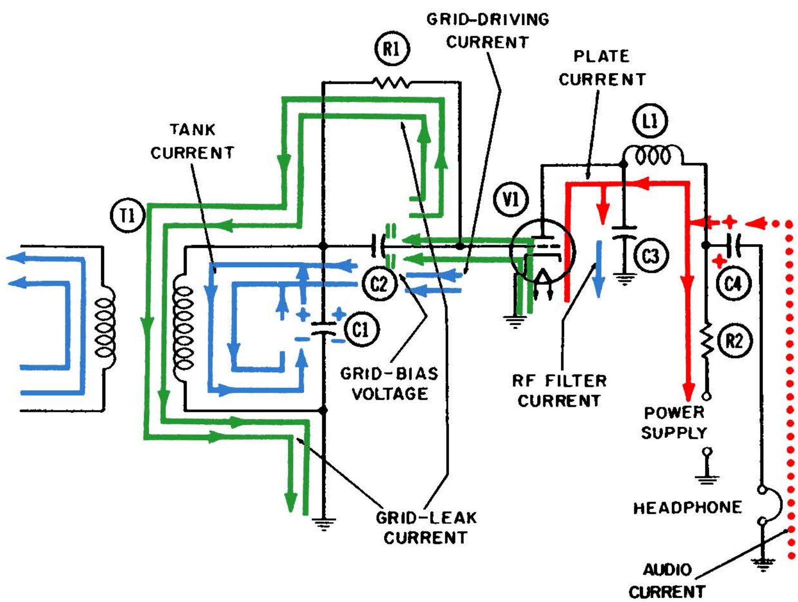


Fig. 6-4. Operation of the grid-leak detector—positive half-cycle of RF during modulation peak.

ventional plate-current path, indicates that some plate current is going through the tube.

When the operating conditions of a tube are such that the plate current is never completely cut off—even when the grid reaches its most negative voltage—the tube is said to be operating "Class A." That is true of the tube in this example, and it accounts for the flow of current through the tube when the grid reaches its most negative value.

Figs 6-1 and 6-2 depict the approximate conditions during a modulation trough, when the carrier wave is weakest. Fig. 6-2 shows the tank current flowing *downward* through the secondary winding of the transformer. Electrons are delivered onto the lower plate of tank capacitor C1, making its voltage negative as indicated by the blue minus sign. At the same time, electrons are withdrawn from the upper plate of tank capacitor C1 and from the left plate of grid coupling capacitor C2, making both points positive as indicated by the blue plus signs on the upper plate of C1.

Normal capacitor action will simultaneously draw electrons onto the right plate of grid coupling capacitor C2. This makes the grid voltage momentarily positive and thereby permits more plate current to flow. (The plate current will be discussed more fully under "Radio-Frequency Unidirectional Currents.")

Figs. 6-3 and 6-4 represent conditions during the modulation peak. The only essential difference between the oscillating grid current from trough to peak is its size—meaning the quantity of electrons that make up the current. In Fig. 6-3 the tank current flows in the same direction as in Fig. 6-1 and achieves the same results, except for being larger. This is indicated by an additional blue line following the path of the tank current.

A larger tank current results in a larger tank voltage. This is indicated by the additional minus and plus signs on the upper plate of the tank capacitor in Figs. 6-3 and 6-4. Since the amount of conduction by the tube depends on the grid voltage, conduction will be greatest when the grid is most positive (Fig. 6-4).

One more radio-frequency alternating current is at work in this circuit—the filter current which flows between ground and the lower plate of filter capacitor C3. This current, shown in blue, will be discussed in the next section, after the tube currents.

RADIO-FREQUENCY UNIDIRECTIONAL CURRENTS

Tube currents—whether plate, screen-grid, or grid-leak—are essentially unidirectional. In other words, they flow in one direction only, and never reverse their direction. This characteristic distinguishes them from alternating currents, which reverse directions at regular intervals. In this chapter, the plate current is shown in red, and the grid-leak current in green.

Referring to Fig. 6-1, note that the alternating tank voltage has made the control grid negative. However, the tube has not been cut off entirely—a small amount of plate current flows through it, but no grid-leak current does during this half-cycle.

In the second diagram (the next half-cycle), the control grid has been made positive and more plate current is released through the tube. Since these grid-voltage changes are occurring at the basic radio frequency being demodulated, the plate current will be turned "down" and "up" in this fashion once each cycle. Therefore, even though it is a direct current, the plate current pulsates at the applied radio frequency. Hence, the plate current is said to be DC with a radio-frequency alternating component superimposed on it.

Fig. 6-2 reveals a small amount of grid-leak current (in green) coming out of the tube at the control grid. These electrons accumulate on the right plate of grid capacitor C2, until they can leak out through grid resistor R1 and the secondary of T1 to ground, then through ground to the cathode. The grid-leak current also flows in one direction only. Since it does not flow from the tube unless the grid is positive, it is obviously an intermittent rather than continuous current. Because of the combined action of the capacitor (which stores the electrons) and the resistor (which passes them), the grid-leak current is smoothed out and becomes a continuous current for the rest of its journey. This resistor-capacitor action is referred to as integration, a term derived from its mathematical background. The RC action is also referred to as a "long time-constant," another term derived from the underlying mathematics. In other words, the electrons come out of the tube on each positive half-cycle and accumulate on the capacitor, but are unable to discharge completely to ground before the next positive half-cycle comes along. A continuous discharge of electrons therefore takes place as the number leaking out during an entire cycle is equaled by the number entering during the brief period when the control grid is positive.

Fig. 6-5 shows a typical transfer characteristic curve for an amplifier tube. This curve relates an instantaneous grid voltage to the resultant instantaneous plate current, using assumed or average values of power-supply voltage, plate-load resistance, etc.

Graphical representations of two currents and two voltages appear in Fig. 6-5. Each current is shown in the same color as

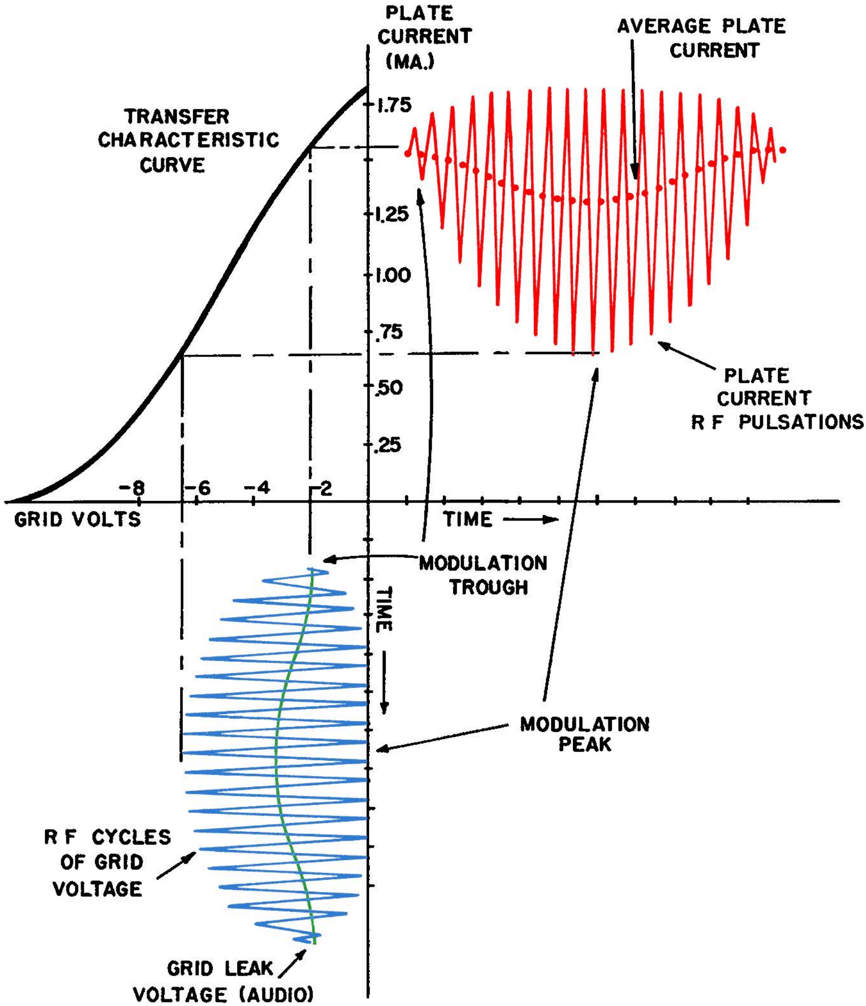


Fig. 6-5. Graphical representation of the grid-voltage, plate-current characteristics of the grid-leak detector.

its related voltage or current in Figs. 6-1 through 6-4. Thus, the radio-frequency grid voltage is shown in blue because it is directly related to the radio-frequency tank current.

The green line down the middle of the RF grid-voltage sine wave represents the grid-leak bias voltage. This voltage is indicated in the circuit diagrams by the green minus signs (representing negative electrons) on the right plate of capacitor C2. From the grid-voltage scale in Fig. 6-5, note that the grid-leak voltage goes from −2 volts during a modulation trough to approximately

−4 volts during a peak. In other words, the strength of these voltage swings rises and falls in step with the modulation imposed at the transmitter.

The grid-leak voltage in this type of detector circuit marks the first appearance of the desired audio voltage in the receiver system. This voltage will more or less faithfully reproduce the variations in frequency and amplitude of the audio voltage used at the transmitter to modulate the transmitted radio-frequency carrier signal.

As previously discussed, the strength of this grid-leak voltage depends on the amount of grid-leak current drawn from the tube during each half-cycle of radio-frequency voltage. By projecting upward from any point on the grid-voltage sine wave to the characteristic curve and thence horizontally, it is thus possible to construct a curve of instantaneous plate currents. This curve is shown in red because it is most directly related to the plate current, also in red. Reference to the scale in the middle of the diagram reveals that the plate current varies between a low and a high positive value—in the example shown, from 0.6 milliamp to about 1.8 milliamps.

The dotted red line which appears to bisect the plate-current RF sine wave is the average plate current. Reference to the plate-current scale shows that the average current varies roughly between 1.35 and 1.6 milliamperes—or 0.25 milliampere peak-to-peak.

In the circuit diagrams, the audio voltage on the left plate of capacitor C4 is shown rising to its highest value (two plus signs) during a modulation peak, and falling to its lowest value (one plus sign) during a trough.

Because the characteristic curve is not a straight line, some distortion of the audio voltage will occur during amplification. (This is known as "square-law" detection. The derivation of this term is beyond the scope of this book.)

On the graphical portion of the diagram, one cycle or pulsation of plate current can be seen occurring for each cycle of radio-frequency current. Since the largest pulsations occur during modulation peaks and the smallest during modulation troughs, it is possible to filter out the radio-frequency characteristics of the plate current and retain only the trough-to-peak variations. Fig. 6-5 shows these variations as "average plate current." They constitute the audio intelligence which the carrier wave has carried from transmitter to receiver.

Capacitor C3 provides the necessary RF filtering in the plate circuit. Its reactance is normally only a few ohms at the carrier frequency. Reactance—in simplest terms, opposition to electron flow—is inversely proportional to both the frequency and the capacitor size, in accordance with the formula:

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

where,

X_C is the reactance in ohms,
f is the current frequency in cycles per second,
C is the capacitance in farads.

The radio-frequency pulsations of plate current which reach the external plate circuit find three alternate paths available. They can flow directly into the filter capacitor, or else they can flow through filter choke L1 and into either coupling-blocking capacitor C4 or directly into resistor R2. The strength of these pulsations will divide betwen the three paths in inverse proportion to the opposition (resistance and/or reactance) offered by each path.

When one or both types of reactances (capacitive and inductive) are combined with resistance, the common name of impedance represents the sum total of this opposition to the passage of electron current. The filter choke in this circuit is designed to have a high inductive reactance at the radio frequencies in use here. Inductive reactance is directly proportional to both the inductance and the frequency, in accordance with the standard formula:

$$X_L = 2\pi f L$$

where,

X_L is the inductive reactance in ohms,
f is the frequency of the current being passed or impeded in cycles per second,
L is the inductance of the coil in henrys.

Since filter choke L1 in effect is in series with load resistor R2 and blocking-coupling capacitor C4 as far as plate-current pulsations are concerned, the impedance of each alternate path can be added to the filter-choke impedance to determine the total impedance of either path. It is hardly necessary to state that most of the plate current (which is pulsating at the basic radio frequency) will choose the low-impedance path to ground offered by filter capacitor C3, rather than the two high-impedance paths through L1 and R2 or C4.

Remember that reactive ohms and resistive ohms cannot be added directly by simple arithmetic; they can only be added vectorially. This is a more complex mathematical process than simple arithmetic and is beyond the scope of this book.

The filter combination of C3 and L1 could be made more elaborate by adding another capacitor leading from the right terminal of choke L1 to ground. It could also be less elaborate, consisting of capacitor C3 without the filter choke. Even so, the impedance of each alternate path for the RF pulsations in the plate current would be great enough that C3 would bypass most of the energy to ground. The load resistor, for example, will normally be several thousand ohms, as opposed to the few ohms offered by C3 to radio frequencies.

The reason why the other alternate path through C4 will also reject radio-frequency currents requires more explanation. Capacitor C4, which must couple the audio or modulating voltage to the headphones (or speaker), must have a low reactance to current flow at audio frequencies. Since audio frequencies are much lower than radio frequencies, C4 must be much larger in value than C3. Therefore, C4 will offer only negligible reactance to the radio-frequency pulsations in the plate-current stream.

