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RADIO ELECTRONICS Made Simple

by MARTIN SCHWARTZ

NO RADIO EXPERIENCE REQUIRED

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TECHNICAL INFORMATION EXPLAINED IN EVERYDAY LANGUAGE

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EXCELLENT BACKGROUND FOR STUDY OF TELEVISION, HIGH-FIDELITY, ETC.

RADIO–ELECTRONICS MADE SIMPLE

by

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PREFACE

The field of radio and electronics has been experiencing a most rapid rate of advancement. The future for this dynamic industry is sufficiently clear to attract the very best people into it. Nevertheless, there is still a tremendous shortage of personnel to occupy the many excellent positions that are presently vacant.

In order to provide the many people who are interested in radio and electronics, either as a hobby or as a career; with a basic and fundamental background, this book has been written. No prior experience or specific education is needed as this book is simple and easy to understand. Using but a minimum of mathematics, it sets forth the basic concepts in a clear, non-technical manner. By means of every-day language, it explains the more difficult principles and scientific laws associated with this field.

The first three chapters of this book deal with basic electricity, magnetism, and alternating current theory. Chapters 4 and 6 cover the principles of the vacuum tube. The uses of vacuum tubes in power supplies and audio amplifiers are taken up in chapters 5 and 7, respectively. The remainder of the book explains the theory of transmitters and receivers as well as the antenna system.

For the beginner, the experimenter, the hobbyist, the HI-Fi enthusiast, and the service-man, this is an ideal book. It is for anyone who wants to gain, with the least difficulty, a complete understanding of the fundamentals of radio and electronics. This book also serves as a stepping stone for further study in the more specialized areas of the electronics field.

New York, N. Y.
September 1956

Martin Schwartz

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CHAPTER 1
DIRECT CURRENT

MATTER

Matter is a general term that is used to describe all the material things about us. Matter includes all man-made structures, liquids, metals, gases, etc.; in other words, everything that has weight and occupies space.

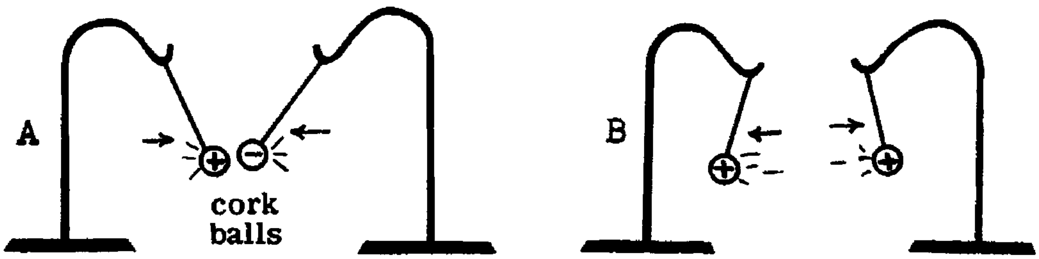
All matter, regardless of size, quality or quantity, can be broken down into approximately 100 different elements. Some of the more common elements are iron, copper, aluminum and oxygen. Elements may exist alone or they may exist in combination with other elements. For instance, copper wire consists only of the element copper; on the other hand, water is a combination of two elements, oxygen and hydrogen.

Each element can be broken down further into two different types of tiny particles. These particles, which are too small to be seen by the most powerful microscope, are called electrons and protons. The two particles differ from each other electrically and physically. Electrically, we say that the proton is positively charged while the electron is negatively charged. Physically, the proton is about 1800 times as heavy as the electron.

THE LAW OF ELECTRIC CHARGES

Most objects, such as a piece of wood, normally have a neutral or zero charge; that is, they contain as many electrons (negatively charged particles) as they do protons (positively charged particles). If this piece of wood can be made to have an excess of electrons, it would lose its neutral charge and become negatively charged. On the other hand, if the wood could be made to have a deficiency of electrons, the protons would predominate and it would become positively charged.

If we took a positively charged body and brought it near a negatively charged body, the two bodies would be drawn together. If, however, the two objects had the same charge (both positive or both negative), then they would repel each other. These two reactions form the basis of our first law of electricity, The Law Of Electric Charges. The law states that: "Like Charges Repel and Unlike Charges Attract." This law is illustrated in figure 1-1. In 1-1A, a positively charged ball of cork is suspended by a piece of string near a negatively charged ball of cork. The two bodies swing towards each other because they attract each other. Figure 1-1B illustrates two positively charged balls repelling each other.



A. Unlike charges attract. B. Like charges repel.

Fig. 1-1. Law of electric charges.

DIFFERENCE OF POTENTIAL

If we were to connect a copper wire between the negative and the positive balls of cork, an electron flow would result. This is illustrated in figure 1-2. The excess electrons from the negative ball flow to the positive ball where there is an electron deficiency and therefore an attraction for the electrons.

This flow continues until the deficiency and excess of electrons has disappeared and the balls become neutral or uncharged. This flow of electrons between the two differently charged bodies is caused by the difference in charge. A difference in charge between two objects will always result in the development of an electrical pressure between them. It is this electrical pressure that causes the electrons to flow when these two bodies are connected by a piece of copper wire. This electrical pressure is defined as a DIFFERENCE OF POTENTIAL.
The word "POTENTIAL" has the same meaning as the word "CHARGE".

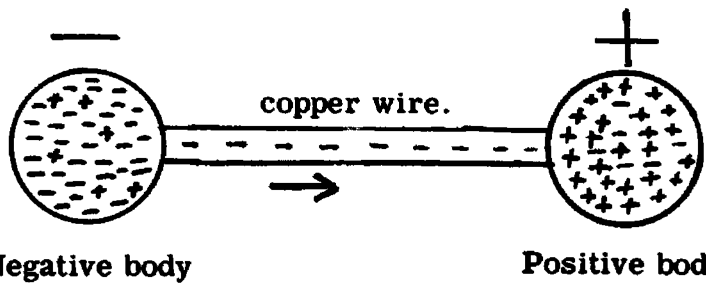


Fig. 1-2. Flow of electrons

CONDUCTORS AND INSULATORS

Materials through which current can easily flow are called CONDUCTORS. Most metals are good conductors. Conductors incorporate a large number of free electrons in their basic structure. These free electrons are not held tightly, and will move freely through the conductor when stimulated by external electrical pressure. Examples of good conductors, in the order of their conductivity, are silver, copper, aluminum, and zinc.

Those materials through which electrons flow with difficulty are called INSULATORS. The electrons are tightly held in the atomic structure of an insulator, and, therefore, cannot move about as freely as in conductors. Examples of insulators are wood, silk, glass, and bakelite.

RESISTANCE

The ability of a material to oppose the flow of electrons is called RESISTANCE. All materials exhibit a certain amount of resistance to electron flow. In order to compare the resistances of various materials we require some standard unit of resistance measurement. The unit of resistance that was adapted for this purpose is the OHM, and the Greek letter Omega (Ω) is its symbol. (For a list of common radio abbreviations, see Appendix I.) One ohm may be defined as the amount of resistance inherent in 1000 feet of #10 copper wire. For example, 5000 feet of #10 copper wire would have a resistance of 5 ohms, 10,000 feet of #10 copper wire would have 10 ohms, etc. Although the ohm is the basic unit, the MEGOHM, meaning 1,000,000 ohms, is frequently used. The instrument used to measure resistance is the OHMETER.

There are four factors which determine the resistance of a conductor. They are:

1. Length - The resistance of a conductor is directly proportional to its length. The longer the conductor, the greater is the resistance. The electrons have to flow through more material in a longer conductor and therefore, meet more opposition.

2. Cross-sectional area - The resistance of a conductor is inversely proportional to the cross-sectional area. This means that the resistance becomes smaller as the thickness or area becomes larger. For example, is we double the cross-sectional area of a conductor of a given length, the resistance will be cut in half. If we triple the area, the resistance will be cut to one-third of its original resistance. The larger the cross-sectional area of a conductor, the easier it is for current to flow. If we

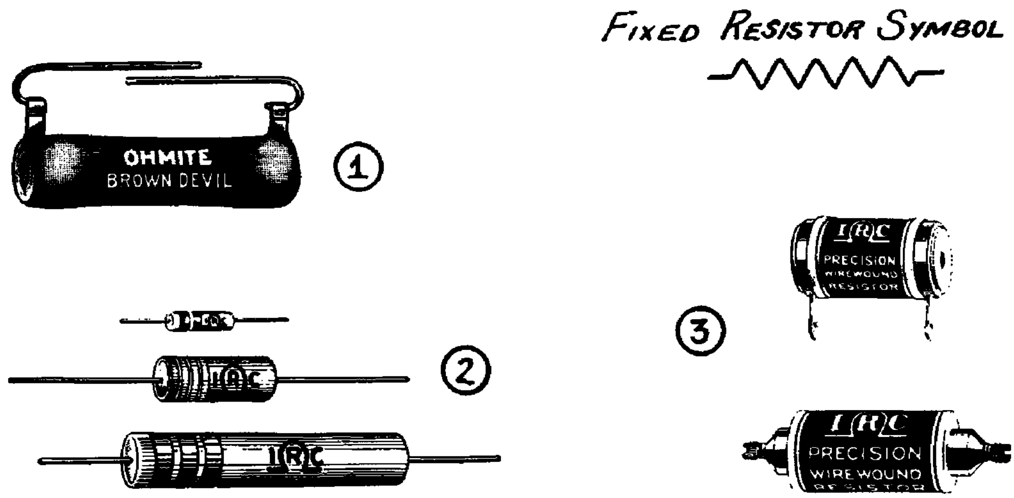
decrease the cross-sectional area of the conductor, less electrons can squeeze through. Hence a greater resistance.

3. Temperature - In practically all conductors, with the exception of carbon, the resistance varies directly with the temperature. As the temperature of a conductor rises, its resistance increases; as the temperature drops, the resistance decreases.

4. Material make-up - The resistance of a conductor depends upon the material of which it is made. Because of their material structure, some conductors have more resistance than others. For example, silver has a very low resistance, whereas nichrome has a high resistance.

RESISTORS

The resistor is a common radio part. Each resistor has a specific amount of resistance. Resistors which are made of mixtures of carbon and clay are called carbon resistors. Carbon resistors are used in low power circuits. Wire wound resistors, which contain special resistance wire, are used in high power circuits. Fig. 1-3 illustrates several types of fixed resistors which are used in radio circuits. The symbol which is used to represent them in circuit diagrams is also shown.

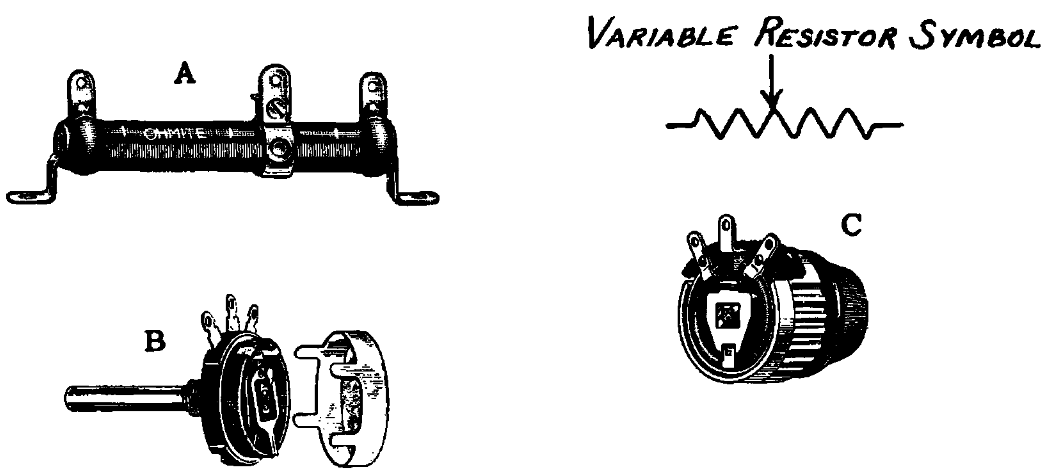


1. High wattage wire wound
2. Carbon resistors.
3. Precision resistors.

Fig. 1-3. Fixed resistors

When it becomes necessary to vary the amount of resistance in a circuit, we use adjustable or VARIABLE RESISTORS. The adjustable resistor has a sliding collar which may be moved along the resistance element to select any desired resistance value.

Variable resistors are used in a circuit when a resistance value must be changed frequently. Variable resistors are commonly called potentiometers or rheostats, depending on their use. The volume control in a radio is a typical example of a variable resistor. Fig. 1-4b illustrates a potentiometer used as a volume control for a radio receiver; Fig. 1-4c illustrates a potentiometer wound of heavier wire for use in a power supply circuit. Fig. 1-4a illustrates a variable resistor which is used where frequent adjustment is not required.



A. Adjustable power resistor

B. Potentiometer for volume control

C. Potentiometer for power supply

Fig. 1-4. Variable resistors

CONDUCTANCE

The reciprocal, or opposite of resistance is called CONDUCTANCE.

$$(1\text{-}1) \quad \text{conductance} = \frac{1}{\text{resistance}}$$

Conductance is the ability of an electrical circuit to pass or conduct electricity. A circuit having a large conductance has a low resistance; a circuit having a low conductance has a high resistance. The unit of conductance is the MHO. A resistance of one ohm has a conductance of one mho; a resistance of 10 ohms has a conductance of .1 mho

(1/10 = 0.1). In other words, to determine the conductance we divide the number 1 by the amount of the resistance in ohms. We frequently use the term MICROMHO, meaning one millionth of a mho.

VOLTAGE AND CURRENT

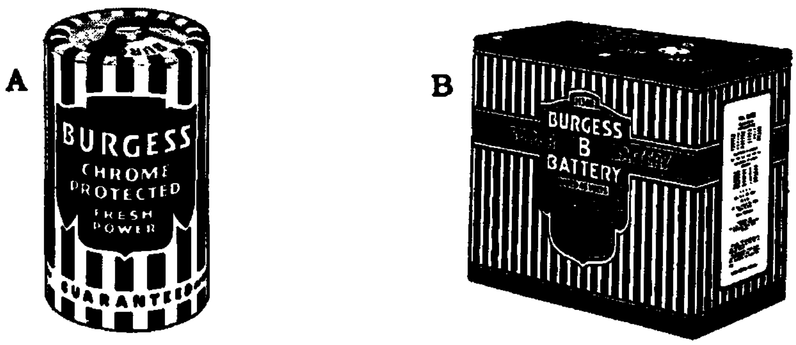
Voltage is another term used to describe the difference of potential or electrical pressure which we spoke about in a preceeding paragraph. It is the force which pushes or forces electrons through a wire, just as water pressure forces water through a pipe. Some other terms used to denote voltage are ELECTRO-MOTIVE FORCE (e. m. f.), IR DROP and FALL OF POTENTIAL. The unit of voltage is the VOLT, and the instrument used to measure voltage is the VOLTMETER. The KILOVOLT is equal to 1000 volts.

CURRENT is the term commonly used to describe the flow of electrons. It is the result of the application of a difference of potential to a circuit. If we increase the number of electrons flowing past a point in a given amount of time, we have more current. Conversely, if we decrease the number of electrons flowing past a point in a given amount of time we decrease the current. The unit of current is the AMPERE, and it is equal to 6, 300, 000,-000,000,000,000 electrons flowing past a point in one second. MILLIAMPERE and MICROAMPERE are terms used to denote one-thousandth and one-millionth of an ampere respectively. Current is measured by an AMMETER.

We have one more important term to define, and that is the COULOMB. The coulomb is the unit of electrical quantity. The coulomb is the number of electrons contained in one ampere. One coulomb flowing past a point in one second is equal to one ampere. Many people confuse the COULOMB with the Ampere.The difference is this: the Ampere represents the RATE OF FLOW of a number of electrons, whereas the Coulomb represents only the quantity of electrons and has nothing to do with the RATE OF FLOW or movement of the electrons. The Coulomb is a unit that is seldom used in radio.

THE DRY CELL

There are several methods that are used to produce electricity. One of the most common methods is the dry cell that is found in a flashlight. The dry cell contains several chemicals combined to cause a chemical reaction which produces a voltage. The voltage produced by all dry cells, regardless of size, is 1 and 1/2 volts. A battery is composed of a number of cells. Therefore, a battery may be 3 volts, 6 volts, 7 and 1/2 volts, etc., depending upon the number of cells it contains. The fact that a cell is larger than another one indicates that the larger cell is capable of delivering a given amount of current for a longer period of time than the smaller one. Fig. 1-5 illustrates a typical 1 and 1/2 volt cell and a 45 volt battery. The 45 volt battery contains 30 small dry cells.



A. 1-1/2 volt flashlight cell. **B. 45 volt "B" battery.**

Fig. 1-5. The dry cell

Every cell has a negative and a positive terminal. The electrons leave the cell at the negative terminal, flow through the circuit, and return to the cell at the positive terminal. This type of current flow is known as DIRECT CURRENT (d-c). Direct current is current that flows only in <u>one</u> direction.

ELECTRICAL CIRCUITS

If we took a dry cell, 2 conductors and a bulb and hooked them up as shown in figure 1-6, the bulb would light up. We would then have a complete electrical circuit. The heavy arrows in figure 1-6 indicate the direction of the current flow. As long as we can trace the current from the negative point of the cell, all around the circuit, and back to the positive point, we have a complete circuit. The important thing to remember is that current will only flow through a complete circuit.

The necessary parts for a complete circuit are:

1. - A source of voltage - the dry cell in Fig. 1-6.
2. - Connecting leads - the copper wire conductors in Fig. 1-6.

3. - A load - the bulb in Fig. 1-6.

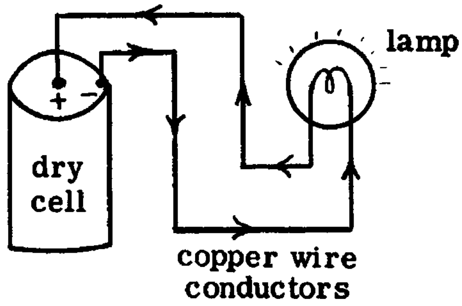


Fig. 1-6. A complete electrical circuit

If there were a break in the conducting leads, or in the wire of the bulb, no current would flow and the light would go out. We would then have an OPEN CIRCUIT. Fig. 1-7 illustrates the open circuit condition.

If we place a piece of wire directly across the two cell terminals, no current will flow through the bulb. This condition is illustrated in Fig. 1-8. The current by-passes the bulb and flows through the path of least resistance, which is the piece of wire. This condition is known as a SHORT CIRCUIT. It is to be avoided because it causes a severe current drain which rapidly wears the battery down.

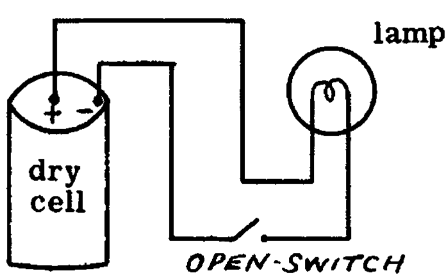


Fig. 1-7. Open circuit

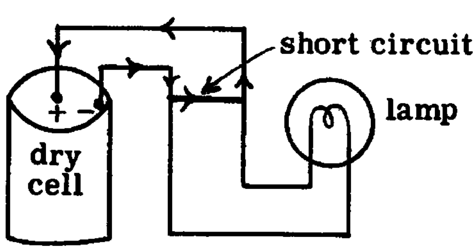
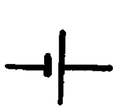
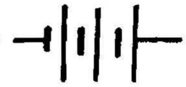


Fig. 1-8. Short circuit

SCHEMATICS

In drawing an electrical circuit on paper, we find it impractical to draw the actual battery or lamp as was done in Figures 1-6 through 1-8. Instead, we use simple symbols to represent the various electrical parts. For instance:

A cell is shown as 

A battery is shown as 

A resistor is shown as 

You will find a complete table of radio symbols in Appendix II. Figures 1-6, 1-7 and 1-8 can now be redrawn in the manner shown in figures 1-9a, 1-9b and 1-9c. Note that we indicate the negative battery terminal by a short line, and the positive terminal by a long line.

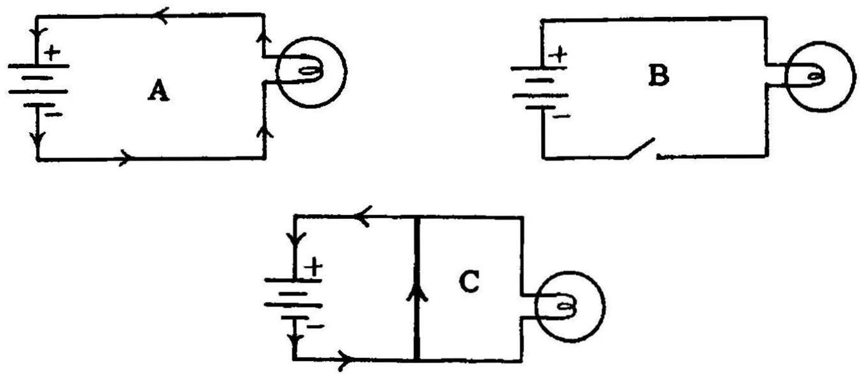


Fig. 1-9. Schematic diagrams of figures 1-6, 1-7 and 1-8

OHM'S LAW

We have discussed the significance of voltage, current and resistance. Now we shall further study the important relationships that exist between these three factors.

If we were to increase the source voltage of fig. 1-6, more electrons would flow through the circuit because of the greater electrical pressure exerted upon them. If we were to decrease the voltage, the flow of electrons would decrease. On the other hand, if the resistance of the circuit were made larger, the current would decrease because of greater opposition to current flow. If the resistance were made smaller, the current would increase by similar reasoning. These relationships are formulated into a law known as OHM'S LAW which is stated as follows: The current is directly proportional to the voltage and inversely proportional to the resistance. Ohm's law, mathematically stated, says that the current, in amperes, is equal to the voltage, in volts, divided by the resistance, in ohms.

The three formulas of Ohm's law are:

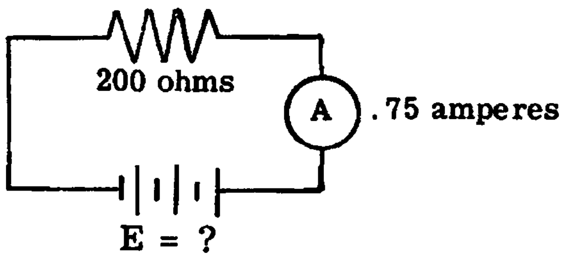
(1-2) $I = \frac{E}{R}$ (1-3) $E = IR$ (1-4) $R = \frac{E}{I}$

"I" stands for the current in amperes, "E" is the voltage in volts, and "R" is the resistance in ohms. It is obvious that it is simpler to use letters such as I, E, and R, than to actually write out the words. Also, note that IR means I multiplied by R. If two out of the three factors of Ohm's law are known (either E, I, or R), the unknown third factor can be found by using one of the above three equations. Several examples will clarify the use of Ohm's law:

PROBLEM 1

Given: Current is .75 amp.
Resistance is 200 ohms

Find: The voltage of the battery:



Soulution: Since we are interested in finding the voltage, we use formula 1-3 because it tells us what the voltage is equal to. We then substitute the known values and solve the problem as follows:

I) E = IR

2) E = .75 x 200

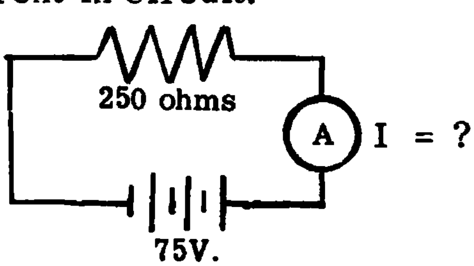
3) E = 150V

200
x .75
1000
1400
150.00

PROBLEM 2

Given: Battery voltage is 75 volts
Resistance of bulb is 250 Ohms

Find: Current in circuit:



Soultion: Use formula 1-2 to find the current.