At first glance it appears that the energy of these pulsations will flow into C4 and be coupled to the headphones (rather than the desired objective of flowing into capacitor C3 and being filtered back to ground). However, this does not occur because of the resistance of the transducer (headphones) beyond the coupling capacitor. (A transducer is a device for converting energy from one form to another. A headphone or speaker, for example, converts electrical energy to sound energy.) A headphone has an internal resistance of several hundred or even several thousand ohms. The RF pulsations will not flow onto the left plate of C4 unless pulsations of equal size are permitted to flow off the lower plate. Since the headphone resistance is in series with the capacitor, the RF pulsations would also have to flow through the phones. Consequently, the total impedance—or opposition to electron flow—at radio frequencies is much greater than the impedance offered by filter capacitor C3. As a result, C3 filters almost the entire radio-frequency component of the plate current to ground. In other words, the RF pulsations in the plate current flow onto the upper plate of C3. Each pulsation drives an equal number of electrons off the lower plate, toward ground. These directions of flow exist only on the alternate half-cycles when the grid is positive (Figs. 6-2 and 6-4).

On the alternate half-cycles when the grid voltage is negative and less plate current flows, these directions are reversed, as depicted in Figs. 6-1 and 6-3. During these half-cycles, the electrons which came out of the tube during the preceding pulsation will complete the path followed by all plate current and move downward through load resistor R2, into the power supply.

The current which flows between the lower plate of capacitor C3 and ground is thus one of the radio-frequency alternating currents. Named the "RF filtering current," it will faithfully reflect the frequency of the carrier current. Also, each of its cycles will always equal the quantity of electrons involved in the accompanying RF pulsation of plate current.

AUDIO-FREQUENCY UNIDIRECTIONAL CURRENTS

The first appearance of an audio-frequency voltage and current in this circuit is at the grid, where grid-leak detection has occurred. This is depicted by the increased number of electrons stored on the right plate of grid capacitor C2 during the modulation peak (Figs. 6-3 and 6-4). Another green line is shown flowing through the grid resistor and transformer secondary to ground and back to the cathode. This higher grid-leak voltage and its associated current are due to the increasing strength of the tank voltage as a modulation peak is approached. A close scrutiny of the grid-voltage representation in Fig. 6-5 will assist the reader in understanding the several, intricately related actions occurring with the circuit.

Fig. 6-5 graphically reveals a series of radio-frequency cycles of grid voltage. These begin small during a modulation trough, build up during the modulation peak, and then decrease again as the next modulation trough approaches. They are of course driven by the oscillating voltage in the grid tank circuit. Observe that the grid voltage cannot be raised appreciably above zero. Thus, as the grid-voltage swing increases, the grid merely becomes more negative during negative half-cycles. A solid green line represents the biasing voltage, which is built up by the grid-leak current from the tube. This changing bias voltage is indicated by the collection of electrons, in green, on the right plate of grid capacitor C2. During the first whole cycle (Figs. 6-1 and 6-2), this collection of electrons consists of one line, and two lines during the second whole cycle (Figs. 6-3 and 6-4).

The solid green line in Fig. 6-5 is not actually a smooth curve as shown. Rather, it is a series of short zigzags which are repeated once during each cycle of RF. During positive (second and fourth) half-cycles, grid-leak current will flow and tend to increase the negative bias. The solid bias line "zigs" to the left at the end of each positive half-cycle, since the higher negative voltages are to the left in this diagram.

During any negative half-cycle (represented by Figs. 6-1 and 6-3), the solid line "zigs" back to the right toward the region of lower negative voltages, indicating that the bias voltage is discharging toward zero. This discharge is shown by the green lines going from the grid-storage area (right plate of the grid capacitor), through the grid resistor and transformer secondary, to ground.

In this type of circuit, there can be a few cycles, close to each modulation trough, when the grid voltage is not driven to the zero-voltage line. Consequently, no grid-leak current can begin to flow and no electrons are added to those already stored on the grid capacitor. As a result, the bias voltage discharges continuously toward ground and zero volts during these few cycles. The normal condition is for some grid-leak current to flow on each positive half-cycle, so that the biasing voltage becomes a fair approximation of the carrier wave's modulation envelope and therefore of the audio voltage "carried" by the wave. The difference between an approximation and an exact reproduction of input waveshape is known as distortion, and this circuit is characterized by high distortion.

Fig. 6-5 is a conventional waveform diagram for this type of circuit. It was made using the transfer characteristic curve of the tube. The reader is cautioned that the radio-frequency cycles shown in blue are grid-*voltage* cycles, whereas those shown in red are plate-*current* cycles; hence, they are pulsating direct current.

Likewise, the audio cycle shown in green is an audio-*voltage* cycle representing the accumulation of grid-leak electrons on the right plate of grid capacitor C2, whereas the audio cycle shown in dotted red is a current cycle and represents the approximate average amount of plate current flowing. The latter cycle is shown in dotted red to relate it to the audio current which flows through the headphone, or load, between the right plate of capacitor C4 and the common ground.

Figs. 6-1 and 6-2 are devoted to a modulation trough. In both diagrams the audio current flows *downward* through the headphones, because of the high *average* plate current and hence the somewhat lower plate voltage. The amount of plate voltage is represented by the number of plus signs on the left plate of capacitor C4. During a modulation trough, the plate voltage has a low positive value.

The only way this voltage can be altered is by adding or withdrawing electrons. The positive voltage stored on the left plate of capacitor C4 can be thought of as a "pool" of positive ions. There is a continuous inflow of electrons into this pool from the plate current, and a continuous drain of electrons out of this pool and through R2 to the higher positive voltage of the power supply.

AUDIO-FREQUENCY ALTERNATING CURRENT

During a period of higher average plate current, electrons are added to this positive-voltage pool faster than they can be drained away through load resistor R2. Consequently, this positive voltage decreases. The normal capacitor action of C4 is such that when additional electrons flow onto the left plate, an equal number are driven off the right plate. This accounts for the downward direction of the audio current through the headphones in Figs. 6-1 and 6-2.

During a period of *lower* average plate current, the power supply (because of its high positive voltage) withdraws electrons from the positive-voltage pool, making it even more positive. Again, the normal capacitor action of C4 is such that an equal number of electrons are drawn onto the right plate of C4. This accounts for the upward direction of the audio current through the headphones in Figs. 6-3 and 6-4.

Chapter 7

DISCRIMINATOR CIRCUITS

In Chapters 4, 5, and 6, the signals to be detected were amplitude-modulated (AM). In this and the next chapter, methods of recovering the modulating signal from a frequency-modulated (FM) carrier will be discussed. Since the FM signal differs from the AM signal in the previous chapters, a brief discussion of the signals will be given before operation of the discriminator circuit is explained.

THE FM SIGNAL

Fig. 7-1 shows a series of waveforms from which it is possible to derive some essential definitions associated with frequency modulation. Figs. 7-1A and 7-1C are audio-frequency sine waves of voltage which have been used to modulate the carrier waves of Figs. 7-1B and 7-1D. Fig. 7-1A represents an audio voltage of low volume of amplitude (meaning loudness), and Fig. 7-1C, an audio voltage of high volume or amplitude. For simplicity we might assume that the audio frequency in each case is 1,000 cps. Hence, an individual audio cycle will be 1/1,000th of a second.

The frequency of the carrier wave may be anywhere in the assigned band of frequencies allocated for FM broadcasting. The latter is from 88 to 108 megacycles. This is considerably above the 550-1600–kc band assigned for amplitude-modulation broadcasting.

In the waveforms of Fig. 7-1, the carrier varies both above and below an assigned frequency called the *center frequency.* When no sound and consequently no modulation are imposed on the carrier at the transmitting end, the carrier frequency will be stabilized at its assigned center frequency. Let us assume this center frequency to be 100 megacycles.

When some audio-modulating voltage is applied to the carrier, its frequency will vary on either side of the center frequency, *but will return to the center frequency twice during each audio cycle.* This occurs as the audio voltage passes through its own reference line and has a value of zero. These are the moments when the audio voltage is changing its polarity.

The number of cycles or kilocycles by which the carrier deviates from its center frequency is called the *frequency deviation.* It is measured from the center frequency to either the highest or the lowest frequency attained by the carrier. The maximum deviation from the center frequency prescribed by regulation for commercial FM broadcasting is 75 kilocycles. Thus, a carrier with an assigned center frequency of 100 megacycles may legally vary, or "deviate," between 99.925 and 100.075 megacycles.

Sound has two distinguishing features—frequency (pitch) and volume (loudness). To be successful, any radio transmitting system must be capable of modulating the radio-frequency wave in such a manner that these two important sound characteristics of pitch and loudness are faithfully reproduced. Fig. 7-1 provides some idea of how this is done in a frequency-modulated carrier.

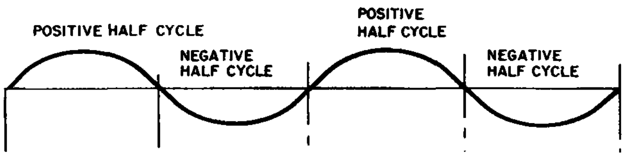
Audio Amplitude

The amount in kilocycles by which the carrier deviates from its center frequency is determined by the *amplitude* of the modulating audio voltage—in other words, by its volume, or loudness. Two successive whole audio cycles, or four half-cycles, are indicated in Fig. 7-1. At the start of each half-cycle, the audio voltage is neither positive nor negative. Rather, it is passing through zero and the carrier is at its center frequency. In the middle of the first half-cycle, the modulating audio voltage reaches a positive peak. Accordingly, the carrier frequency will have deviated to a somewhat higher frequency—perhaps 25 kilocycles above the center frequency, or 100.025 megacycles.

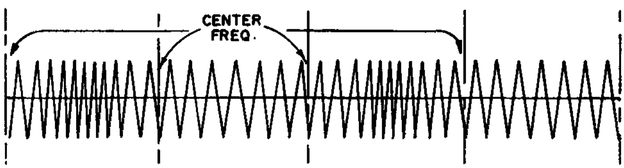
Midway in the second half-cycle, the modulating audio voltage has reached its negative peak and the carrier frequency accordingly will have deviated to a somewhat *lower* frequency. Only this time the deviation is 25 kilocycles *below* the center frequency, or 99.975 megacycles.

As stated before, Fig. 7-1A represents the waveform of an audio voltage of *low volume,* or amplitude. Fig. 7-1C represents the waveform of an audio voltage of the same frequency but with a *high volume,* or amplitude. Because of this higher volume, the frequency deviations of the carrier will be greater. Midway in the first half-cycle in Fig. 7-1C and 7-1D, the audio voltage reaches its positive peak. At this time the carrier frequency will have deviated 50 kilocycles *above* the center frequency, to a new frequency of 100.050 megacycles. Midway in the second half of the audio cycle in Figs. 7-1C and 7-1D, the modulating audio voltages reaches its negative peak. Now the carrier will have deviated the same amount of 50 kilocycles *below* the center frequency, to a new value of 99.950 megacycles.

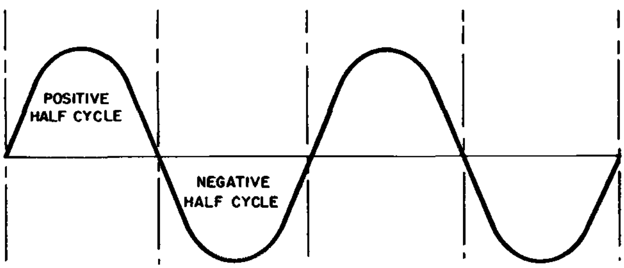
In a properly adjusted modulating system, the frequency deviation should at all times be proportionate to the amplitude of the modulating voltage. Consequently, for a frequency deviation of 50 kilocycles to be achieved as in Fig. 7-1D, *versus* the deviation



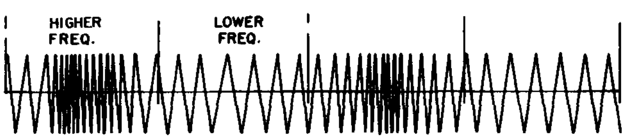
(*A*) *Low-amplitude audio-modulating voltage.*



(*B*) *Carrier resulting from modulation by A.*



(*C*) *High-amplitude audio-modulating voltage.*



(*D*) *Carrier resulting from modulation by C.*

Fig. 7-1. The relationships between the amplitude and frequency of the audio signal with the carrier.

of 25 kilocycles achieved in Fig. 7-1B, the modulating audio voltage in Fig. 7-1C would have to have twice the amplitude of the voltage in Fig. 7-1A.

Audio Frequency

The rate at which the carrier deviates in frequency between its two extremes is determined by the frequency of the modulating audio voltage. This should be fairly evident from Fig. 7-1. During the two audio cycles shown in this figure, the carrier completes two cycles of deviation. From center to maximum frequency, to center and to minimum, and back to the center frequency constitutes one complete cycle. The rate at which the carrier frequency deviates is sometimes called the *excursion* frequency, and it will always be equal to the frequency of the modulating audio voltage.

THE DETUNED DISCRIMINATOR

Figs. 7-2, and 7-4 show a fairly standard discriminator circuit used for demodulating a frequency-modulated carrier wave. Each of these figures depicts a different operating condition for the circuit. Fig. 7-2 shows significant currents and voltages when the circuit is being operated exactly at the center frequency. Fig. 7-3 shows currents and voltages when the carrier frequency has deviated *above* the center frequency, and Fig. 7-4, when the carrier frequency has deviated *below* the center frequency.

The circuit components of this type of discriminator circuit are as follows:

R1—Filter resistor for V2.
R2—Filter resistor for V3.
C1—Tank capacitor for final RF- or IF-amplifier stage.
C2—Tank capacitor for "high" deviation tank circuit.
C3—Tank capacitor for "low" deviation tank circuit.
C4—Filter capacitor for V2.
C5—Filter capacitor for V3.
L1—Tank inductor for final amplifier stage.
L2—Tank inductor for "high" deviation tank circuit.
L3—Tank inductor for "low" deviation tank circuit.
V1—Pentode RF- or IF-amplifier tube.
V2 and V3—Diode detector tubes.

Identification of Currents

Operation of this type of circuit can be understood from a discussion of the following electron currents:

1. Plate current through tube V1 (solid red).
2. Oscillating current in final amplifier tank circuit (dotted red).
3. Current through first rectifier diode, V2 (solid blue).
4. Oscillating current in upper tuned tank circuit (dotted blue).
5. Current through second diode rectifier tube, V3 (solid green).
6. Oscillating current in lower tuned tank circuit (dotted green).
7. Radio-frequency filter currents in two filter capacitors, C4 and C5 (solid blue and solid green, respectively).

Details of Operation

The three tank circuits are each tuned to different frequencies. The first circuit, consisting of L1 and C1, will be tuned exactly to the center frequency. Since frequency conversion undoubtedly has already taken place, the center frequency in the demodulation process will be much lower than the center frequency that exists during transmission and the initial reception. When the carrier initially was received, its center frequency may have been 100 megacycles and the frequency deviations due to modulation may have caused it to vary 75 kilocycles (the maximum allowable) on either side. However, after frequency conversion (called heterodyning), the new center frequency may be 10 megacycles. The same frequency deviations will have been preserved, of course. In other words, if the original carrier deviated the full 75 kilocycles—from 100 to 100.075 megacycles—the new IF carrier will also deviate 75 kilocycles, from 10 to 10.075 megacycles.

Assume that tank L1-C1 is tuned to this new center frequency of 10 megacycles. The tank consisting of inductor L2 and capacitor C2 will be tuned to a higher frequency, and the other tank (L3 and C3) will be tuned to a lower frequency. Hence, these two tank circuits are not tuned to the center frequency to which the first tank is tuned. They are said to be detuned and the circuit is named a detuned discriminator.

Discriminator Response Curve

Fig. 7-5 shows a typical frequency-response curve for the average discriminator circuit. A response curve is defined as a graphical representation of the response, or *output,* of the circuit throughout the entire range of frequencies in which the circuit operates. Fig. 7-5 has three essential parts: The response curve of the *upper*-detector circuit (blue) consists of tank L2-C2, diode V2, load resistor R1, and filter capacitor C4. The response curve

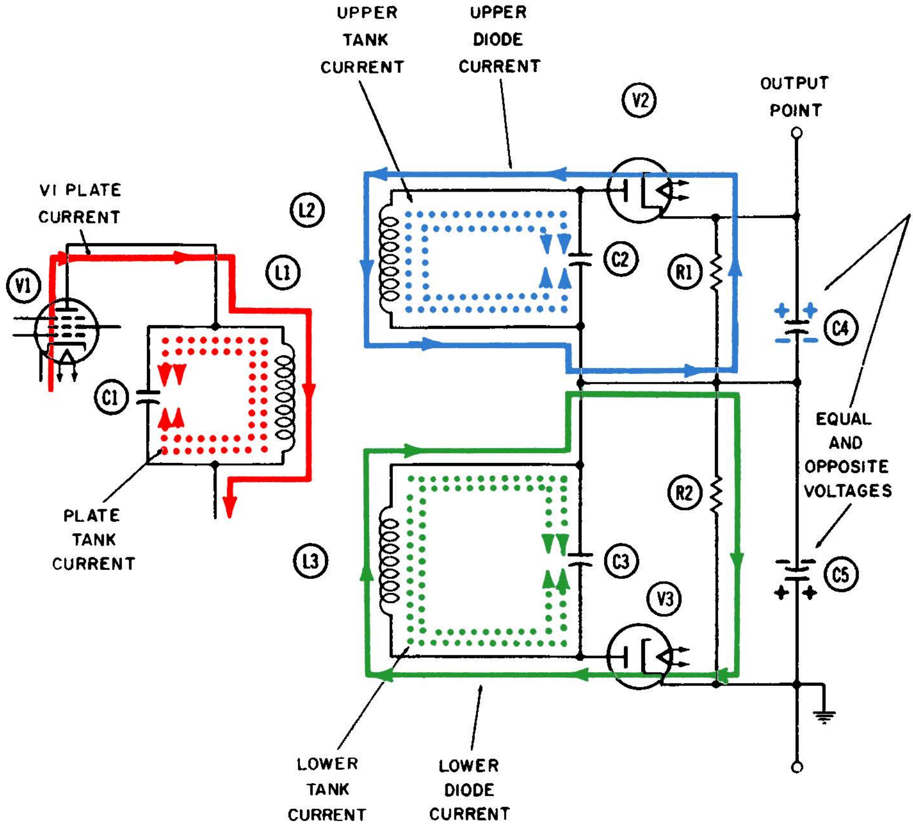


Fig. 7-2. The detuned discriminator—operation at its resonant frequency.

of the *lower*-detector circuit (green) consists of tank L3-C3, diode V3, load resistor R2, and filter capacitor C5. The response curve of the two detector circuits taken together is shown in black. It is desirable for a discriminator to be operated along the linear portion of its over-all response curve. (See Fig. 7-5.) The response curve of the whole circuit is merely an algebraic addition of the two individual response curves. On either side of the center frequency, the sum of these two curves gives a fairly straight line, as indicated. As the carrier frequency deviates farther from the center frequency, the response of one of the two diode-rectifier circuits dwindles to the vanishing point. Eventually the total response curve has almost the same shape as the response curve of the other diode.

If the linear portion of the response curve extends, say, 75 kilocycles on either side of the center frequency, the two detuned

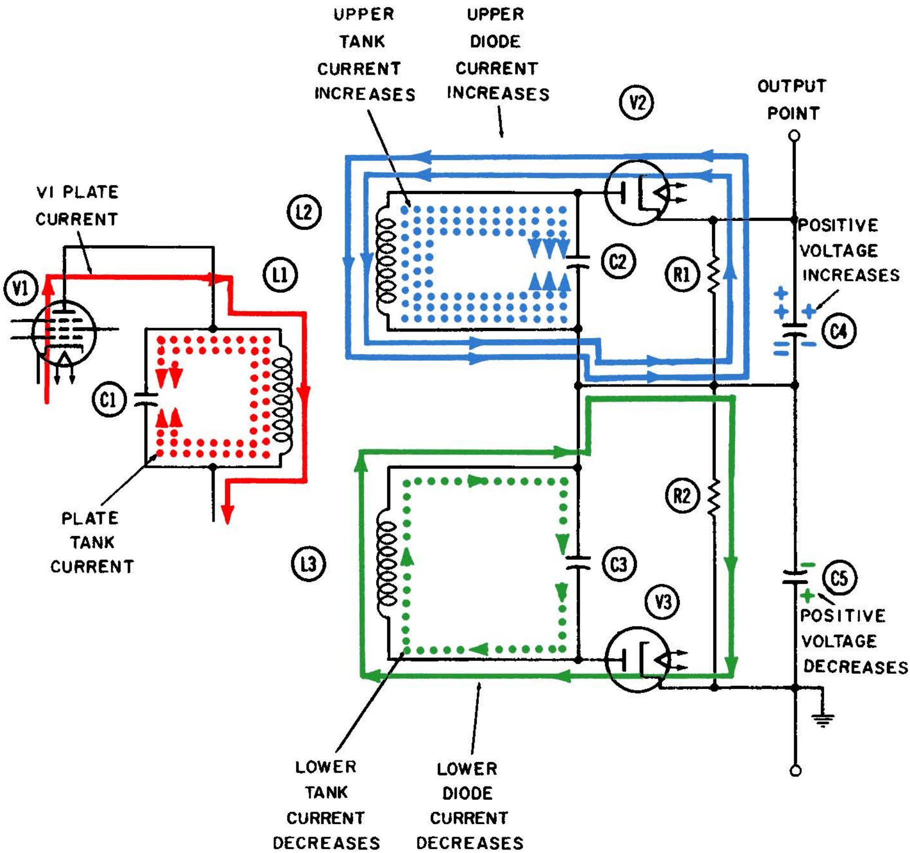


Fig. 7-3. The detuned discriminator—operation above resonance.

peaks must be resonant at frequencies *farther* removed than this amount from the center frequency. As an example, tank L2-C2 might be tuned 150 kilocycles *higher* than 10 megacycles, to a resonant frequency of 10.150 megacycles. Tank L3-C3 would then have to be tuned 150 kilocycles *lower* than the center frequency, or 9.850 megacycles.

Operation at the Center Frequency

Fig. 7-2 shows the significant currents and voltages when this discriminator circuit is being operated at the exact center frequency. The frequency at which this circuit is being operated is of course determined by the carrier frequency. When it is exactly 10 megacycles, ten *million* pulsations of plate current will pass through amplifier tube V1 each second. (This is the current shown by the solid red line.) Each such pulsation sustains one cycle of oscillation of the electrons which make up the plate-tank current (shown in dotted red).

Since both L2 and L3 act as secondary windings in their relationships with L1, the plate tank current will induce a current in each coil. This current in turn will set up and sustain electron oscillations in each of the two tank circuits, L2-C2 and L3-C3. The upper tank circuit (L2-C2) will be operating *below* its own resonant frequency, whereas the other will be operating *above* its own resonant frequency. Nevertheless, the most important result is that the oscillation in each tank is considerably weaker than if each tank were operated at resonance. Further, the two oscillations are reduced equally in strength, so that they remain equal. (This presupposes that the two diode circuits have identical designs and degrees of coupling to primary winding L1. Unfortunately, such design objectives are not easily achieved.)

Rectification

Each diode circuit operates in the manner described in the diode-detector portion of this book, the only difference being in the placement of the RC filter combination. In that chapter, the RC filter was located where it could "bias" the diode plate with a negative voltage. In this chapter, this bias is a positive voltage. In both cases the bias is the detected voltage.

In the upper-diode circuit, each positive half-cycle will drive the plate of diode V1 to a slightly more positive voltage peak than the cathode. This causes electron current (shown in solid blue) to cross from cathode to plate, downward through inductor L2, across to the junction with resistor R1, and upward through R1 to the cathode. This is not a continuous current, but an intermittent one that flows only at the peaks of positive half-cycles of tank voltage. However, the portion that flows through resistor R1 is of course a continuous current, since it is drawn upward by the electron deficiency (positive voltage) on the upper plate of capacitor C4.

The output for the upper-diode circuit is this positive voltage stored on the upper plate of C4. Under the conditions described earlier, it might have a value of +10 volts when the carrier is exactly on the center frequency. Since the output voltage for the entire circuit is measured across *both* RI *and* R2, this portion of the output voltage must be added algebraically to that portion developed independently across R2 by the current through the second diode. The latter will also equal 10 volts, but the *bottom* of R2 will be positive. Let us see why.

During the peaks of the positive half-cycles of tank voltage in the lower tank circuit, diode V3 will conduct from cathode to plate. These electrons, shown by solid green lines, then flow upward through inductor L3 to the junction with R2, and downward through R2 to the cathode. Like the current through diode V2, this current is also intermittent except through R3, where it flows continuously towards the cathode.

When we say the voltage at the cathode is a positive 10 volts, we mean of course that it is positive with respect to the voltage at the *other end* of resistor R2. Since the cathode of V2 has been grounded in this particular circuit, the voltage at the top of R2 must be −10 volts. The voltage at the cathode of the upper diode is +10 volts with respect to this voltage at the junction of the two resistors, by virtue of the upper-diode current. Hence, the voltage at the cathode of V2, as at the cathode of V3, will have a true value of zero.

Since the voltages at the two diode cathodes both equal zero, the difference between them—which is also the output voltage for the entire circuit—is zero. This is as it should be, and can be confirmed by referring to Fig. 7-1. At those two moments in each cycle when the audio-modulating voltage was passing through the reference line and therefore was equal to zero, the carrier was exactly equal to the center frequency.

Operation Above the Center Frequency

Fig. 7-3 shows significant currents and voltages when the carrier is higher than the center frequency. Now tuned circuit L2-C2 will be operating more nearly at its own resonant frequency. In accordance with the selectivity or response curve of Fig. 7-5, a stronger oscillation of electrons will be built up in the tank, as indicated by the three dotted-blue lines. Each positive voltage peak which is applied to the plate of diode V2 will be proportionately higher, and more current will flow through the diode. This increases the electron deficiency (positive voltage) on the upper plate of capacitor C4, and of course the amount of current flowing upward through R1. The amount of voltage stored in the capacitor is always the same as developed across the resistor.

Since tuned circuit L3-C3 is tuned *lower* than the center frequency, in Fig. 7-3 this circuit will be operating even farther from its resonant frequency than in Fig. 7-2. Its response curve from Fig. 7-5 indicates that a comparatively weak oscillation of electrons (indicated by the single dotted-green line) will be in motion in the tank. Consequently, diode V3 will conduct fewer electrons than before. Less current will flow through resistor R2, and less voltage will be developed across it.