1) $I = \dfrac{E}{R}$

2) $I = \dfrac{75}{250}$

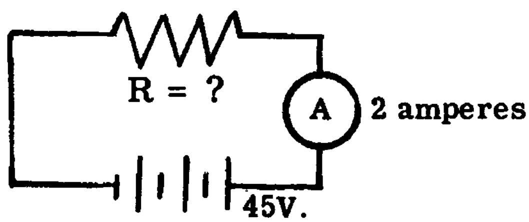
3) $I = .3$ amp.

$$250 \overline{)75.0} = .3 \qquad 750 \qquad 000$$

PROBLEM 3

Given: Current in circuit is 2 amp.
Battery voltage is 45 volts.

Find: Resistance of circuit.



Solution: Use formula 1-4, and substitute for E and I to find R.

1) $R = \dfrac{E}{I}$

2) $R = \dfrac{45}{2}$

3) $R = 22.5$ ohms.

RESISTANCES IN SERIES

If two or more resistances are connected end to end as shown in figure 1-10a, we say that the resistors are hooked up in a SERIES CIRCUIT. Any current flowing through one of the resistors will also flow through the others. The arrows indicate the direction of current flow.

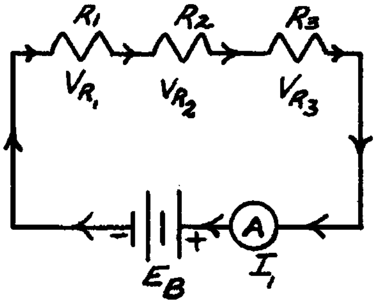


Fig. 1-10A. Series circuit.

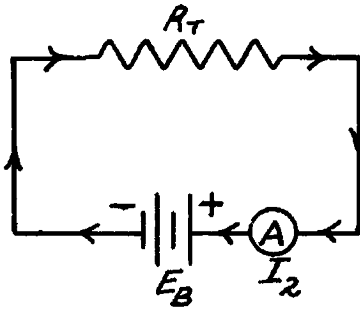


Fig. 1-10B. Equivalent circuit.

Since the same current flows through each resistor, the CURRENT IS THE SAME AT EVERY POINT IN A SERIES CIRCUIT. Similarly, the total current is the same as the current in any part of the series circuit. To put it mathematically:

$$\text{(1-5)}\quad I_{(total)} = I_{R_1} = I_{R_2} = I_{R_3}$$

It is important to note that the current in Fig. 1-10a will remain unchanged if the separate series resistors are replaced by a single resistor whose resistance value is equal to the sum of the three resistors. Fig. 1-10b illustrates the equivalent circuit of Fig. 1-10a. We can therefore say that THE TOTAL RESISTANCE IS A SERIES CIRCUIT IS EQUAL TO THE SUM OF THE INDIVIDUAL RESISTANCES.

(1-6) $R_T = R_1 + R_2 + R_3$, etc. where R_T is total resistance

Whenever current flows through a resistance in a circuit, a part of the source voltage is used up in forcing the current to flow through the particular resistance. The voltage that is used up in this manner is known as the VOLTAGE DROP or fall of potential across that particular resistor. The voltage drop is equal to the current through the resistor multiplied by the resistance of the resistor.

If we add up the voltage drops across all the parts of a series circuit, the sum would be equal to the source or battery voltage.

$$\text{(1-7)}\quad E_B = V_{R_1} + V_{R_2} + V_{R_3}, \text{etc.}$$

where E_B is the battery voltage
V_{R1} is the voltage across R_1
V_{R2} is the voltage across R_2, etc.

PROBLEM:

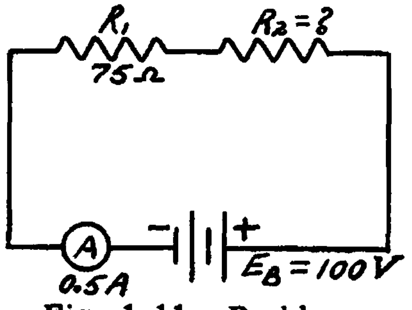


Fig. 1-11. Problem.

Find the resistance of R_2 in Fig. 1-11:

Solution: (1) Since we know the total current and the battery voltage, we can use ohms law to find the total resistance.

$$(1)\quad R_T = \frac{E}{I} = \frac{100}{.5} = 200$$

(2) Since the total resistance in this series circuit is 200Ω , and R = 75; then $R_2=R_T-R_1$

(3) $R_2 = 200 - 75$

(4) $R_2 = \underline{\underline{125\Omega}}$

RESISTANCES IN PARALLEL

The circuit in Fig. 1-12a is called a PARALLEL CIRCUIT. R_1 and R_2 are in parallel with each other. The

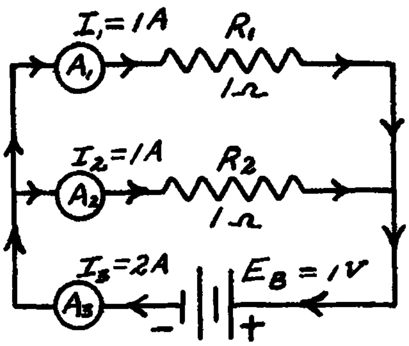


Fig. 1-12A. Parallel circuit.

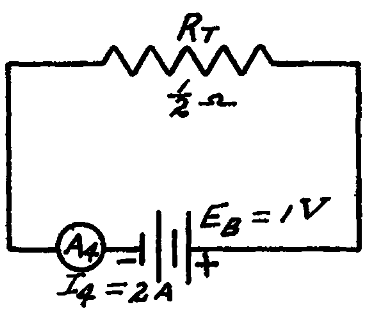


Fig. 1-12B. Equivalent circuit.

current in the circuit now has two paths to flow through from the negative end of the battery to the positive end. If we remove resistor R_1 or R_2 from the circuit, the current has only one path to flow through from the negative to the positive end of the battery. Since it is easier for the current to flow through two paths instead of one, THE TOTAL RESISTANCE OF A PARALLEL COMBINATION IS LESS THAN THE RESISTANCE OF EITHER RESISTOR IN THE CIRCUIT. The more resistors we add in parallel, the less becomes the total resistance. This is because we increase the number of paths through which the current can flow. An analogy for this would be to consider the number of people that can pass through one door in a given time compared to the number of people that can pass through several doors in the same time.

If each resistor in Fig. 1-12a had a value of one ohm, it would be twice as easy for the current to pass through the parallel combination than it would be for it to pass through either one of the resistors alone. The total parallel resistance would therefore be one-half of either one of the resistors, or one-half ohm. THUS, WE CAN SAY THAT THE TOTAL RESISTANCE OF 2 EQUAL RESISTORS IN PARALLEL IS EQUAL TO 1/2 OF ONE OF THEM. Figure 1-12b shows the equivalent circuit of figure 1-12a.

The total resistance of ANY TWO resistors in parallel may be found by using the following formula.

$$(1\text{-}8)\quad R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

For example, if R_1 and R_2 of Fig. 1-12a were 3and 6 ohms respectively, the total resistance would be:

$$1)\ R_T = \frac{R_1 \times R_2}{R_1 + R_2} \qquad 2)\ R_T = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = \underline{\underline{2 \text{ ohms.}}}$$

The total resistance of ANY NUMBER of resistors in parallel may be found by applying the following formula.

$$(1\text{-}9)\quad R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \text{ etc.}}$$

For example, if three resistors of 5, 10, and 20 ohms were connected in parallel, the total resistance would be;

$$1)\ R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \qquad 2)\ R_T = \frac{1}{\frac{1}{5} + \frac{1}{10} + \frac{1}{20}}$$ (least common denominator is 20)

$$3)\ \frac{1}{\frac{4+2+1}{20}} = \frac{1}{\frac{7}{20}} \qquad 4)\ 1 \times \frac{20}{7} = \underline{\underline{2\frac{6}{7} \text{ ohms.}}}$$

CHARACTERISTICS OF A PARALLEL CIRCUIT

1. The total resistance of several resistors hooked in parallel is less than the smallest resistor.

2. Different amounts of current flow through the different branches of a parallel circuit. The amount of current flowing through each branch depends upon the resistance of the individual branch. The total current drawn from the battery is equal to the sum of the individual branch currents.

3. The voltage across all the branches of a parallel circuit is the same; in Fig. 1-12a the voltage across R_1 is

the same as the voltage across R_2.

An example will illustrate the above principles. Refer to Fig. 1-13.

Given: current through R_1 is .2A
$R_1 = 50\Omega$
$R_2 = 200\Omega$

Find: 1. Current through R_2.
2. Total current.

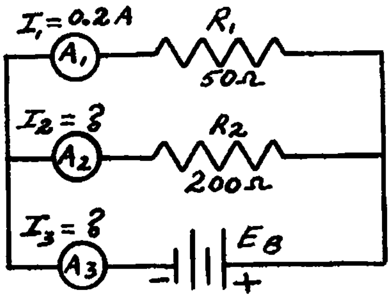


Fig. 1-13. Problem.

Solution: Since we know the resistance of R_1 and the current through R_1, we can find the voltage across R_1 by using ohms law.

1) $E_{R_1} = I_{R_1} \times R_1$ 2) $E_{R_1} = .2 \times 50$ 3) $E_{R_1} = \underline{\underline{10V}}$

Since R_1 is in parallel with R_2, the voltage across R_2 is the same as that across R_1. Therefore, E_{R_2}=10V

Knowing the resistance of R_2 (given) and the voltage across it, we can find the current through R_2:

$$I_{R_2} = \frac{E_{R_2}}{R_2} = \frac{10}{200} = \underline{\underline{.05 \text{ amp. current through } R_2}}$$

In a parallel circuit, the total current is equal to the sum of the individual branch currents; therefore:

1) $I_T = I_{R_1} + I_{R_2}$
2) $I_T = .2A + .05A = \underline{\underline{.25 \text{ amp. total current}}}$

SERIES-PARALLEL CIRCUITS

Circuits A and B of Fig. 1-14 are called SERIES-PARALLEL circuits. In circuit A, the 10 ohm resistors are in parallel with each other. But, this parallel combination is in series with the 20 ohm resistor. The total resistance of circuit A is computed as follows:

First find the resistance of the two 10 ohm parallel resistors using formula 1-8.

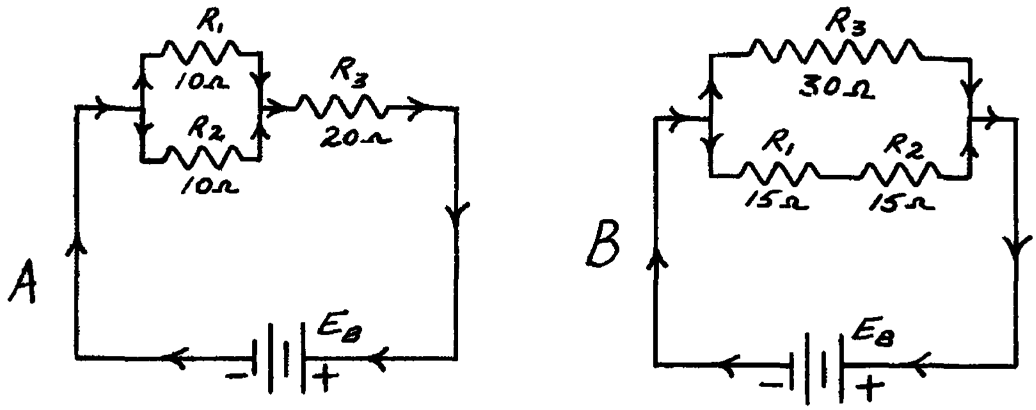


Fig. 1-14. Series-Parallel circuits.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{10 \times 10}{10 + 10} = \frac{100}{20} = 5\Omega$$

Since the parallel resistors are in series with the 20Ω resistor, then the total resistance of this combination is:

$$5 + 20 \text{ or } \underline{\underline{25\Omega}}$$

In diagram B, the two 15 ohm resistors are in series with each other. This series combination is in parallel with the 30 ohm resistor. The total resistance of series-parallel circuit B is computed as follows:

The resistance of the two 15 ohm resistors in series is 15+15 or 30 ohms. Since this 30 ohms is in parallel with the 30 ohm resistor, the total resistance of the combination is:

$$R_T = \frac{30 \times 30}{30 + 30} = \frac{900}{60} = \underline{\underline{15\Omega}}$$

POWER

Whenever current flows through a resistance, there is friction between the moving electrons and the particles of the resistor. This friction causes heat to be generated, as does all friction. We could also say that electrical energy is changed to heat energy whenever current flows through a resistor. The unit of energy is the JOULE. The rate at which the heat energy is generated is the power that the resistor consumes. This power consumption in the form of heat represents a loss because we do not make use of the heat generated in radio circuits.