Since the output voltage of the entire circuit is the algebraic sum of the two separate voltages across R1 and R2, it is obvious

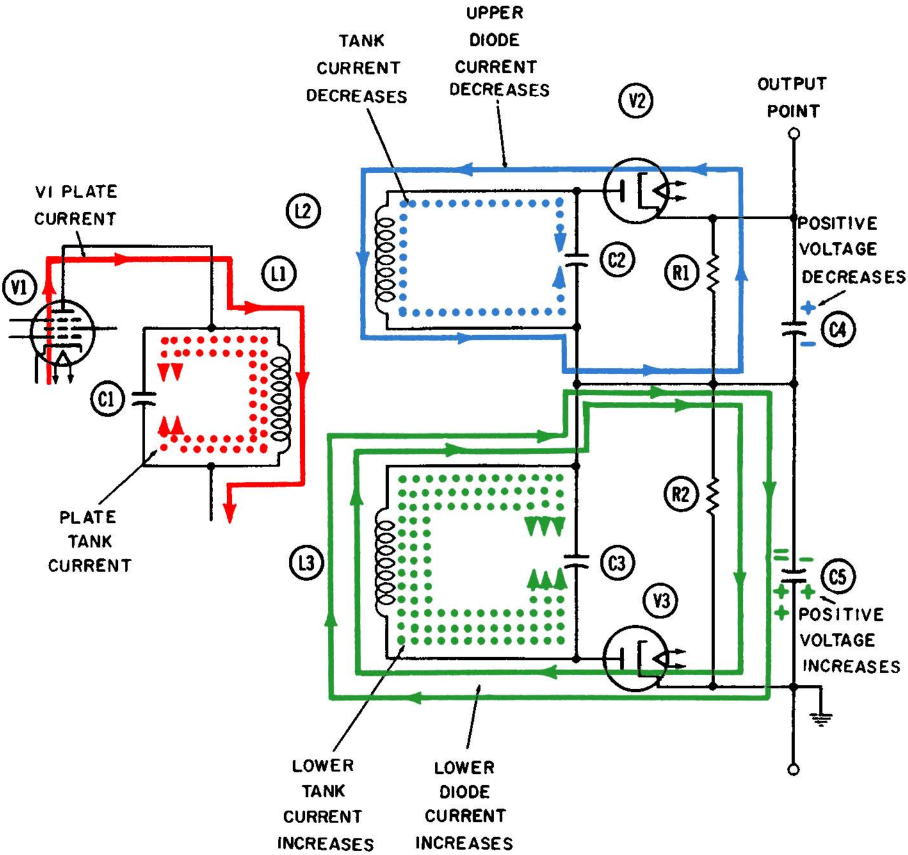


Fig. 7-4. The detuned discriminator—operation below resonance.

that when the circuit is operated above the center frequency, the output voltage at the top of resistor R1 will be positive. The *amount* of this voltage depends on the amounts of conduction in each diode tube. In turn, these amounts depend on the strength of each electron oscillation in the two tuned tanks, L2-C2 and L3-C3. As the operating frequency moves higher and higher toward the resonant frequency of tank L2-C2, the amount of voltage developed across R1 increases steadily, whereas the amount across R2 *decreases*. Consequently, the sum of these two voltages —which is the output of the circuit—is a positive voltage which *increases* as the carrier frequency does. From Fig. 7-1 we deduce that a positive voltage output is associated with a positive peak in the modulating audio voltage. Also, we see that the output-voltage peak is directly proportionate in size to the modulating audio voltage.

Operation Below the Center Frequency

Fig. 7-4 shows the important currents and voltages in this circuit when the carrier is below the center frequency. Tuned circuit L3-C3 will now be operating more nearly at its resonant frequency. The oscillation of electrons in that tank becomes stronger, and more current flows through diode V3 and resistor R2. This results in a much greater voltage drop across R2.

At the same time, the oscillation in upper tank L2-C2 will be drastically weakened because it will be operating far from its resonant frequency. The response curve of Fig. 7-5 which applies to this tank indicates a very low response. So only a small current will flow upward through R1 and develop only a small voltage across this resistor. This voltage will be positive at the top of R1.

The output is the sum of the two voltages across R1 and R2. The junction of these two resistors is at a fairly large negative voltage with respect to ground, by virtue of the larger current flowing through R2. Thus the total output voltage, measured at the top of R1, will also be negative. Again this is consistent with Fig. 7-1, which indicates that a negative audio peak voltage is associated with a lower operating frequency. It is also consistent with Fig. 7-5, which illustrates that a lower operating frequency leads to negative output voltages.

Summary

From the foregoing discussion it is evident that the output voltage varies from positive to negative at an audio rate which de-

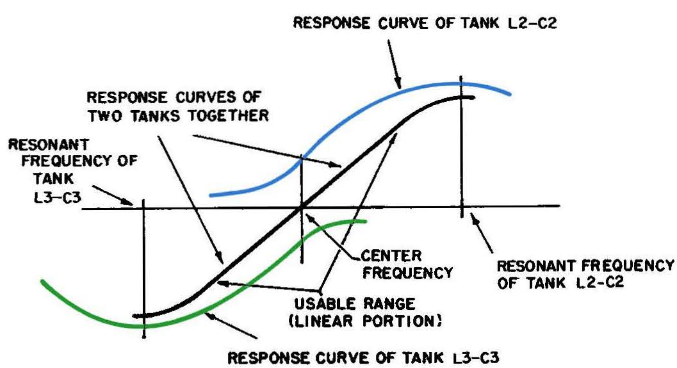


Fig. 7-5. Response curve of the detuned discriminator.

pends on the excursion frequency of the carrier. The latter is of course the same as the frequency of the modulating audio voltage. Thus the audio frequency has been reproduced by this type of demodulation.

The *amplitude* of the audio-output voltage depends on how greatly the carrier deviates from the center frequency. A deviation toward a higher frequency causes a *positive* voltage at the output point, and a deviation toward the lower frequencies causes a *negative* voltage. In either case the size of the deviation determines the size of the output voltage. Since the amount of frequency deviation is controlled by the amplitude of the modulating audio voltage within the transmitter, this discriminator circuit can accurately reproduce the intended audio amplitude as well as frequency.

TUNED DISCRIMINATOR

Figs. 7-6, 7-7, 7-8, and 7-9 represent four quarter-cycles in the operation of a tuned discriminator circuit at the center frequency. As with the detuned discriminator discussed previously, the function of this circuit is to demodulate a frequency-modulated signal. Unlike the detuned discriminator, however, two tuned circuits are used instead of three, and the primary and secondary tuned circuits are coupled inductively *and* capacitively. (The significance of this dual coupling will be discussed later.) The operation of this circuit is somewhat more difficult to visualize than it is for the detuned discriminator.

Identification of Components

The tuned discriminator includes the following necessary circuit components:

R1—Cathode biasing resistor for V1.
R2—Output resistor for V2.
R3—Output resistor for V3.
C1—Primary tank tuning capacitor.
C2—Coupling capacitor between two tank circuits.
C3—Secondary tank tuning capacitor.
C4—Filter capacitor for V2.
C5—Filter capacitor for V3.
L1—Primary tank inductor.
L2—Secondary tank inductor.
V1—Final IF amplifier tube, usually a pentode.
V2—Upper-diode detector tube.
V3—Lower-diode detector tube.

Identification of Currents

The following electron currents are at work in this circuit:

1. Plate tank current (solid red).
2. External current driven by plate tank current (dotted red).
3. Secondary tank current (dotted blue).
4. Upper-diode current (solid blue).
5. Lower-diode current (green).

Details of Operation

To understand the operation of this circuit, it is necessary to review its operation on a single-cycle basis at the center frequency, and also above this frequency. Figs. 7-6 through 7-9 show the four successive quarter-cycles of operation at the center frequency, and Fig. 7-10 the significant voltage waveforms during a single cycle.

Operation at the Center Frequency

It is not readily apparent from the circuit diagrams, but inductors L1 and L2 are two halves of a radio-frequency transformer. Hence, any change in the amount of current flowing through L1 will *induce* a voltage and a companion current in secondary winding L2. Also, any changes in the voltage at the top of the primary tank circuit simultaneously will be coupled—via capacitor C2—to both sides of the secondary tank and to both detector diodes.

It is a well-established fact that when two tuned circuits are operated exactly at resonance, the two tank voltages will be exactly 90°, or a quarter of a cycle, out of phase. Usually the secondary tank voltage is said to lag the primary tank voltage by a quarter of a cycle—meaning the voltage at the top of the secondary tank circuit will reach its positive peak a quarter of a cycle *after* the voltage at the top of the primary tank reaches *its* positive peak.

The resonant frequency of these tank circuits is the center frequency. In the amplifier volume of this series, the chapter on radio-frequency amplifiers contains a detailed discussion of tuned circuits and their operation in the vicinity of their resonant frequency. The entire discussion will not be repeated here; any readers wishing to learn more about tuned circuits are referred to this volume.

Looking at Fig. 7-10 in conjunction with the four quarter-cycle diagrams, you will see that the voltage across primary tank circuit L1-C1 is positive during the first two quarter-cycles, reaching its peak at the end of the first quarter-cycle. During the last two

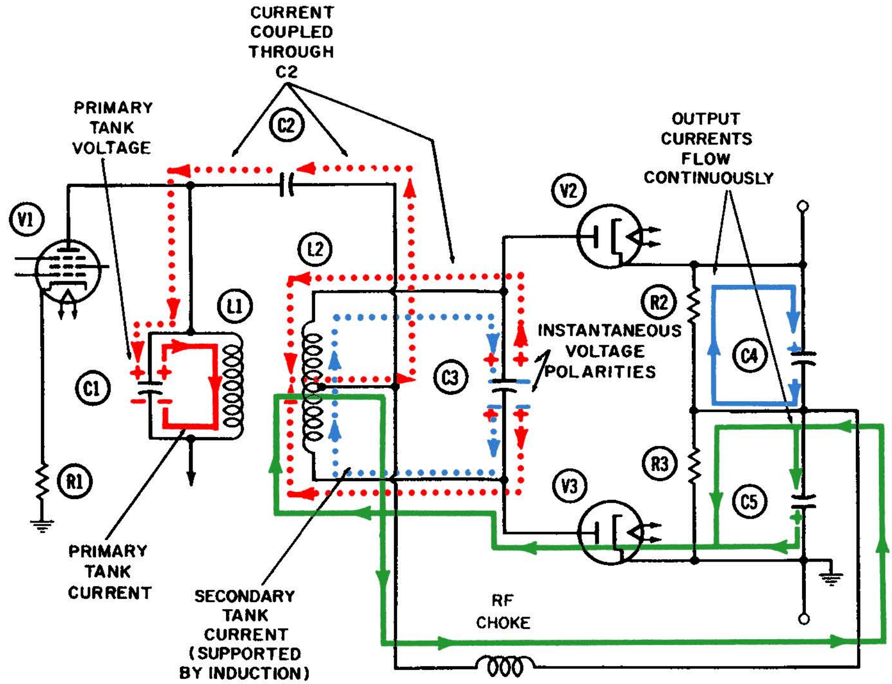


Fig. 7-6. Operation of the tuned discriminator at the center frequency—first quarter-cycle.

quarter-cycles, the tank voltage is negative, reaching its peak at the end of the third quarter-cycle. This oscillatory voltage across the primary tank is accompanied by an oscillatory current (red) *through* it. During the first quarter-cycle (Fig. 7-6), this current flows downward through coil L1 and delivers electrons to the lower plate of tank capacitor C1, leading to a negative peak voltage on the lower plate and a positive one on the upper plate.

During the second quarter-cycle (Fig. 7-7), this tank current reverses and flows upward through the coil. The charge (electrons) stored in the capacitor is redistributed, taking a half-cycle to do so, and the tank voltage reverses polarity. The voltage at the top of the primary tank reaches its negative peak at the end of the third quarter-cycle (Fig. 7-7).

The purpose of capacitor C2 is to couple this tank voltage directly to both sides of the secondary tank circuit. This is accomplished by connecting C2 to a center tap on coil L2. The resultant current flow, shown in dotted red lines, flows to the left during the first two quarter-cycles and to the right during the last two.

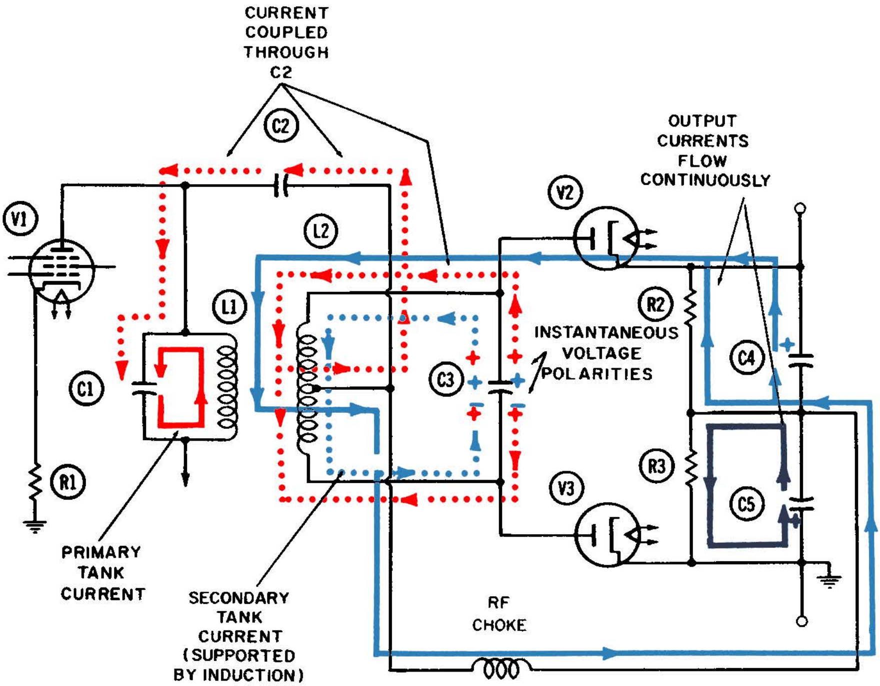


Fig. 7-7. Operation of the tuned discriminator at the center frequency—second quarter-cycle.

Called an "external" current to the oscillation in the primary tank, it constitutes a load on the primary tank oscillation and, like any other loss or load current, should be kept as small as possible.

This current provides the necessary function of *simultaneously* transferring the polarity of the voltage at the top of the primary tank to *both* sides of the secondary tank. This positive polarity—indicated by the red plus signs on both plates of capacitor C3 during the first two quarter-cycles—results from the fact that the external current from the primary tank is drawing electrons away from both sides of the secondary tank. These electrons, which make up the external current, will continue to be drawn *toward* the primary tank during the first two quarter-cycles as long as the voltage across the primary tank is positive. During the third and fourth quarter-cycles, the tank voltage across the primary tank circuit has a negative polarity at the top and these electrons will be repelled. This accounts for the red minus signs on both sides of capacitor C3 in Figs. 7-8 and 7-9.

A primary function of coupling capacitor C2 is to isolate—or "block"—the high positive voltage of the power supply connected to the bottom of L1 and C1 from the plates of the two diode detectors. This coupling function can always be performed better by a piece of straight wire than by a capacitor. It should be understood that neither side of the primary tank ever reaches a true negative voltage; instead, the voltage varies between a low and a high positive value. Thus, on alternate half-cycles, each plate of capacitor C1 is shown as being negative, but actually it is negative only *with respect to the other plate.*

The oscillating voltage in the secondary tank circuit is supported by induction between L1 and L2. These two coils are in reality two windings of a radio-frequency transformer. Fig. 7-10 indicates that this oscillation of electrons leads to a peak of positive voltage on the upper plate of capacitor C3, and to a peak of negative voltage on the lower plate, at the end of the second quarter-cycle.

To determine the total voltage applied to the plate of the upper diode at any moment, it is necessary to add the amplitudes of the two separate voltages at that point. Since the amplitudes are represented by the waveforms labeled A and B in Fig. 7-10, the sum of the two can be represented by waveform E. Observe that the positive peak of this voltage sine wave occurs *midway* in the second quarter-cycle—after the peak of coupled voltage but before the peak of oscillatory voltage. This is the moment when upper diode V2 will conduct the most electrons. This diode current (solid blue in Fig. 7-7) flows from cathode to plate within the tube, downward through coil L2 to the center tap, and back through the RF choke to the bottom of resistor R2. From here it flows upward through R2 and returns to the cathode. This current causes a positive voltage at the top of R2, and also on the upper plate of capacitor C4. This positive voltage becomes a portion of the discriminator output voltage. The balance of the output voltage is developed across resistor R3 by the other diode current.

The sine wave (labeled waveform C in Fig. 7-10) represents the amplitude of the oscillatory voltage at the *bottom* of tuned secondary tank L2-C3. Obviously, this voltage should always be a half-cycle out of phase with the oscillatory voltage at the top of the tank. From waveform C we can observe that the oscillatory voltage at the bottom of the tank reaches its positive peak at the start of the first quarter-cycle.

The *total* voltage at the bottom of the tank is found by adding waveforms A and C together, giving the waveform labeled E in Fig. 7-10. This voltage reaches its positive peak midway in the first quarter-cycle—after the oscillatory tank-voltage peak but before the voltage peak due to the capacitive coupling from the primary tank circuit. This is the moment when maximum conduction occurs through lower diode V3. The complete path of these electrons is indicated (in green) in Fig. 7-6 only, since this is probably the only quarter-cycle in which the lower diode conducts at all. The complete path takes the electrons from cathode to plate within the tube, upward through the lower half of coil L2 to the center tap and out, through the common return line to the upper end of R3, then downward through this resistor and back to the cathode. This current flow develops a voltage across R3 which then becomes part of the output voltage. Since the lower end of R3 is connected to ground, the upper end must be more *negative*. The downward flow of electrons toward the more positive lower end verifies this statement.

The detector output voltage is the algebraic sum of the voltages across output resistors R2 and R3. When the discriminator circuit is operated exactly at resonance—which is the center frequency—these two voltages will be equal in value but opposite in sign, so their sum will be zero. Recall that Fig. 7-1 related the modulating audio-voltage waveform to the carrier-frequency waveform. Here you can see that when the modulating audio voltage is crossing its own reference line and is therefore zero, the carrier will be exactly on its center frequency. Thus, when the modulating audio voltage is zero, so is the demodulated (detected) output voltage.

The Filtering Actions

C4 and C5 act as conventional filter capacitors, in conjunction with output resistors R2 and R3, respectively. When upper diode V2 conducts during the second quarter-cycle, it draws electrons from the upper plate of capacitor C4, making this plate positive (electron deficiency). This positive voltage, which persists throughout the entire cycle, accounts for the continuous upward flow of electron current through R2.

By somewhat analogous reasoning, we can show that the upper plate of C5 assumes a negative voltage by virtue of the electrons delivered there during the first quarter-cycle. The negative voltage on the upper plate of C5 will drive electrons downward through resistor R3 during the entire cycle, as depicted in each quarter-cycle diagram.

The fact that the two resultant voltage waveforms of Fig. 7-10 are exactly 90°, or a quarter of a cycle, apart stems directly from the original assumption that the oscillating tank voltage (shown in dotted blue) and the capacitively coupled voltage (shown in dotted red) are equal in amplitude. Otherwise, the phase of the resultant voltages would be shifted. As a result, both peaks of

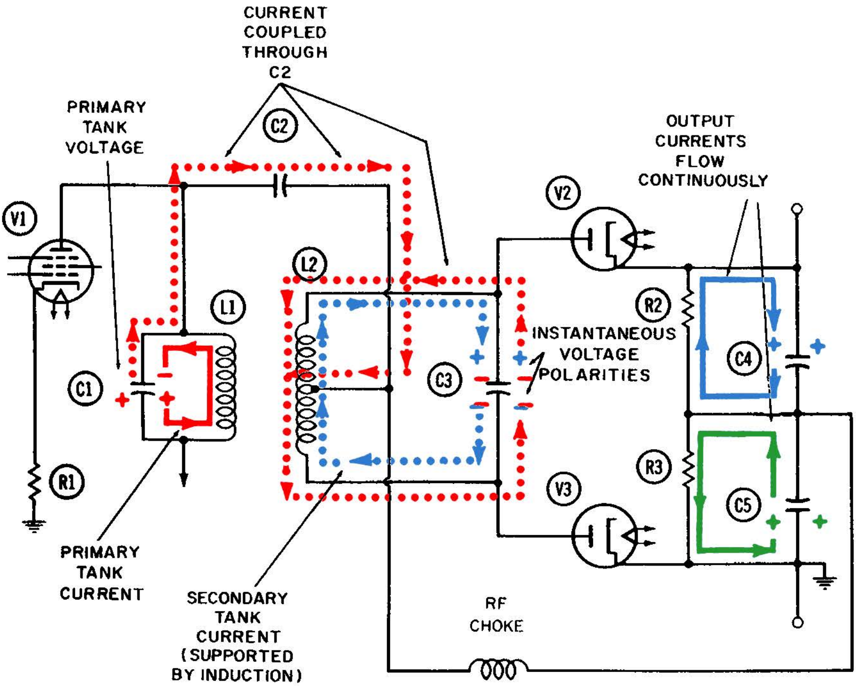


Fig. 7-8. Operation of the tuned discriminator at the center frequency—third quarter-cycle.

positive voltage (waveforms D and E of Fig. 7-10) would shift in phase and occur closer in time to the positive peak voltage of the *larger* driving voltage.

As an extreme example, imagine the inductive coupling between coils L1 and L2 were reduced until the oscillation of electrons in the secondary tank (the current shown in dotted blue) could barely be sustained and almost vanished. The amplitude of waveforms B and C of Fig. 7-10 would progressively diminish, too. Should oscillation cease, these two waveforms would be straight horizontal lines coinciding with the reference line. The sum voltage waveform A and each line would give a waveform equal in size and phase to voltage waveform A. Obviously, then, the two diodes would conduct at the same instant. This would occur at the end of the first quarter-cycle, when the primary tank voltage (represented by waveform A) had reached its positive peak.

As another extreme example, consider what would happen if the voltage coupled from the primary to the secondary tank via

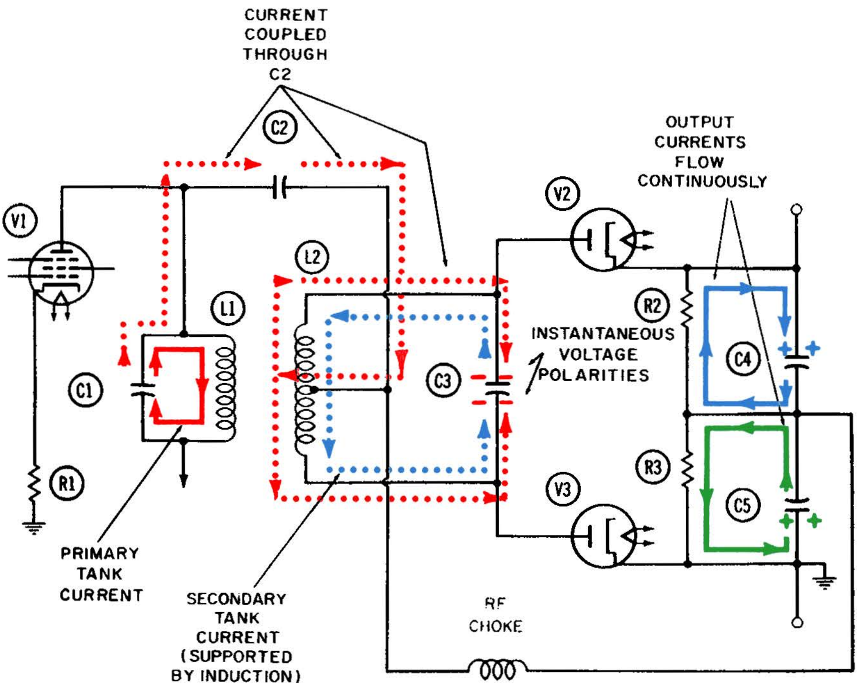


Fig. 7-9. Operation of the tuned discriminator at the center frequency—fourth quarter-cycle.

capacitor C2 were reduced almost to the vanishing point. Voltage waveform A would decrease in amplitude and, if *no* voltage were coupled across C2, would become a straight line coinciding with the reference line. Obviously, if this hypothetical waveform A were added to C, the resultant waveform would be in phase with C and also have the same amplitude. The upper diode would then have maximum conduction at the end of the second quarter-cycle.

By the same token, the algebraic sum of waveform B and a waveform of zero amplitude (a straight line) will give a waveform which is in phase with waveform B and has the same size. The lower diode will thus have its maximum conduction at the end of the fourth quarter-cycle.

Operation Above the Center Frequency

Figs. 7-11 and 7-12 show two successive half-cycles in the operation of the tuned discriminator. Here the operating frequency is *higher* than the center frequency. From Fig. 7-1 we see that the carrier frequency is modulated by the audio voltage, so that frequencies higher than the center frequency represent positive peaks of audio voltage and lower frequencies represent negative troughs.

The voltage polarities applied to the two diode plates are indicated by red and blue plus and minus signs on both plates of tank capacitor C3. The blue signs represent the voltage polarity resulting from the oscillating tank current. Observe that during the first half-cycle of Fig. 7-11, this voltage makes the upper plate of C3 positive and the lower plate negative. But something else occurs during this same half-cycle—*both* plates are made negative by virtue of being coupled capacitively to the voltage at the top of the primary tank. The coupling current, shown in dotted red lines, alternately delivers electrons to both sides of the secondary tank during the first half-cycle, making both sides of the tank negative. During the second half-cycle, it then withdraws electrons and both sides are made positive.

As a result of these two voltages acting independently on the secondary tank circuit, neither diode can conduct electrons during the first half-cycle. The reason is that the lower-diode plate is

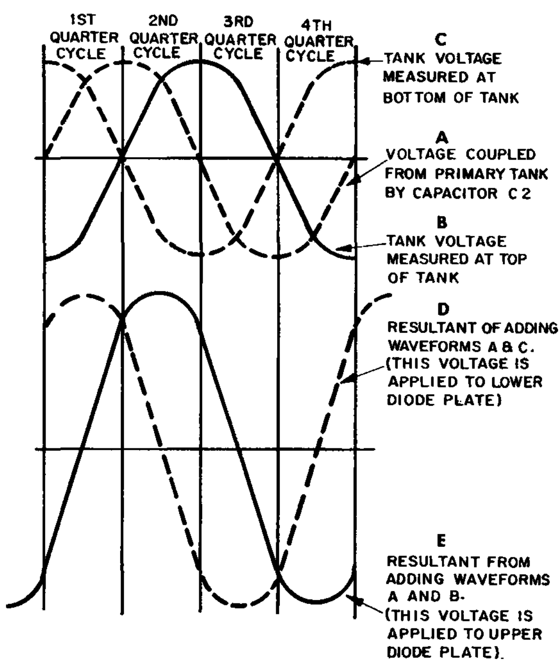


Fig. 7-10. Waveforms in the tuned discriminator circuit when operated at the resonant frequency.

at a high negative voltage, while the upper-diode plate remains at a neutral voltage. (In essence, the positive and negative components cancel each other at the upper-diode plate.) The lower diode conducts electrons during the second half-cycle because both applied voltages are positive. The upper-diode plate is again at a neutral voltage, and the positive and negative applied voltages cancel each other as before. Thus we have a means of assuring that the lower diode will conduct more electrons than the upper diode when the circuit is operated above the center frequency. This fact has a direct bearing on the voltages developed across output resistors R2 and R3—and on the sum of these two voltages, which is the discriminator output voltage.

Under the conditions shown in Figs. 7-11 and 7-12 (the upper diode not conducting), no current will flow through resistor R2 and no voltage will be developed across it. Consequently, the total output voltage across both resistors will equal the voltage drop across R3 resulting from the lower diode current flowing through it. Therefore the output voltage, measured at the top of the resistor combination, will be negative.

The results indicated by this discussion would appear to conflict with the classical response curve of an FM detector in Fig. 7-5. As shown, the voltage is positive above the center frequency and negative below it. This discrepancy is not of great significance. It stems from the assumptions made at the outset, and in particular from the manner in which these assumptions were defined and interpreted. It is accepted, for instance, that when two tank circuits are inductively coupled together and operated at resonance, their oscillatory voltages will be a quarter of a cycle out of phase with each other. However, *it was an act of interpretation* to assume that the points for measuring and comparing these two voltages would be the tops of the two tank circuits, as they are drawn in the various circuit diagrams in this chapter, beginning with Fig. 7-6.

Depending on the manner in which a particular transformer is wound or is connected into the circuit, we might just as naturally be comparing the voltage at the bottom of the secondary tank with the voltage at the top of the primary. If this were done, the output voltage of this tuned discriminator would then be consistent with the classical response curve of Fig. 7-5.