We should know how much heat power a resistor is consuming or dissipating. This is important because a resistor will burn up if it cannot stand the heat that is being generated by current flow. Resistors are therefore rated, not only in ohms, but in the amount of power that they can dissipate without overheating. The unit of electrical power is the WATT. A resistor rated at 5 watts is one which can safely dissipate up to 5 watts of power. If this resistor is made to dissipate 10 watts, by increased current flow, it will burn up.

Let us see how much power is dissipated in a particular circuit, and upon what factors the power dissipation depends. Since the power is the result of friction between the flowing electrons and the resistance in the circuit, the actual power dissipated depends upon the current and the resistance. The more current that flows, the more electrons there are to collide with the particles of the resistance material. Also, the greater the resistance, the greater is the resulting friction. The actual power dissipated in a resistor can be found by the following formula:

(1-10) $P = I^2 \times R$

where: P is the power in watts

I is the current in amperes

R is the resistance in ohms.

(I^2 means I x I.)

Problem: Find the power dissipated in a 200 ohm resistor with 50 milliamperes flowing through it.

Solution: First change milliamperes to amperes. This is done by moving the decimal three places to the left. Thus 50 milliamperes = .05 amperes. Then substitute the values given in formula 1-10.

1) $P = I^2 \times R$

2) $P = .05 \times .05 \times 200$

3) $P = \underline{\underline{.5 \text{ watts}}}$

$$\begin{array}{r} .05 \\ \times .05 \\ \hline .0025 \end{array} \qquad \begin{array}{r} .0025 \\ \times 200 \\ \hline .5000 \end{array}$$

By using ohms law, and algebraically substituting in formula 1-10, we can arrive at two more formulas for obtaining power dissipation.

(1-11) $P = E \times I$ (1-12) $P = \dfrac{E^2}{R}$

where: P is the power in watts, E is the voltage in volts, I is the current in amperes and R is the resistance in ohms.

Formula 1-11 states that the power is equal to the product of the voltage across the resistor and the current through the resistor.

The Wattmeter is the instrument that is used to measure power. The Watt-hour meter is the instrument that is used to measure energy.

CHAPTER 2

MAGNETISM AND METERS

THE MAGNET

We are all familiar with the effects of magnetism. A horseshoe magnet will attract and pull to it iron filings. A powerful crane electromagnet will pick up heavy pieces of iron. A compass needle will point to the north pole. A magnet, therefore, is any object which has the ability of attracting to itself magnetic materials such as iron or steel. Fig. 2-1 shows a horseshoe magnet attracting particles of iron filings.

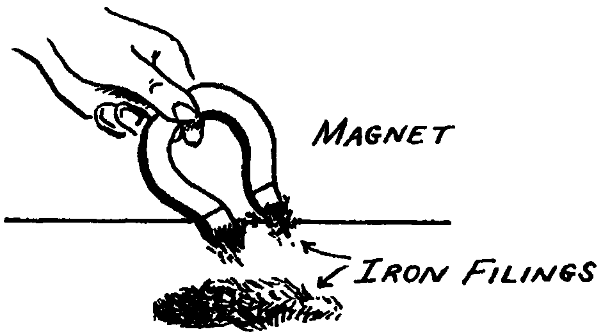


Fig. 2-1. Magnet's attractive power.

When a magnetized bar of iron is suspended from a string tied around its center so that it is free to rotate, it will come to rest with one end pointing almost directly north. The end that points north is called the NORTH POLE, and the opposite end of the magnetized bar of iron is called the SOUTH POLE.

LAW OF MAGNETIC POLES

If the north pole end of one magnet is brought near the north pole end of another magnet, the magnets will repel each other. The same reaction of repulsion will occur if two south pole ends are brought close to each other. If, however, a north pole end and south pole end are brought close to each other, the magnets will attract each other. The reason that the north pole of a suspended magnet points to the earth's north geographical pole is that the earth itself is a magnet. The earth's south magnetic pole is located near the north geographical pole. The results of experiments in magnetic attraction and repulsion were formulated into the law of poles which states that OPPOSITE POLES ATTRACT EACH OTHER, WHEREAS LIKE POLES REPEL EACH OTHER. Fig. 2-2 illustrates this principle.

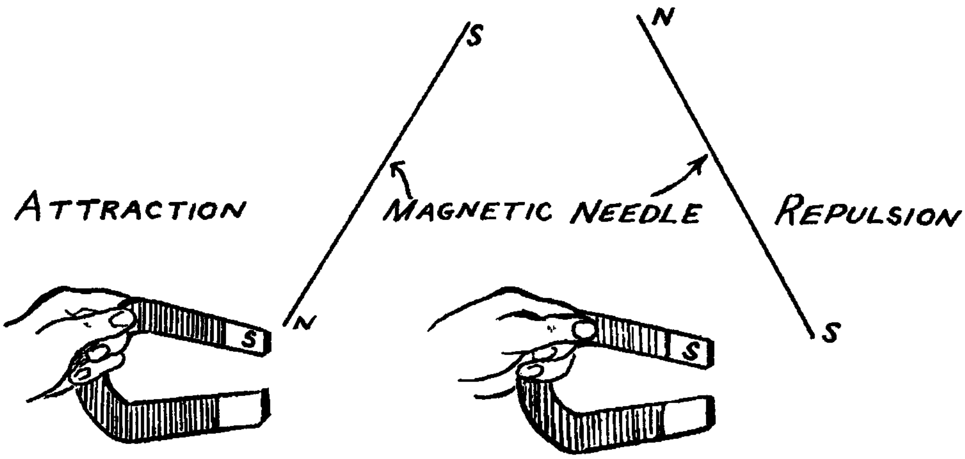


Fig. 2-2. Attraction and repulsion.

MAGNETIC LINES OF FORCE

We cannot see the forces of repulsion or attraction that exist between the pole pieces of two magnets. However, we must assume that the north pole of one magnet sends out some kind of invisible force which has the ability to act through air and pull the south pole of the other magnet to it. If we had unique vision we would be able to see certain lines leaving the north pole of one magnet and crossing over to the south pole of the other magnet. These lines are known as magnetic lines of force, and as a group are called a MAGNETIC FIELD or FLUX. Fig. 2-3 illustrates the magnetic field as it exists around a bar magnet.

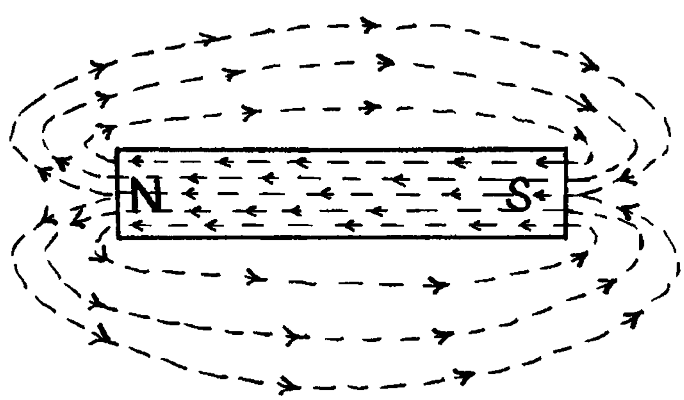


Fig. 2-3. Magnetic lines of force.

Notice that the lines of force leave the magnet at the north pole and return to the magnet at the south pole. Note, also, that the magnetic field continues flowing inside the magnet from the south to the north pole. The complete path of the magnetic flux is called the magnetic circuit.

One way to show magnetic lines of force is to sprinkle iron filings on a piece of paper under which we place a bar magnet. The result is shown in figure 2-4.

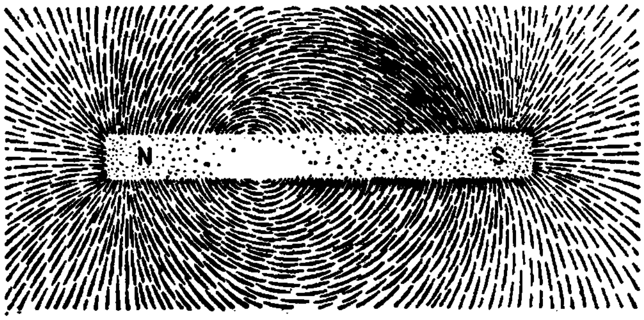


Fig. 2-4. Picture of iron filings.

The iron filings arrange themselves so as to look like the lines of force that surround the magnet. Fig. 2-5 illustrates the magnetic field of attraction as it exists between the north and south poles of two magnets. Notice that the magnetic field appears to be "pulling" the two pole ends together.

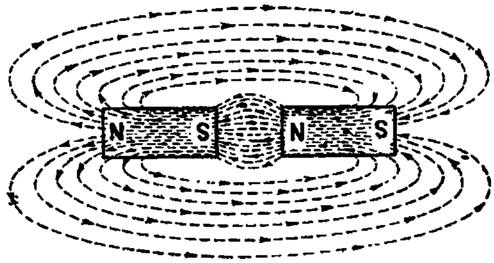


Fig. 2-5. Unlike magnetic poles attract.

Fig. 2-6 illustrates the magnetic field of repulsion between two like poles. Notice that the magnetic fields appear to be "pushing" each other away.

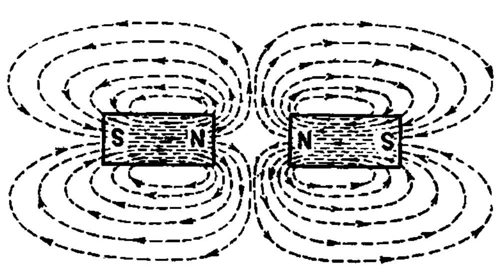


Fig. 2-6. Like magnetic poles repel.

THE MAGNETIC CIRCUIT

Magnetic flux flowing in a magnetic circuit is similar to electric current flowing in an electrical circuit. The magnetic flux has a direction of flow as well as a given strength or amplitude. Just as a current will flow only when the electrical circuit is complete, similarly, a magnetic flux can exist only if there exists a complete magnetic path.

SHIELDING

If a non-magnetic object, such as a tennis ball, were placed in the path of a magnetic field, as shown in Fig. 2-7, the lines of force would pass right through the ball just as the light shines through a piece of glass. However, if the tennis ball were covered up with a thick layer of soft iron, the lines of force would flow through the soft iron and not through the center of the ball. The reason for this is that the soft iron offers much less resistance to the magnetic flux than the air does. This is illustrated in figure 2-8.

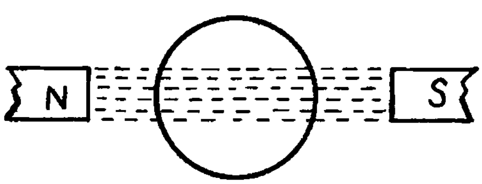


Fig. 2-7. No shielding.

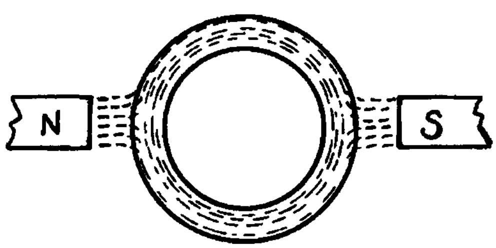


Fig. 2-8. Shielding.

Notice that the area in the center of the ball is now free of magnetic flux. The above example illustrates the principle of magnetic shielding which is so extensively used in electronic circuits.

People who work near strong magnetic fields usually encase their watches in soft iron through which the magnetic field will not penetrate. The delicate watch movement is therefore protected and will not be adversely affected by the magnetic field.

TEMPORARY AND PERMANENT MAGNETS

Soft iron can be magnetized easily by placing it in a magnetic field. However, as soon as the iron is removed from the magnetic field, it loses its magnetism. Such a magnet is called a TEMPORARY MAGNET. Steel or hard iron, on the other hand, which is difficult to magnetize, retains it magnetism after it has been removed from the magnetic field. A magnet of this type is called a PERMANENT MAGNET. Permanent magnets are usually made in the shape of a bar or a horse-shoe. The horse-shoe type has the stronger magnetic field because the magnetic poles are closer to each other. Horse-shoe magnets are used in the construction of headphones and loudspeakers.