Actually, the human ear cannot differentiate between the negative and positive half-cycles, so it makes no difference whether they are reproduced in accordance with the original modulating signal or not. Also, each stage of amplification following the detector will shift the phase of the signal 180°. Therefore, if it is desired to have the same polarity as the original modulating signal

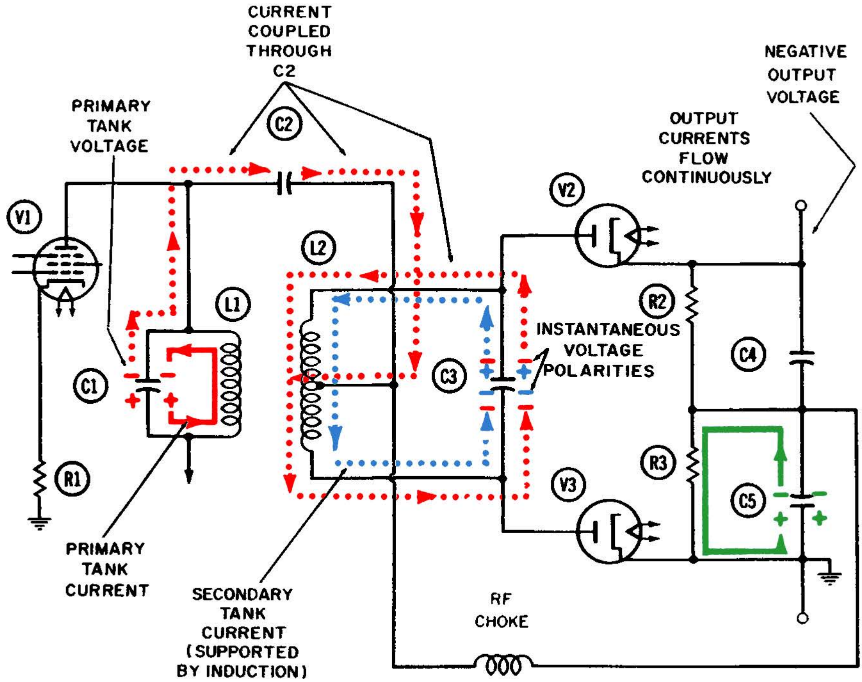


Fig. 7-11. Operation of the tuned discriminator above the center frequency —first half-cycle.

at the output, all that is required is to use an odd number of amplifying stages following the detector.

Simplifying Assumptions

The example in Figs. 7-11 and 7-12 is a special case in which two assumptions have been made to simplify the discussion. These assumptions are that (1) the two voltages applied to the diodes are equal in amplitude or strength, and (2) although exactly in phase on one side of the secondary tank, the two voltages are exactly out of phase on the other side. Fig. 7-13 shows this phase relationship.

Waveform C represents the amplitude of the oscillatory tank voltage *at the lower side* of the tank, and waveform A, the amplitude of the voltage coupled to the tank by capacitor C2. These two waveforms are essentially equal in amplitude and phase, and their algebraic sum is the waveform shown at E. (Note that it has twice the amplitude of either applied voltage.) This voltage is applied to the plate of lower diode V3 during the second half-

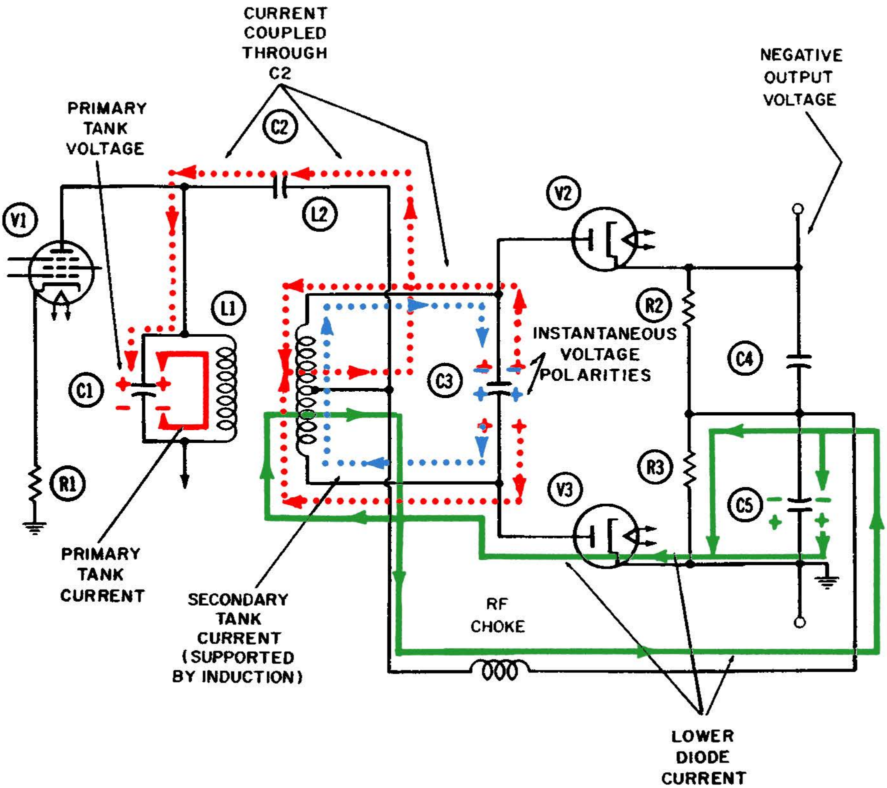


Fig. 7-12. Operation of the tuned discriminator above the center frequency —second half-cycle.

cycle. As a result, the plate is made positive and is able to conduct electrons.

Waveform B of Fig. 7-13 represents the amplitude at any instant when the oscillatory tank voltage is measured at the upper side of the tank. This waveform is assumed to be essentially equal in amplitude to voltage waveform A but 180° (half a cycle) out of phase with it. The algebraic sum of these two waveforms is a sine wave of extremely low amplitude (waveform E). If the two applied voltages were *exactly* equal in amplitude, waveform E would have zero amplitude and thus be a straight line. This sine wave of voltage is applied to the upper-diode plate and prevents this plate from becoming sufficiently positive that the tube will conduct.

There is only one occasion when two inductively coupled tuned circuits like these will have two tank voltages with the precise phase relationship shown. This is when the two coils are slightly overcoupled and when the operating frequency has *one particular value* which is somewhat higher than the true resonant frequency to which the circuits are tuned. What this operating frequency is depends both on the degree of coupling between coils and on the respective circuit Q's.

The response curve for overcoupled circuits indicates that new resonant peaks occur at two particular frequencies, one above resonance and one below. It is precisely at these two new frequencies that the two tank voltages are either 180° out of phase, or exactly in phase, with each other.

Figs. 7-11, 7-12, and 7-13 apply to operation at the *one and only frequency above resonance* at which the two tank voltages are exactly 180° out of phase.

In these examples, the terms "in phase" and "out of phase" mean the phase relationships of the two tank voltages are being compared *as measured at the tops of the two tanks.* In considering the phase of a tank voltage—particularly at each end of a tank—it is always desirable to clarify which voltage is under discussion, since the ones at the top and bottom of any oscillating tank are themselves 180° out of phase with each other.

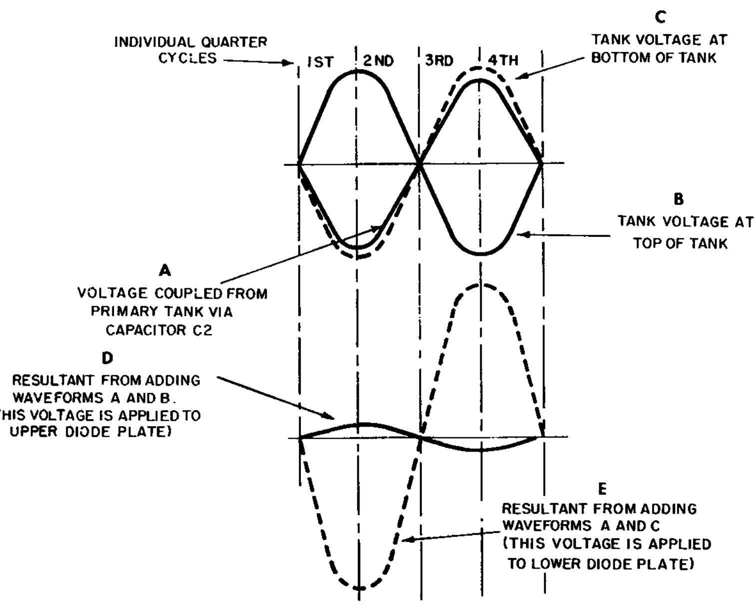


Fig. 7-13. Waveforms in the tuned discriminator circuit when operated above the center frequency.

Operation Below the Center Frequency

Figs. 7-14 and 7-15 show two successive half-cycles in the operation of the tuned discriminator, when the operating frequency is below the center frequency. The same simplifying assumptions have been made as in the previous example. The two tank voltages are now assumed to be exactly in phase, with their positive voltage peaks (measured at the tops of the tanks) occurring at the same instant. This is portrayed in Fig. 7-16, where voltage waveforms A and B are in phase with each other and have essentially the same amplitude. Their algebraic sum is shown by waveform D, which reaches its positive peak during the middle of the first half-cycle. This is the moment when the most electrons are conducted through upper diode V2. Fig. 7-14 shows this tube current in solid blue. It follows the expected path from cathode to plate within the tube, then downward through the upper half of winding L2 to the center tap. Here it exits from the coil and returns, via the external line, to the junction of output resistors R2 and R3. This upward flow signifies that the voltage is more positive at the top of R2 than at the bottom.

This positive voltage (indicated in Fig. 7-14 by the blue plus sign on the upper plate of capacitor C3) is preserved throughout the half-cycle of Fig. 7-15, when diode V2 has a negative plate voltage and does not conduct electrons. Fig. 7-15 shows this positive capacitor voltage continuing to draw electron current upward through resistor R2 in an attempt to discharge itself to zero volts.

Waveform C of Fig. 7-16 represents the oscillatory tank voltage as measured at the bottom of the secondary tank circuit. Since it is exactly out of phase with waveform A and essentially of equal amplitude, the algebraic sum of the two is of very low amplitude, as shown by waveform E. In the hypothetical example where the two applied voltages have the same amplitude, their resultant will be a straight line coinciding with the reference line.

Since waveform D achieves no significant amplitude, the plate of diode V3 has a very low positive voltage applied to it during the second half-cycle. Hence, no appreciable current flows through it during the entire cycle. Thus, the output voltage of the discriminator is made up entirely of the negative voltage developed across resistor R2 by virtue of the electron current flowing through upper diode V2.

The examples used here—where upper diode V2 does not conduct when operating *above* the center frequency, and the lower diode does not conduct when operating *below* the center frequency—are extreme cases which might not be desirable or even realized in practice. Nevertheless, the output voltage achieved

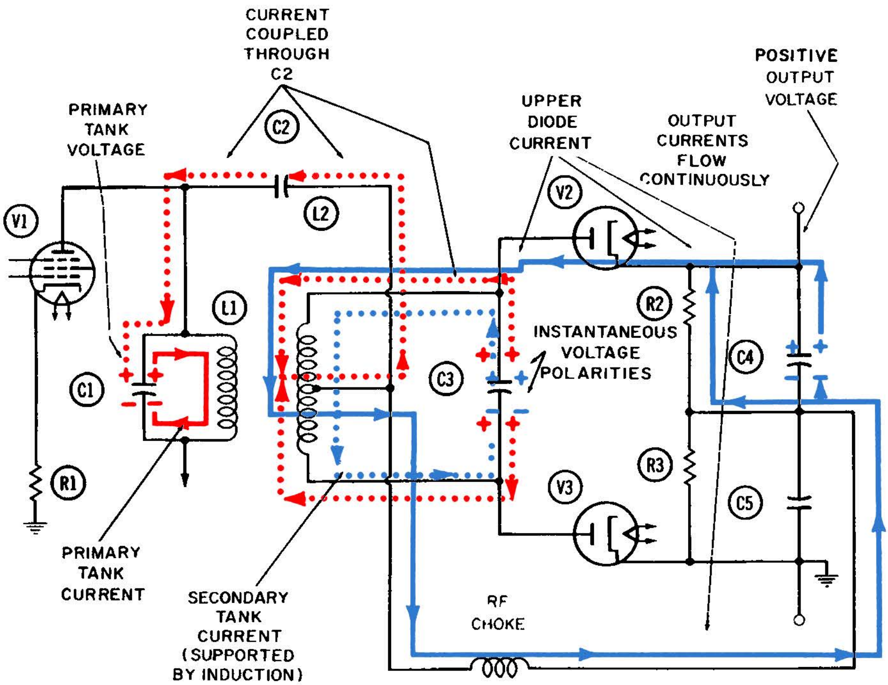


Fig. 7-14. Operation of the tuned discriminator below the center frequency —first half-cycle.

across the two output resistors, when the upper diode does not conduct, would clearly be the maximum attainable negative voltage. Likewise, the output voltage achieved when the lower diode does not conduct would clearly be the maximum attainable positive voltage. The resultant audio voltage, as the output varies between these two positive and negative peaks, would have the maximum amplitude attainable and would correspond to the waveform in Fig. 7-1C.

Audio voltages of lower amplitude, corresponding to the waveform of Fig. 7-1A, would be achieved with smaller deviations of the carrier from the center frequency. In all such cases, the operating conditions shown in Figs. 7-11, 7-12, 7-14, and 7-15 would be modified. The 180° phase relationships between the two applied voltages would of course not exist, and each diode would conduct *some* electrons above and below the center frequency.