RESIDUAL MAGNETISM

We stated above that a temporary magnet loses its magnetism when it is removed from a magnetic field. This is not entirely true because a small amount of magnetism does remain. This small amount is called the RESIDUAL MAGNETISM. Its importance will become apparent when we study the subject of generators.

ELECTROMAGNETISM

The same type of magnetic field that we have been discussing, exists around all wires carrying current. This can be proven by placing a compass next to a current-carrying conductor. It will be found that the compass needle will turn until it is at right angles to the conductor. Since a compass needle lines up in the direction of the magnetic field, the field must exist in a plane at right angles to the conductor. Fig. 2-9 illustrates a current-carrying conductor with its associated magnetic field. The current flows from left to right and the magnetic field is in the direction shown by the arrows. In Fig. 2-10, the current flows from right to left and the magnetic field is in the opposite direction.

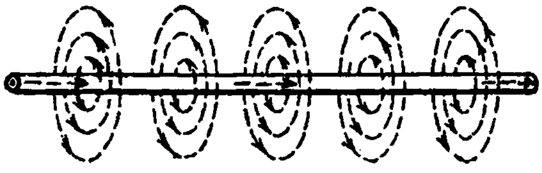


Fig. 2-9. Current left to right.

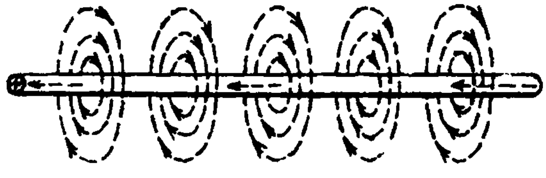


Fig. 2-10. Current right to left.

This magnetic field, of which only a number of cross-sections are shown, encircles the wire all along its length like a cylinder. Notice that the direction of the magnetic field, as indicated by the arrows, depends upon the direction of current flow in the wire.

THE COIL

If the same conductor is wound in the form of a coil, the total magnetic field about the coil will be greatly increased because the magnetic fields of each turn add up to make one large resultant magnetic field. See Fig. 2-11. The coil is called a SOLENOID or ELECTROMAGNET. The electromagnet has a north and south pole just like a permanent magnet. The rule for determining which end is the north pole and which end is the south pole is as follows: If we grasp the coil with the left hand so that the finger tips point in the direction of the current flow, the thumb will automatically point to the north pole of the electromagnet. Thus, we see that the polarity of an electromagnet depends upon both the way in which the turns are wound and the direction of the current flow. If we reverse either the direction of the current flow or the direction of the windings, the north pole will become the south pole; and the south pole will become the north pole.

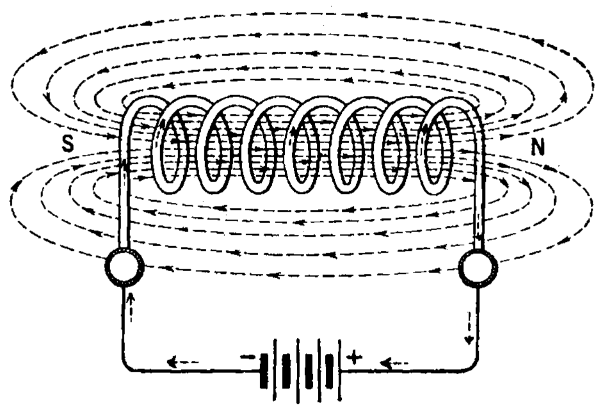


Fig. 2-11. Magnetic field produced by current flowing through coil of wire or solenoid.

A compass placed within a coil carrying an electric current, will point to the north pole of the coil. The reason for this is that the compass needle lines itself up in the direction of the magnetic lines of force. You will recall that inside a magnet, the direction of the field is from the south pole to the north pole. This is also true in the electromagnet illustrated in Fig. 2-11.

There are various factors which influence the strength of an electromagnet. They are:

1. The number of turns. - An increase in the number of turns in a coil increases the magnetic strength of the coil.

2. The amount of current. - If we increase the amount of current in a coil, the magnetic strength increases.

3. Permeability of the core. - The core of the coil is the material within the coil. It may be air, glass, wood or metal. If we wind the coil on an iron core, we find that the strength of the electromagnet is increased by several

hundred times over what it is with an air core. The iron is said to have more permeability that air; PERMEABILITY is the ability of a substance to conduct magnetic lines of force easily. Permeability is to a magnetic circuit as conductance is to an electrical circuit. If we have a core with a high permeability, we will have a large number of magnetic lines of force. This will result in a stronger magnetic field. Iron and permalloy are examples of materials having high permeability. Air is arbitrarily given a permeability of "one". The permeability of air is the basis for comparing the permeability of other materials. Iron and steel, for example, have a permeability of several hundred.

RELUCTANCE

Magnetic reluctance is similar to electrical resistance. Magnetic reluctance is the opposition that a substance offers to magnetic lines of force. It is the property of a material that opposes the creation of a magnetic flux within itself. The unit of reluctance is the REL or the OERSTED.

MAGNETOMOTIVE FORCE

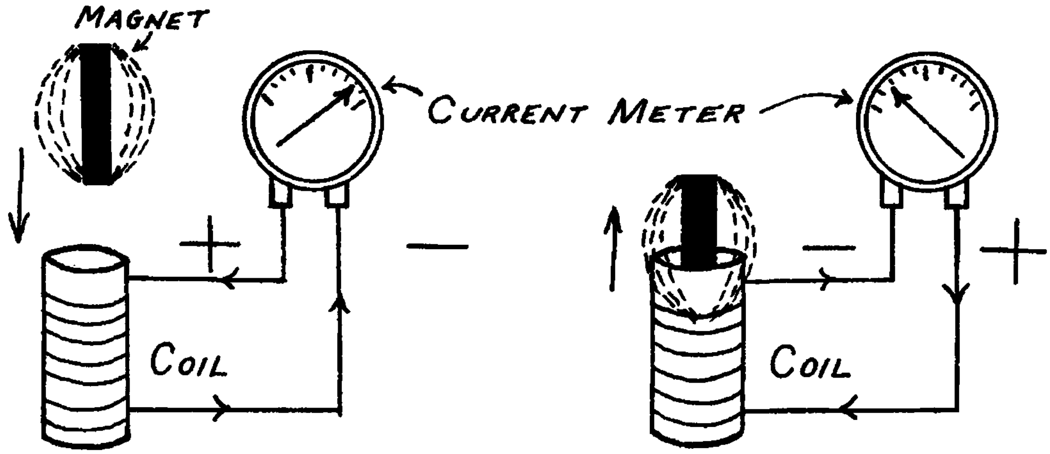
The magnetomotive force of a magnetic circuit is similar to the electromotive force of an electrical circuit. The magnetomotive force is the force which produces the magnetic lines of force or flux. The unit of magnetomotive force is the GILBERT. The number of gilberts in a circuit is equal to 1.26 x N x I, where N is the number of turns in the coil and I is the number of amperes. N x I, alone, is also known by the term AMPERE-TURNS. It is the number of turns multiplied by the number of amperes flowing in the circuit.

INDUCED VOLTAGE

If a coil of wire is made to cut a magnetic field, a voltage is induced in the coil of wire. The same reaction will occur if the magnetic field cuts the coil of wire. In other words, as long as there is relative motion between a conductor and a magnetic field, a voltage will be generated in the conductor. An induced voltage is sometimes called an induced e.m.f (e.m.f. is the abbreviation for electromotive force).

Fig. 2-12A shows an iron bar magnet being thrust into a coil of wire. The dotted lines about the magnet represent magnetic lines of force. The relative movement between the coil and magnet will result in the turns of wire of the coil cutting the lines of force of the magnetic field.

The net result of this action will be an induced voltage generated in the turns of the coil. This induced voltage will in turn cause a current to flow in the coil. A galvanometer (an instrument used to detect the presence of small currents) will deflect to the right indicating a current flow as a result of the induced e.m.f. Fig. 2-12B shows the magnet being pulled out of the coil. The galvanometer needle will now deflect to the left indicating that the current is now in the opposite direction. Reversing the direction of the motion of the magnet in relation to the coil reverses the direction of the induced e.m.f. This is indicated in Fig. 2-12B by the position of the galvanometer needle.



A. Magnet moving into coil. B. Magnet moving out of coil.

Fig. 2-12. Inducing a voltage in a coil of wire.

This method of electromagnetic induction is used in the generators which supply us with our electricity. If we wish to increase the strength of the induced e.m.f., we can do the following:

1. Use a stronger magnet.
2. Use more turns on the coil.
3. Move the magnet or the coil back and forth at a faster rate.
4. Have the coil cut the lines of force at right angles if it is not already doing so. In other words, the more lines of force cut per second, the stronger is the resultant, induced e.m.f.

In order to determine the direction in which the induced current will flow, we use LENZ'S LAW. Lenz's law states that: when a moving magnetic field induces an e.m.f. in a coil, a current will flow in such a direction as to form a magnetic field within the coil which will oppose the motion of the original magnetic field.

METERS

There are many different types of meters and instruments used in the electronics field. However, the most common meters are the voltmeter, the ammeter and the ohmmeter. While the function of each of these meters is different, they all make use of a basic meter movement, known as the D'Arsonval type of meter movement. We shall now discuss this movement as well as the three different meters.

D'ARSONVAL MOVEMENT

The D'Arsonval type of meter movement makes use of the principle of magnetic attraction and repulsion that has been described earlier in this chapter. A simplified illustration of the D'Arsonval movement is shown in figure 2-13. A coil of fine wire is suspended by 2 spiral springs in a magnetic field created by a permanent horseshoe magnet. A pointer is attached to the coil. If current flows through the coil, a magnetic field will be set up around the coil that will react with the field of the permanent magnet. If the current flows through the coil in the direction of the arrows, the left hand side of the coil will become a South magnetic pole and the right hand side will become a North magnetic pole. This will cause the coil to rotate in a clockwise direction (the South pole of the coil moves toward the North pole of the permanent magnet).

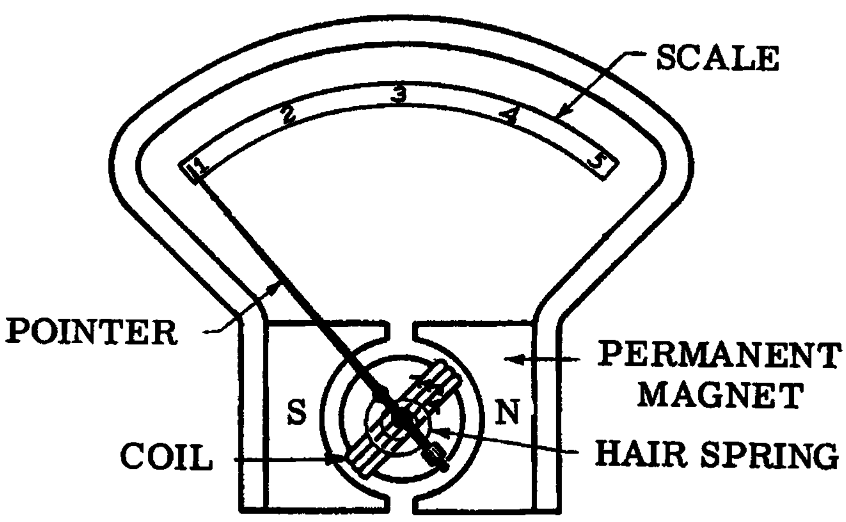


Fig. 2-13. The D'Arsonval meter movement.

The spiral springs at the ends of the coil (In figure 2-13, only one spring is shown; the other is hidden by the coil) tend to keep the coil from rotating. The magnetic reaction between the coil and the permanent magnet overcomes this resistance of the springs. If we increase the current through the coil, the coil will rotate more. This is due to the increased magnetic reaction between the permanent magnet and the stronger field of the coil. When the current through the coil is removed, the 2 springs force the coil to return to its original position. The pointer that is attached to the coil deflects across a scale, thereby indicating relative amounts of current that flow through the movement.

If the D'Arsonval meter movement is used alone as an instrument, it is called a Galvanometer. The Galvanometer merely indicates the presence of current; its scale is not calibrated to read amperes or volts.

THE AMMETER

In order to convert the D'Arsonval meter movement to an ammeter, we must add a SHUNT to it. A shunt is a very low value of resistance that is connected parallel to the meter movement. This is shown in figure 2-14.

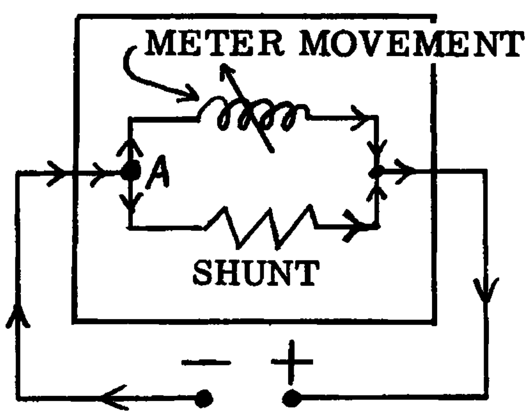


Fig. 2-14. The ammeter.

The current that enters the ammeter divides itself into two paths at point A. Because the shunt has a much lower resistance than the meter movement, most of the current flows through the shunt. Only a small amount of current flows through the meter movement. This is done because the meter movement is made up of very thin wire and would burn up if too much current flowed through it. The scale is calibrated so that it reads the total current flowing through both the meter movement and the shunt. The ammeter is always hooked up in series with the circuit that it is measuring. An ammeter that is used to measure current in the order of milliamperes is called a Milliammeter.

VOLTMETER

By adding a high resistance in series with the basic meter movement, we convert it to a voltmeter. This is shown in figure 2-15. The high resistance is called a multiplier and it limits the flow of current through the delicate meter movement. We know exactly how much voltage at the voltmeter's terminals will cause a certain amount

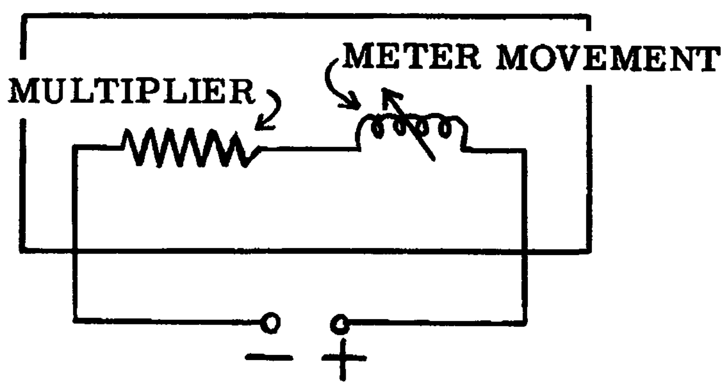


Fig. 2-15. The voltmeter.

of current to flow through the meter movement. We can, therefore, accurately calibrate the scale in volts. A voltmeter is always hooked in parallel to the part across which it is measuring the voltage.

OHMMETER

Figure 2-16 illustrates the basic ohmmeter. Unlike

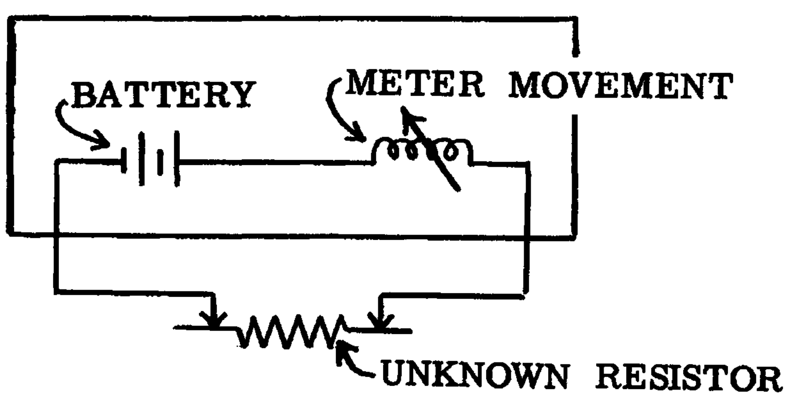


Fig. 2-16. The ohmmeter.

the voltmeter and ammeter, a source of voltage is required for the ohmmeter. We use a small dry cell battery for this. The battery is in series with the meter movement and the unknown resistance. As we place different amounts of resistance across the ohmmeter terminals we get different amounts of current flowing through the meter. Although the meter is actually reading current flow, the various amounts of current are the results of the different resistances measured by the ohmmeter. The scale is therefore calibrated in ohms.

CHAPTER 3

ALTERNATING CURRENT

INTRODUCTION

Chapter 1 deals with d-c, current that flows in one direction only. In this chapter, we will study a type of current that periodically reverses its direction of flow. This type of current is called ALTERNATING CURRENT (abbreviated a-c.). A popular method of producing Direct Current is by means of a battery; Alternating Current is produced by means of an a-c. generator.

DEVELOPMENT OF THE ALTERNATING CURRENT WAVE

Let us see how we can develop or generate Alternating Current. Figure 3-1 illustrates a loop of wire which can be rotated between the poles of a magnet. (The magnetic field that exists between the North and South poles is not shown in the diagram.)

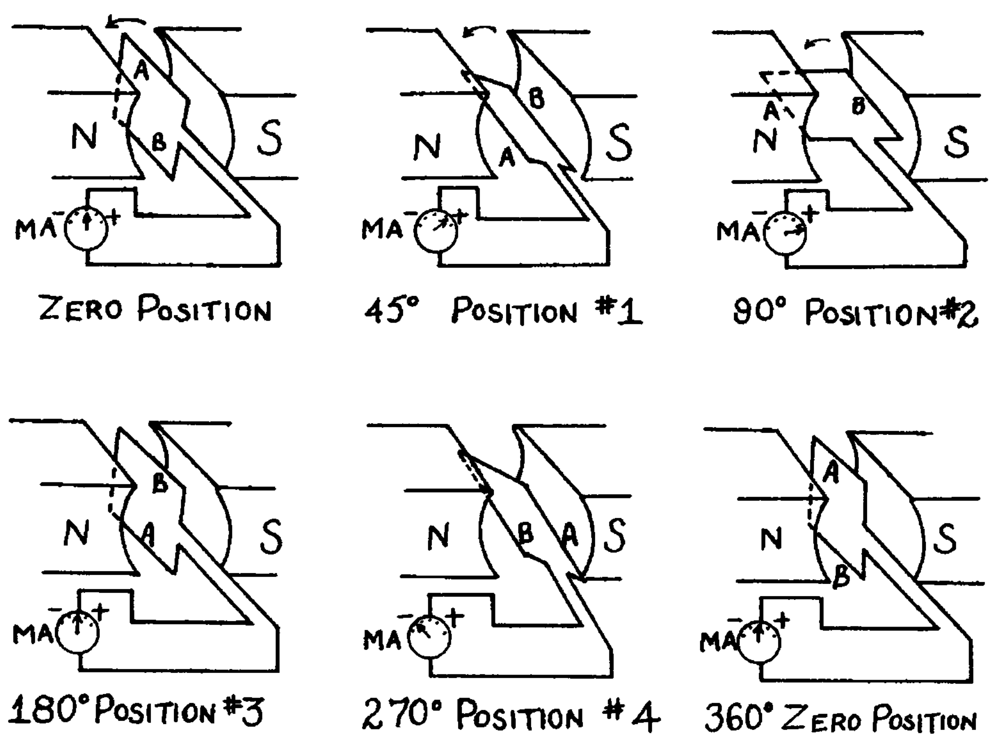


Fig. 3-1. Generating the alternating current sine wave.

If the loop of wire is rotated through the magnetic field, an electromotive force or voltage will be induced in the wire of the loop. This is because a conductor is cutting a magnetic field and whenever this happens, a voltage is induced in the conductor.

The voltage developed in the loop of wire will cause a flow of current. The milliammeter in series with the loop will indicate this current flow.

One of the factors influencing the strength of the induced e.m.f. is the relative cutting position of the loop as compared to the direction of the magnetic field. When the conductors of the loop cut perpendicular to the magnetic field, a maximum induced voltage will be generated. When the conductors of the loop are moving parallel to the magnetic field, no lines of force will be cut, and therefore no voltage will be generated. If the loop is rotated at a constant speed in a counter-clockwise direction, a current will flow those strength and direction will vary with different positions of the loop. The strength and direction of the current for different loop positions are indicated in fig. 3-1. Figure 3-2 is a graph showing the relationship between the amounts of current at different positions of the loop. Let us see exactly what happens at the various loop positions. At zero position the loop begins its rotation

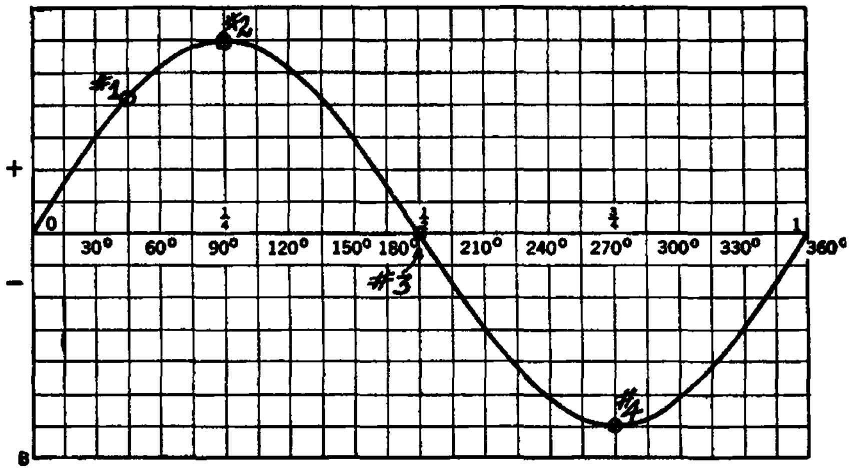


Fig. 3-2. The sine wave.

with the ammeter indicating zero current. (The conductors of the loop are moving parallel to the magnetic lines; therefore no induced e. m. f. will be generated.) When the loop has reached position #1, (45 degrees) the current flow which is indicated on the meter is in a direction which we shall arbitrarily call positive. When the loop has reached position #2, (90 degrees) the current is at a maximum since the conductors are cutting into the magnetic field at right angles. The current flow is still in a positive direction. From position #2 to position #3, the current decreases in value and is still positive. At position #3, (180 degrees) the current is zero once again, as it was at the start. This is because the conductor is moving parallel with the magnetic field but is not actually cutting it. From position #3, through #4 and back to the starting position, the current goes through the same changes as it has gone through from starting position (zero degrees) to position #3 (180 degrees). However, from position #3 to position zero, the direction of the current has reversed itself and is now considered negative. This is because the loop of wire is now cutting the magnetic field in the opposite direction. The opposite of positive is negative and this is shown on the graph by drawing the curve below the horizontal center line. The curve of figure 3-2, representing the varying current through the loop, is a waveform known as the ALTERNATING CURRENT wave. The mathematical name for a fundamental alternating current wave is a SINE WAVE.

The action just described is the basis for the alternating current generators that supply us with our electricity. Instead of one loop of wire, there are many turns of wire that are rotated through strong magnetic fields.

TO SUMMARIZE: ALTERNATING CURRENT, AS OPPOSED TO DIRECT CURRENT, CONTINUOUSLY VARIES IN STRENGTH (OR AMPLITUDE) AND PERIODICALLY REVERSES ITS DIRECTION OF FLOW.

CHARACTERISTICS OF THE SINE WAVE.

A sine wave has the following important characteristics:

1. The complete wave as shown in fig. 3-3 is known as a CYCLE. The wave is generated in one complete revolution of the loop from 0 to 360 degrees.