Referring to Fig. 7-10, note that the phase relationships between the two applied voltages represent the normal condition when no modulation exists. Consequently the carrier does not

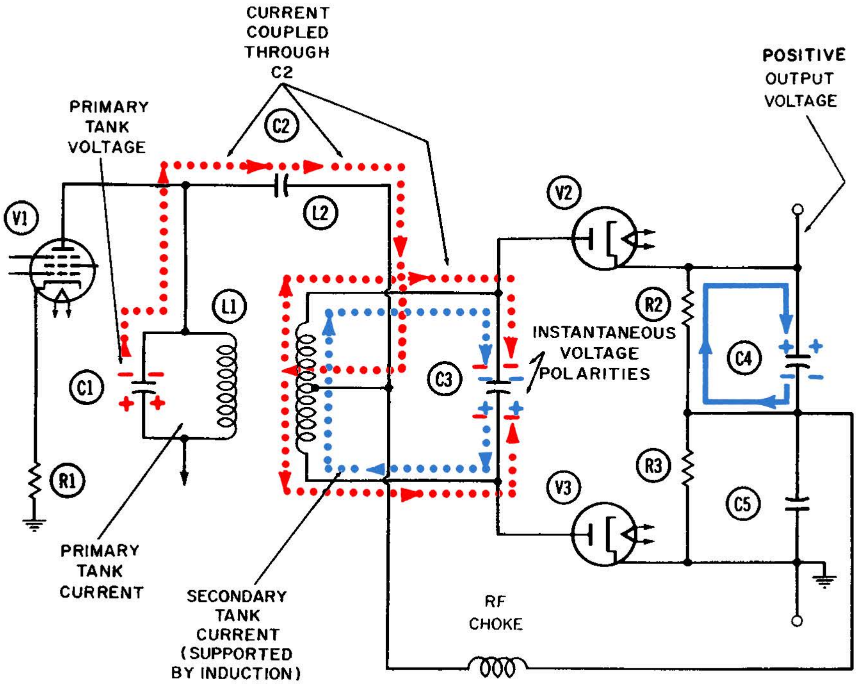


Fig. 7-15. Operation of the tuned discriminator below the center frequency —second half-cycle.

deviate from the center frequency. When two tuned tank circuits are inductively coupled and are operating exactly at resonance, their tank voltages will be 90° out of phase with each other.

When applied to the carrier frequency at the transmitter, an audio voltage of small amplitude causes the carrier frequency to deviate slightly in both directions. At the positive audio peak it goes above the center frequency, and at the negative audio trough it goes below. Any variation from this resonant, or center, frequency destroys the precise 90° phase relationship between the two tank voltages. Inevitably, voltage waveform A is moved closer to waveform C (when above the center frequency) and farther from waveform B.

Under these conditions waveform D would increase slightly in amplitude, causing a slightly greater current flow through the lower diode than existed at the center frequency. At the same time, waveform E would *decrease* slightly in amplitude, and fewer electrons would flow through the upper diode. At this instant, the output voltage has a small negative value.

When the carrier deviated slightly below the center frequency, an opposite set of conditions prevails. Waveforms A and B move closer together in phase. The amplitude of their resultant (waveform E) increases slightly and a few more electrons flow through upper diode V2. Waveforms A and C move farther apart in phase. Their resultant (waveform D) decreases slightly in amplitude, and not as many electrons flow through lower diode V3. At this instant, the detector output voltage will have a small positive value.

For greater frequency deviations, the detector output voltage will increase. Since it goes from positive to negative whenever the carrier frequency goes from below to above resonance, the *frequency* of the modulating audio voltage as well as its *amplitude* will be accurately reproduced.

The key to the operation of this type of circuit is to understand the phase relationships between two tuned radio-frequency circuits which are inductively coupled together and are operated near their resonant frequency. The significant fact is that under these conditions the tank voltages of two circuits will be exactly one-quarter cycle out of phase at resonance. As the frequency increases above resonance, this phase difference will increase to a

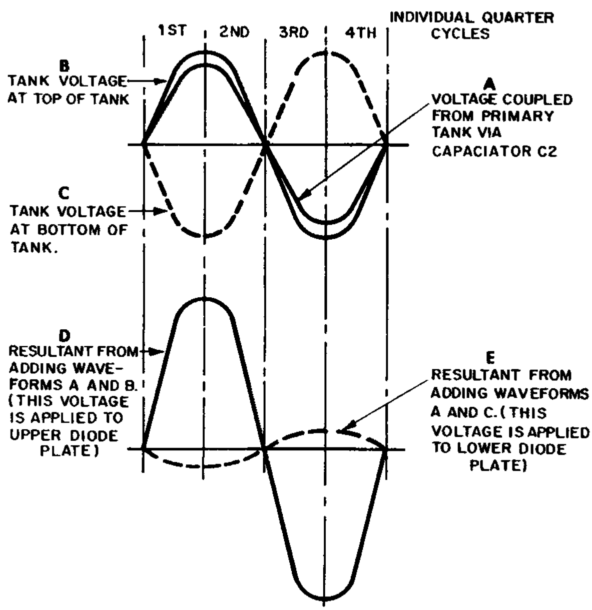


Fig. 7-16. Waveforms in the tuned discriminator circuit when operated below the resonant frequency.

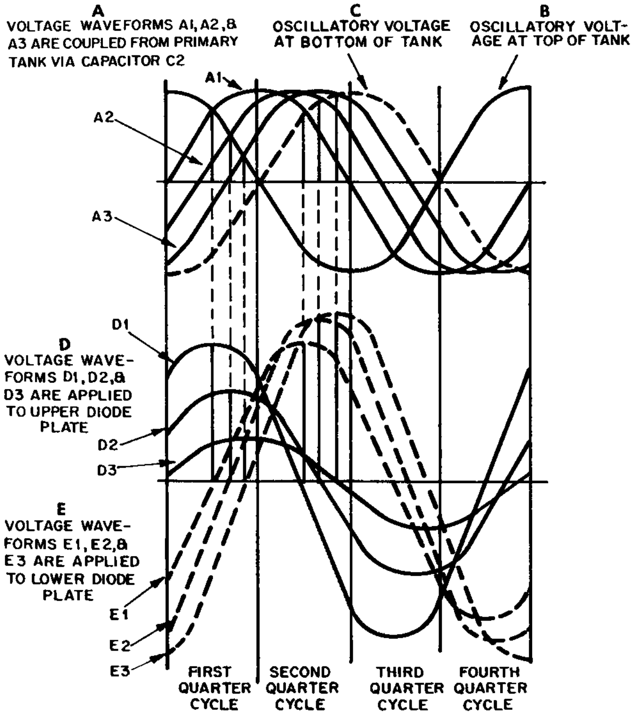


Fig. 7-17. How variations in phase between the two driving voltages will increase the voltage applied to the lower diode and decrease the voltage applied to the upper diode when operating above the resonant, or center, frequency.

maximum of half a cycle, or 180°. Conversely, as the frequency decreases below resonance, this phase difference will decrease from 90° toward zero, meaning the two tank voltages are exactly in phase.

The phase relationships between these two oscillatory tank voltages are important in this circuit only because of what happens when the two voltage waveforms are added algebraically. The use of both capacitive and inductive coupling provides the means for adding these two voltages. Fig. 7-17 shows several sample waveforms resulting when the carrier frequency deviates farther and farther above the resonant, or center, frequency. It can be seen from this figure that the amplitudes of the waveforms at D increase as the frequency excursion does, whereas the amplitude of the waveforms at E decrease in like amounts.

The waveform, shown as curve A1 in Fig. 7-17 and corresponding to waveform A of Fig. 7-10, reaches its positive peak a quarter of a cycle after waveform B (the latter is the oscillatory voltage measured at the top of the tank), and a quarter of a cycle before waveform C (the oscillatory voltage measured at the bottom of the tank). These phase relationships exist only at the resonant, or center, frequency.

Curve A2 shows how the phase of the capacitively-coupled voltage waveform has shifted slightly to the right as the frequency deviates above resonance. This *reduces* the phase difference between waveforms A2 and C and increases the amplitude of their resultant (the curve labeled E2). This phase shift of waveform A2 also *increases* the phase difference between it and waveform B, and thus decreases the amplitude of their resultant (the curve labeled D2).

Waveform A3 represents a further deviation in phase of the primary tank voltage *when compared with the phase of the secondary tank voltage*. Waveform A3 moves closer to coincidence with waveform C. As a result, their sum—shown as curve E3—undergoes another increase in amplitude. Curve A3 also moves

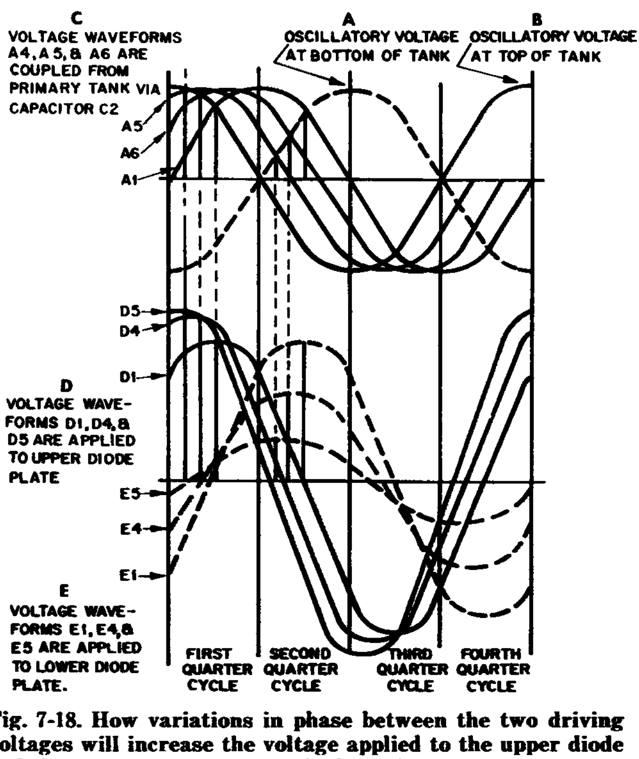


Fig. 7-18. How variations in phase between the two driving voltages will increase the voltage applied to the upper diode and decrease the voltage applied to the lower diode when operating below the resonant, or center, frequency.

farther away from coincidence with waveform B, so that the amplitude of their resultant (labeled curve D3) again decreases.

A similar set of waveforms has been drawn in Fig. 7-18 to illustrate the phase relationships between the two applied voltages when operating below resonance, and the changes in amplitude of the resultant voltages applied to the two diode-detector plates. With such a set of curves, waveform A shifts to the left instead of the right, bringing it toward phase coincidence with waveform B and toward phase opposition with waveform C. Under these conditions, waveform D progressively increases in amplitude as the frequency excursion does, while waveform E progressively decreases in amplitude.

In Fig. 7-18, waveforms A1, B, and C are identical to the waveforms having the same designations in Fig. 7-17. Waveforms A4 and A5, however, represent the progressive shifts in phase of the directly-coupled voltage with respect to the phase of the secondary tank voltage.

Inspection of Fig. 7-18 should reveal that the various waveforms are related as follows:

A1 plus C combine to produce waveform E1.
A4 plus C combine to produce waveform E4.
A5 plus C combine to produce waveform E5.
A1 plus B combine to produce waveform D1.
A4 plus B combine to produce waveform D4.
A5 plus B combine to produce waveform D5.

Waveforms D and E represent the total voltages applied to the plates of the upper and lower diode-detector tubes, respectively. Consequently, their amplitudes will be roughly proportionate to the amount of electron current through each diode, and therefore to the voltages developed across R2 and R3 during any RF cycle.

Because of the opposing polarities of the voltages developed across R2 and R3, the total output voltage across the two resistors will always be negative when operating above resonance and positive when operating below.

Chapter 8

RATIO DETECTOR

Both the detuned and the tuned discriminators discussed in the previous chapter share a disadvantage—the FM signal being demodulated must be of *constant amplitude* when it reaches the discriminator. In addition, the discriminator stage must be preceded by several amplifier stages, in order to build up even the weakest signal enough that the audio output from the discriminator will have sufficient volume. After this elaborate amplification process, the frequency-modulated signal must also be passed through one or more *limiter* stages. Here, any traces of amplitude modulation caused by atmospheric or propagation conditions are removed.

Unless these conditions are met by the two previous discriminators, they will respond to amplitude as well as frequency modulation. The result will then be a distorted audio output. This statement may be clarified with the aid of an example. In the tuned-discriminator operation, the assumption was made that at some frequency above resonance, the secondary tank voltage and the directly coupled voltage (also known as the reference voltage) were exactly in phase with each other. This caused the upper-diode detector to conduct heavily, and prevented the lower diode from conducting at all. The amount of electron current flowing through the upper diode then determined the amount of instantaneous output voltage developed across the appropriate output resistor. This amount of electron current depended of course on the *strength* of the tank and reference voltages.

A little reflection on the nature of these alternating voltages will reveal that both will be large when the received signal is strong, and small when it is weak. Furthermore, these changes in signal strength will be independent of the resonant tank frequency, and also of those frequencies both above and below resonance when the three voltage waveforms are exactly in or out of phase. Consequently, when a strong FM signal is received, the amount of electron current through either diode will be caused partly by the frequency deviations of the carrier (which is good) and partly by the excessively strong amplitude of the carrier (which is bad).

CIRCUIT DESCRIPTION

The ratio detector (Figs. 8-1 through 8-4) is one of the most widely used circuits for demodulating FM signals. One reason is that it responds only to frequency deviations of the signal; it remains unaffected by any amplitude variations caused by unusual propagation phenomena. The fact that the ratio detector is able to do this without additional amplifier or limiter stages makes it possible to build FM receivers which are competitive in price and in size with conventional AM broadcast receivers.

Circuit Components

The components and their functional titles in the ratio-detector circuit include:

R1—Output resistor.
R2—AVC resistor.
C1—Final IF tank capacitor.
C2—Capacitor for coupling the reference voltage to the detector tubes.
C3—Tuned tank capacitor.
C4—Filter capacitor for V1.
C5—Filter capacitor for V2.
C6—Large capacitor for stabilizing the voltage across C4 and C5.
C7—Coupling capacitor for the audio output.
L1—Final IF tank inductor.
L2—Tuned tank inductor.
L3—Radio-frequency choke.
V1 and V2—Diode-detector tubes.

Identification of Currents

The various electron currents at work in this circuit include:

1. Final IF tank current oscillating at the intermediate frequency between L1 and C1 (solid red).
2. Current which is directly coupled from the top of the primary tank to the center tap of the secondary tank inductor (dotted red).