2. An alteration is one-half cycle, from 0° to 180°, or from 180° to 360°.

3. The frequency of a sine wave is the number of complete cycles in one second. Assuming that the sine

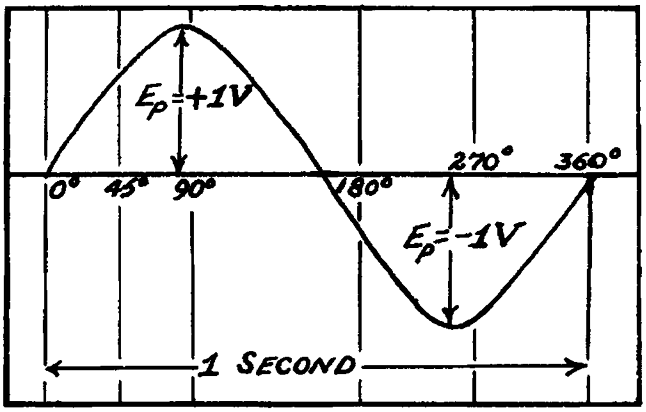


Fig. 3-3. The sine wave.

wave of figure 3-3 takes one second from 0° to 360°, then we have a frequency of one cycle per second. If 60 such cycles were completed in one second, the frequency would be 60 cycles per second. The time taken for one such cycle would be 1/60th of a second.

4. The height of the wave at any point is known as its AMPLITUDE. The highest point of the wave is called the maximum or PEAK AMPLITUDE, which in figure 3-3 is one volt. In a sine wave, the peaks always occur at 90 degrees and 270 degrees; the zero points always occur at 0, 180, and 360 degrees.

FREQUENCY

The unit of frequency is cycles per second or simply cycles. The abbreviation for cycles per second is CPS.

The frequency of the a-c power that is supplied to most homes is the United States today is 60 cycles per second. This is known as the POWER FREQUENCY. Radio waves transmitted by radio stations have a much higher frequency than the 60 cps. power frequency; they are usually above 400,000 cps. The abbreviation for radio frequency is r-f. Fig. 3-4 illustrates a low frequency of 60 cps and a high frequency of 1,000,000 cps.

Sound waves which can be heard by the human ear are called audible sounds, or audio sounds. The frequency range of audio sounds is from 16 to 16,000 cps. When sound waves are converted into electrical waves, they become known as audio frequencies (abbreviated a-f). For example, when our voice is amplified by a public address system, the sound waves from our throats strike the mic-

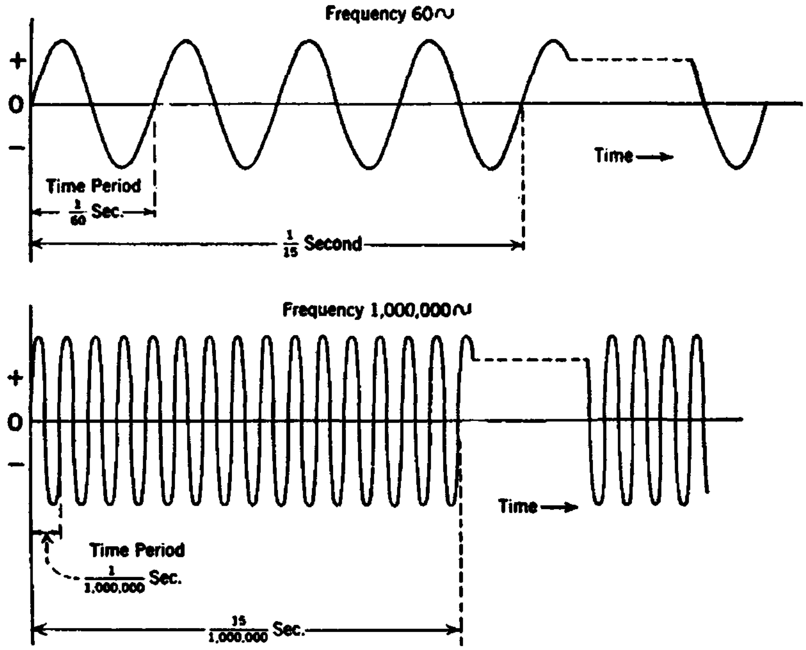


Fig. 3-4. Low and high frequency waves.

rophone and are converted into electrical frequencies in the audio range.

Higher frequencies are generally expressed in kilocycles or megacycles. A kilocycle (kc.) is equal to 1,000 cycles. The prefix "kilo" stands for one thousand. In order to convert cycles to kilocycles, we divide the number of cycles by 1,000.

For example: $25,000 \text{ cps} = \frac{25,000}{1,000} = 25 \text{ kc.}$

A megacycle (Mc.) is equal to 1,000,000 cycles. The prefix "meg" stands for one million. In order to convert cycles into megacycles, we divide the number of cycles by a million.

For example: $4,000,000 \text{ cps.} = \frac{4,000,000}{1,000,000} = 4 \text{ Mc.}$

THE MEANING OF PHASE RELATIONSHIP

If two alternating current generators are connected in parallel across a load, and if their armatures are started rotating together from exactly the same point, two e.m.f.s will be produced. Let us assume that the peak output of generator #1 is 7 volts, and the peak output of generator #2 is 5 volts. Since both generators start from the same position, at the same time and at the same speed, they will both produce the maximum and minimum voltages at the same instant. This is illustrated in fig. 3-5.

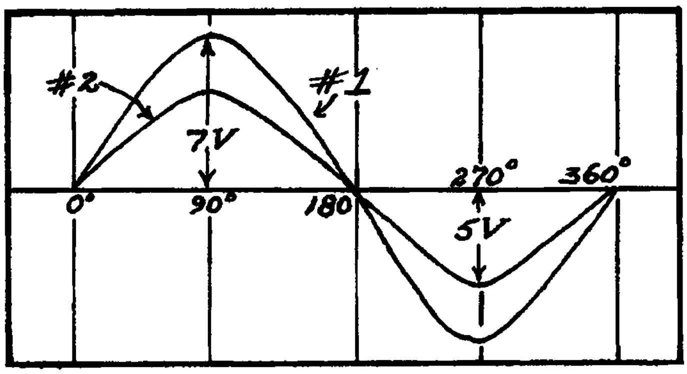


Fig. 3-5. In phase.

Because the maximums and minimums of the two waves occur at the same time, we say that they are IN PHASE WITH EACH OTHER. Being in phase, the voltages become additive. Therefore the resultant peak will be neither 7 volts nor 5 volts, but 12 volts, the combination of the two.

Now, let us assume that generator #2 is started an eighth of a revolution (45 degrees) after generator #1 has started. The output of the two generators will reach maximum and minimum points at different times. They will now be OUT OF PHASE as shown in fig. 3-6. It should be observed that the same voltages are being considered here as in fig. 3-5, but that the 5 volt wave LAGS 45° behind the 7 volt wave. These waves are said to be out of phase by 45°. If the 5 volt wave had started 90° later then the other, the 5 volt wave would be lagging the 7 volt wave by 90°. The angle by which one wave leads or lags another wave is known as the PHASE ANGLE.

EFFECTIVE VALUE OF AN A-C WAVE

Let us consider a d-c voltage of 100 volts, and an a-c wave whose peak is 100 volts (see fig. 3-7). We can see that the d-c voltage is really peak voltage at all times; that is, it remains constant. The a-c wave reaches its

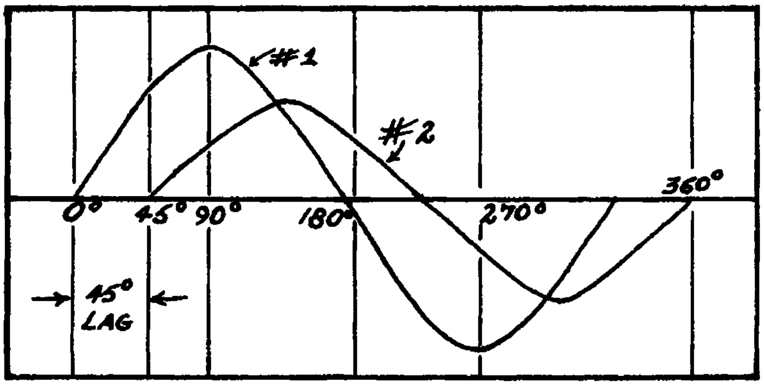


Fig. 3-6. Out of phase.

peak value only for a fraction of each cycle. If we connect a lamp first to the d-c voltage and then to the a-c, the lamp will light up more brilliantly when connected to the d-c. This is because the d-c voltage remains at 100 volts continuously, whereas the a-c voltage reaches a 100 volt peak only at two points during the cycle. In order for the lamp to light with equal brilliance on a-c as well as on d-c, we must raise the a-c voltage to 141 peak volts. Effectively then, 141 peak volts of a-c will light up a lamp as brilliantly as does 100 volts of d-c. The EFFECTIVE value of the 141 volt peak a-c wave is therefore 100 volts. This is illustrated in figure 3-8.

The effective value of an a-c wave (either voltage or current) is 0.707 times as great as its peak value. For example, the effective value of the above a-c wave is 0.707 x 141 volts or 100 volts, which is also the value of the d-c wave. The magnitude of an a-c wave is usually given by its effective value from which the peak value can be calculated to be 1.41 x the effective value. The effective volt-

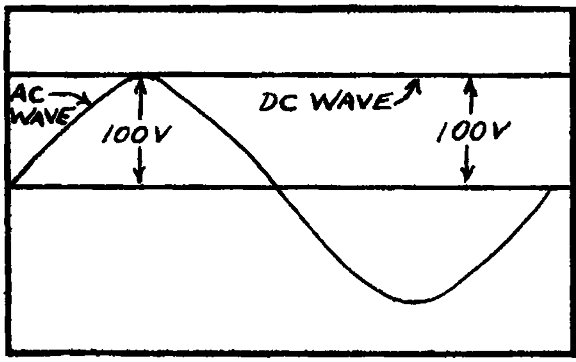


Fig. 3-7. D-C wave equals peak of A-C wave.

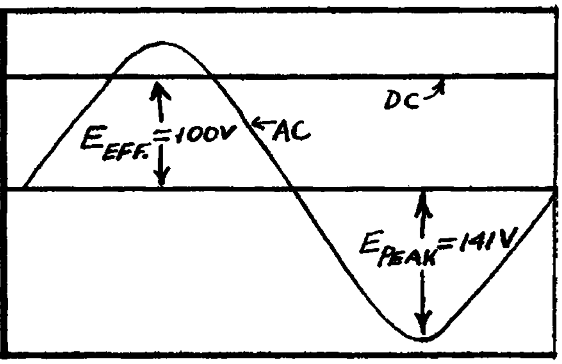


Fig. 3-8. Effective value of a sine wave.

age or current is frequently referred to as the rms (root-mean-square) value.

CALCULATION OF PEAK AND EFFECTIVE VALUE

The peak value of an a-c wave can be calculated from its effective value by using the following formula:

$$3\text{-}1) \qquad E_{peak} = 1.41 \times E_{eff}$$

The effective value of an a-c wave can be calculated from the peak value by using the following formula:

$$3\text{-}2) \qquad E_{eff} = 0.707 \times E_{peak}$$

Formulas 3-1 and 3-2 apply for all sine waves whether voltage or current.

The value given to an a-c wave will always be the effective value, unless otherwise stated. A-c voltmeters and ammeters will always read the effective value of the a-c wave unless it is otherwise indicated.

INDUCTANCE

In a previous paragraph we learned that a current-carrying coil of many turns behaves just like a magnet. The current will cause a magnetic field to surround the coil. If the current flowing through the coil is alternating, the magnetic field surrounding the coil will also be alternating. In fig. 3-9 we have a coil which has an alternating current flowing through it. This alternating current produces an alternating magnetic field around the coil which expands and collapses in step (or in phase) with the alternating current. When the current is zero, the magnetic field is zero; when the current reaches its peak at 90°, the

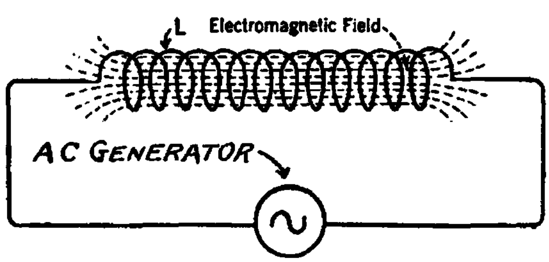


Fig. 3-9. A-C flowing through coil.