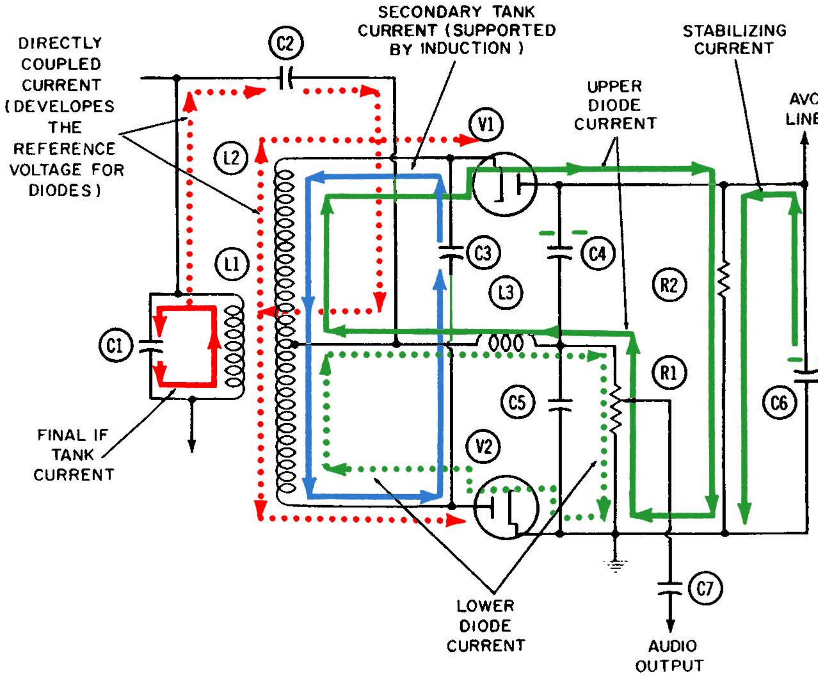


Fig. 8-1. Operation of the ratio detector—at center frequency, during a period of normal signal strength.

3. Secondary tank current which oscillates between L2 and C3 and is supported by induction between L1 and L2 (blue).
4. Current through upper diode V1 (solid green).
5. Current through lower diode V2 (dotted green).
6. Stabilizing current flowing out of C6 and down through R2 (solid green).

CIRCUIT OPERATION

This type of circuit differs from the discriminators discussed in the previous chapter in three important particulars. They are:

1. The position of the lower diode, V2, is reversed, so that electron current flows in the opposite direction. This is called a *series-aiding* connection.
2. Both diode currents flow through output resistor R1, whereas in the discriminator circuits they flowed through separate load resistors.

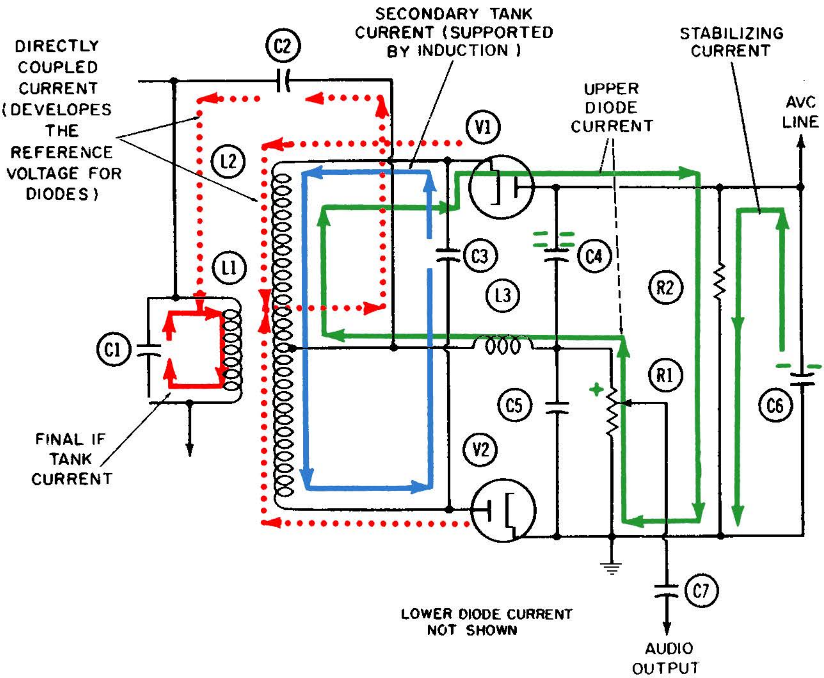


Fig. 8-2. Operation of the ratio detector—above center frequency, during a period of normal signal strength.

3. A long time-constant combination, consisting of R2 and C6, has been added so the circuit will not respond to undesired modulations in signal amplitude.

The same waveform diagrams shown in the preceding chapter on the detuned discriminator also apply to this ratio detector.

The fact that the lower diode, V2, has been reversed means of course that its current flows *clockwise* around the lower portion of the detector circuit. The important difference between the operation of this circuit and the tuned discriminator is that diode V2 conducts during different portions of the whole cycle. However, the quantity of electrons conducted during any individual cycle is the same in each circuit. Because of this, the waveform diagrams of the tuned discriminator will not be repeated here.

Fig. 8-1 depicts the conditions when this circuit is operated at its center frequency. The upper-diode current (solid green) and lower-diode current (dotted green) will now flow in equal amounts. Since both diode currents are equal but flow through output resistor R1 in opposite directions, no output voltage is developed across R1.

The complete path for the electron current through upper diode V1 is clockwise through V1, then downward through R2 to ground. From ground, the path is upward through R1 and to the left, through L3, to the center tap of L2. From here it flows upward through the upper half of L2 and returns to the cathode. A steady negative voltage builds up on the upper plate of capacitor C4 as a result of this current flow.

As the frequency deviates above resonance, this negative voltage on the upper plate of C4 will increase proportionately. Fig. 8-2 depicts this condition. V1 conducts more and more as the frequency increases, and V2 conducts less and less. Although Fig. 8-2 does not show any current through V2, some current usually will be flowing through it. However, the current through V1 predominates.

Fig. 8-3 depicts conditions when the ratio detector is operated at any reasonable frequency *lower* than the center or resonant frequency. As the frequency deviation below resonance increases, diode V2 will conduct *more* electron current and diode V1 will conduct progressively less. (As before, the current through V1 is not shown.) The complete path of the electron current through V2 is also *clockwise*, from cathode to plate and upward through the lower half of inductor L2 to the center tap. Here it flows to the right through L3, and down through R1 to the common ground connection, through which it has easy access back to the cathode.

At any frequency below resonance, more current flows through V2 than through V1. The difference between these two currents increases as the frequency deviation does. Because more current flows through V2 than through V1, more current will flow downward through R1 than upward. This establishes the fact that the voltage at any point along R1 is *negative* with respect to ground.

Figs. 8-2 and 8-3 represent positive and negative half-cycles of audio-output voltage, respectively. Capacitor C6 (usually 8 or 10 microfarads) operates in conjunction with resistor R2 to form a long time-constant combination. Its purpose is to restrict the amount of current through the two diodes when the signal is excessively strong, but to encourage their flow when the signal is weak. In this respect, the combination functions somewhat like the AVC combination discussed in a previous chapter.

Fig. 8-4 depicts operating conditions during a signal build-up at a frequency above resonance. Now the received carrier signal is stronger. When this occurs, *both* of the principal currents through the two diodes will be increased proportionately. Since these currents flow in opposite directions through resistor R1, the voltage developed across R1 will depend on the *difference* between these two currents, As both currents are increased proportionately, so does the difference between them. Consequently, a signal build-up—one of the commonest forms of undesired amplitude modulation, along with signal fade—will change the instantaneous audio-output voltage across R1. Hence, the circuit will now respond to amplitude modulation.

This undesirable state of affairs is prevented by the voltage accumulated on the upper plate of capacitor C6. As you can see, capacitors C4 and C5 are connected in parallel with C6; therefore, the instantaneous voltages on the upper plates of C4 and C5 must always add up to the voltage on C6, even though these voltages are themselves constantly changing in step with the frequency deviations of the carrier. It is the presence of this fairly stable voltage on capacitor C6 which biases both diodes so they will conduct enough current to produce the two voltages on capacitors C4 and C5.

In summary, the voltage across capacitor C6, and simultaneously across resistor R2, will always be equal to the sum of the voltages across capacitors C4 and C5. This is inevitable, since the tops of C4 and C6 are connected together, as are the bottoms of C6 and C5. The voltages across C4 and C5 always add up to the voltage on C6, but will change individually so that their difference is always proportionate to the frequency deviation of the carrier.

When both diodes in Fig. 8-1 are conducting equal amounts of current, the voltage at the top of resistor R1 will be zero, since its bottom is connected to ground (zero) and equal currents flow in opposite directions through it. A negative voltage will exist at the top of capacitor C4. This is due to the accumulation of electrons on its upper plate as a result of the plate current through diode V1. *The same negative voltage* will exist from top to bottom of capacitor C6 because it is the sum of these two voltages, one of which is zero.

When operating above resonance, in Fig. 8-2 diode V1 conducts more current and delivers more electrons to the upper plate of C4. As a result, the negative voltage across C4 increases. However, because diode V1 is conducting more electrons than V2, the top of resistor R1 must be more positive than the bottom, which is connected to ground. The reason is that more current is flowing upward through R1 than downward.

Because of the long time-constant of R2 and C6, the voltage across them does not change during the one-quarter of an audio cycle between Figs. 8-1 and 8-2. This voltage is represented by the electrons stored on the upper plate of C6. In Fig. 8-2 this

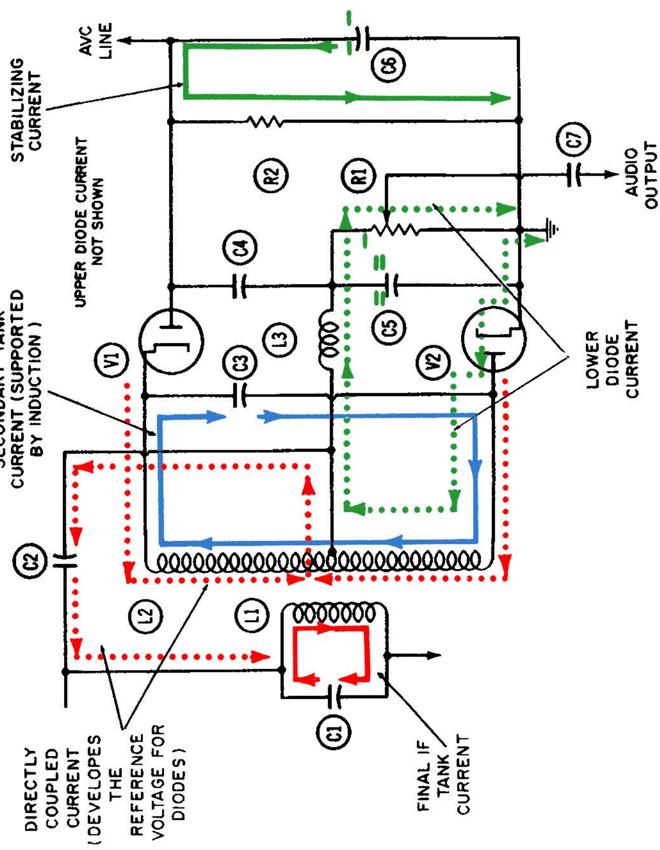


Fig. 8-3. Operation of the ratio detector—below center frequency, during a period of normal signal strength.

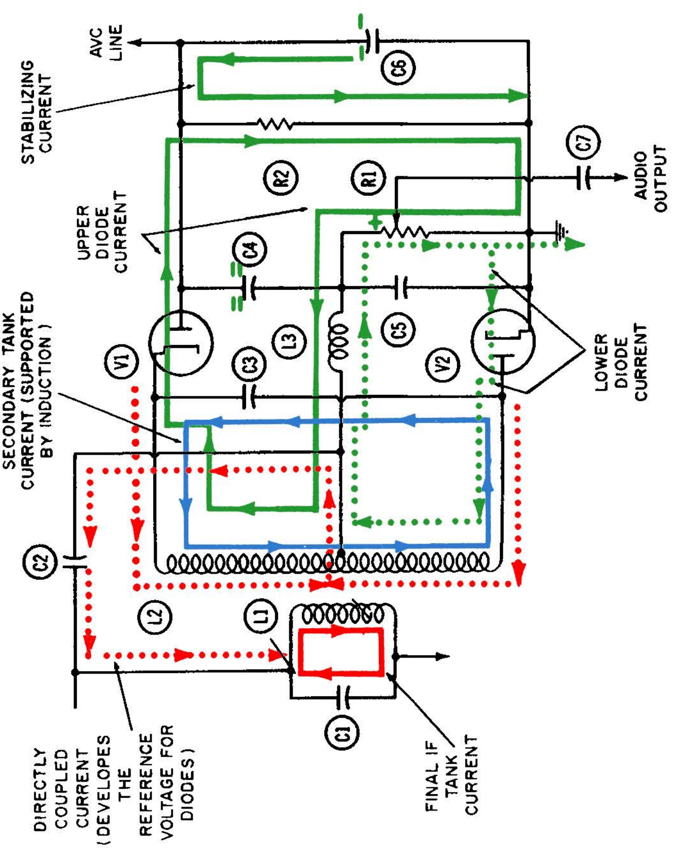


Fig. 8-4. Operation of the ratio detector—above center frequency, during a period of signal build-up.

voltage is the sum of the large negative voltage across C4 and the smaller positive voltage across C5.

When operating below resonance, diode V2 in Fig. 8-2 conducts more electrons than V1. Therefore, the top of resistor R1 must be more negative than the bottom. This negative voltage is indicated by the green minus sign at this point in the figure. The voltage across C6 and R2 is still unchanged and is now equal to the sum of the reduced negative voltage across C4 and the negative voltage which now exists across C5.

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