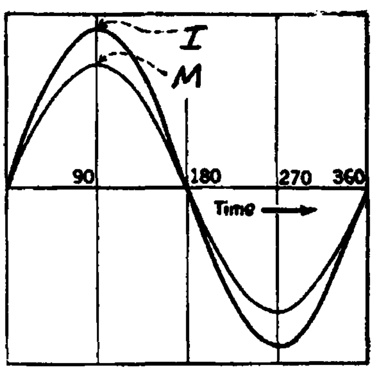


Fig. 3-10. Magnetic field and current in phase.

magnetic field reaches its maximum value. This is shown in fig. 3-10. Since the field starts from zero and builds up to a maximum, it is an expanding field. This expanding field must cut through the conductors of the coil itself. According to Lenz's law, the cutting action induces an e.m.f. in the coil which opposes the original current. In other words, alternating current flowing through a coil induces a voltage into the coil that is in opposition to the original voltage. The process wherein an induced e.m.f. is generated in a coil is called SELF-INDUCTION. The coil of wire is called an INDUCTANCE. The unit of inductance is the HENRY; and the abbreviation of henry is h. The symbol for inductance if L. Smaller and more practical units of inductance are the millihenry (mh) and the microhenry (μh).

$$1 \text{ millihenry} = \frac{1}{1000} \text{ of a henry}$$

$$1 \text{ microhenry} = \frac{1}{1,000,000} \text{ of a henry}$$

FACTORS AFFECTING THE INDUCTANCE OF A COIL

1. Number of turns - The inductance of a coil varies as the square of the number of turns. For example, if we have two coils of the same length and diameter, and coil #1 has four turns while coil #2 has eight turns, the inductance of coil #2 will be four times the inductance of coil #1.

$$\frac{L_2}{L_1} = \frac{8^2}{4} = \frac{64}{16} = \frac{4}{1} ; \; L_2 = 4 \times L_1$$

2. Core material - The inductance of a coil varies with the core material. An iron-core coil will have a higher inductance than an air-core coil. Since iron has a higher permeability than air there will be a stronger magnetic field around the iron-core coil which results in a high inductance.

3. Length of coil - As the length of a coil increases, the number of turns remaining constant, the inductance of the coil decreases. This is because the reluctance of the magnetic circuit increases due to the increased coil length. This results in a weakening of the magnetic field.

4. Diameter of coil - The inductance of a coil varies directly as the square of the diameter. For example, if we double the diameter of a coil, the inductance will increase four times.

INDUCTIVE REACTANCE

Due to the counter-electromotive force of self-induction, an inductance resists a change of current flow. This resistance or holding-back effect is measured in ohms. Instead of being called a resistance, however, it is called a reactance; an INDUCTIVE REACTANCE. The symbol for inductive reactance is X_L.

The formula for computing inductive reactance is:

3-3) $X_L = 2\pi fL$

where: the symbol π = 3.14
f = frequency of the applied voltage in cps.
L = inductance of the coil in henries.

(If the inductance is given in mh or μh, it must first be converted into henries before it can be used in formula 3-3).

Problem: Find the inductive reactance of a 10 millihenry coil at a frequency of 60 cycles per second.

Solution: First convert 10 mh to h; then use formula 3-3.

1) $10 \text{ mh} = \frac{10}{1000} \text{ h} = \frac{1}{100} \text{ h}$

2) $X_L = 2\pi fL$

3) $2 \times 3.14 \times 60 \times \frac{1}{100} = 3.768 \text{ ohms}$

PHASE ANGLE IN AN INDUCTIVE CIRCUIT

If a-c is applied to an ordinary resistive circuit the voltage and current are in phase with one another. However, this is not true if a-c is applied to an inductive circuit. If we apply a-c to a "pure" inductive circuit (one that contains only inductance and no resistance), the current will lag the impressed voltage by 90°. This is illustrated in fig. 3-11. The waveform E starts 90° ahead of the waveform I. We say that the phase angle between the voltage and current is 90°. Since, in actual practice, a coil or inductance will always have some resistance (the resistance of the wire), the phase angle between the impressed e.m.f. and the current becomes less than 90°. The greater the proportion of resistance, the smaller will be the phase angle. Fig. 3-12 illustrates the current lag-

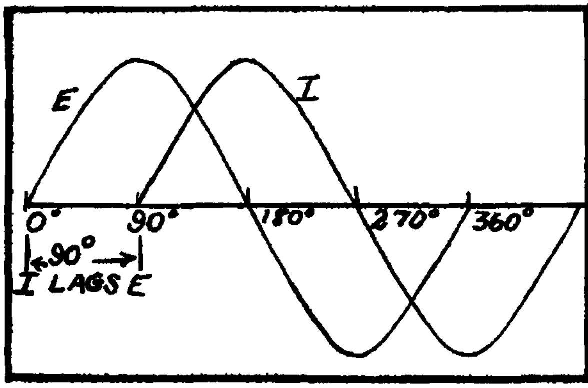


Fig. 3-11. Pure inductive circuit.

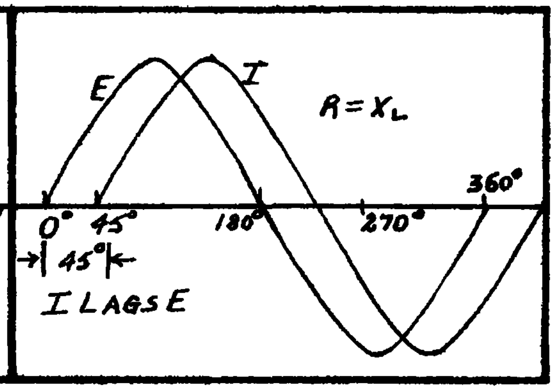


Fig. 3-12. Inductive-resistive circuit.

ging the impressed voltage by 45° in a circuit containing equal amounts of resistance and inductive reactance. When there is all resistance and no inductance, the phase angle becomes 0 degrees. The current and voltage are then in phase. This is to be expected since it is the counter e. m. f. of the inductance which causes the current to lag.

IMPEDANCE OF AN INDUCTIVE CIRCUIT

In fig. 3-13A the total resistance which opposes the flow of current is $R_1 + R_2$. The total resistance to current flow in a series circuit is the sum total of the individual resistances. If the circuit consists of resistance and inductive reactance, as shown in fig. 3-13B, the total

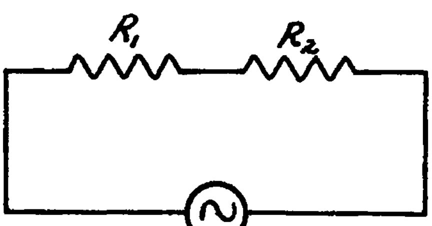


Fig. 3-13A. Resistive circuit.

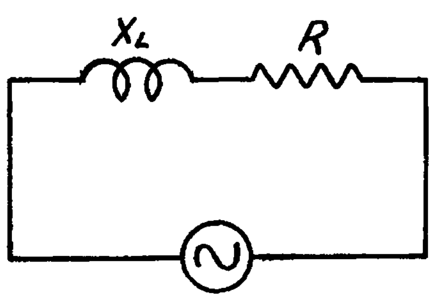


Fig. 3-13B. Inductive-resistive circuit.

resistance to the flow of current is called the IMPEDANCE. The symbol for impedance is Z. The unit of impedance is the ohm. Unlike a resistive circuit, the impedance of an inductive circuit is NOT equal to the simple sum of the resistance and the inductive reactance. The impedance of an inductive circuit can be calculated by using the following formula:

$$3\text{-}4)\quad Z = \sqrt{R^2 + X_L{}^2}\ \text{ohms}$$

where: Z is the total impedance in ohms
X_L is the inductive reactance in ohms.
R is the series resistance in ohms

Problem: If a circuit contains a coil and resistor in series, and if the coil has a reactance of 12 ohms and the resistor is 5Ω, what is (1) the total impedance and (2) the current? The source voltage is 130 volts.

Solution: Note that the impedance IS NOT simply the sum of R and X_L, or 17 ohms. The impedance in an INDUCTIVE CIRCUIT must be calculated by using formula 3-4.

1) $Z = \sqrt{R^2 + X_L{}^2}$

2) $\sqrt{5^2 + 12^2} = \sqrt{25 + 144} = \sqrt{169}$

3) $Z = 13$ ohms

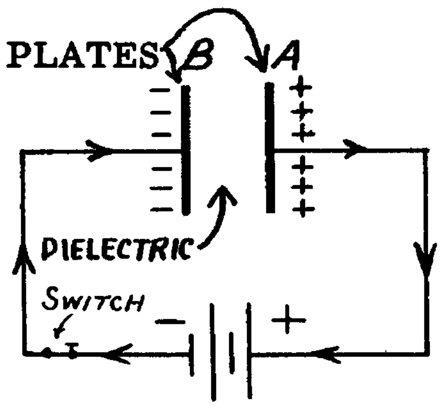
The current in the circuit is simply the total voltage divided by the impedance. This is in accordance with Ohm's Law.

$$I = \frac{E}{Z} = \frac{130}{13} = 10 \text{ amperes}$$

THE CONDENSER

We have thus far studied two radio parts which exert a limiting effect upon current: 1) resistors and 2) coils or inductors (which exert a limiting effect upon a-c only.) We shall now investigate another limiting device which has a tremendous application in radio: the CONDENSER or CAPACITOR.

A condenser is a device having, in its simplest form, two conducting plates separated from each other by an insulator. This insulator is called a DIELECTRIC. The dielectric may be air, mica, oil, paraffined paper, etc. Fig. 3-14 illustrates a two plate condenser connected across a battery. When the switch is closed, a certain



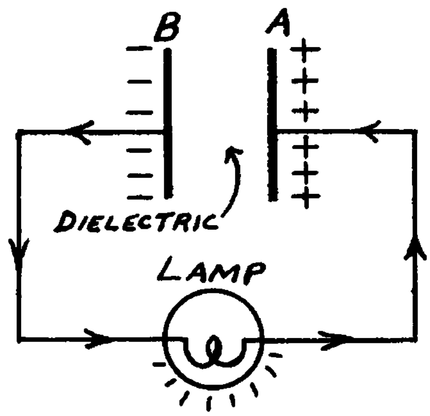


Fig. 3-14. Charging a condenser. Fig. 3-15. Condenser discharging.

number of free electrons on plate A will be attracted to the positive side of the battery. Plate A will therefore be left with a positive charge. At the same time, plate B will have the same number of electrons pushed on to it by the negative side of the battery. This electron flow continues until a charge is built up on the condenser plates which develop a voltage equal to the battery voltage. The plates of the condenser are now said to be electrically charged. The charge on the condenser plates depends upon the size of the plates (the capacity), and the force of the battery (the e.m.f.). Notice that the accumulated electrons on plate B cannot cross to the other plate because of the insulator dielectric between them.

When the condenser has become fully charged, the voltage across the condenser is equal to the battery voltage. If we disconnect the battery from the condenser, the condenser will continue to hold its charge. If a lamp is now connected across the charged condenser (see fig. 3-15), the excess electrons on plate B will flow through the lamp and onto positive plate A. This is because electrons are attracted to a positively charged body. During the brief duration of the electron flow, the lamp will light for an instant indicating that a current is passing through it. The electrons will continue to flow until plate B no longer has a surplus of electrons. Plate B is then said to have a zero charge. Plate B is now neutral, and of course plate A will have regained its electrons so that it is also neutral. The condenser is now said to be DISCHARGED. A condenser, then, is a device in which electricity may be stored for a period of time.

CAPACITANCE

The capacitance of a condenser is determined by the following factors: the surface area of the plates, the number of plates, the spacing between plates and the type of dielectric used.

The symbol for capacitance is C. The unit of capacitance is the FARAD; the abbreviation for farad is fd. Since the farad is an extremely large unit of capacitance, it is very rarely used. The more common smaller units of capacitance are the microfarad and the micro-microfarad. The symbol for microfarad is μ fd; the symbol for micromicrofarad is $\mu\mu$ fd.

$$1 \text{ microfarad} = \frac{1}{1,000,000} \text{ of a farad}$$

$$1 \text{ micromicrofarad} = \frac{1}{1,000,000,000,000} \text{ of a farad}$$

The range of condensers used in radio work may vary all the way from 5 $\mu\mu$fd up to 100 μfd. Figure 3-16 illustrates several different types of condensers used in radio work.

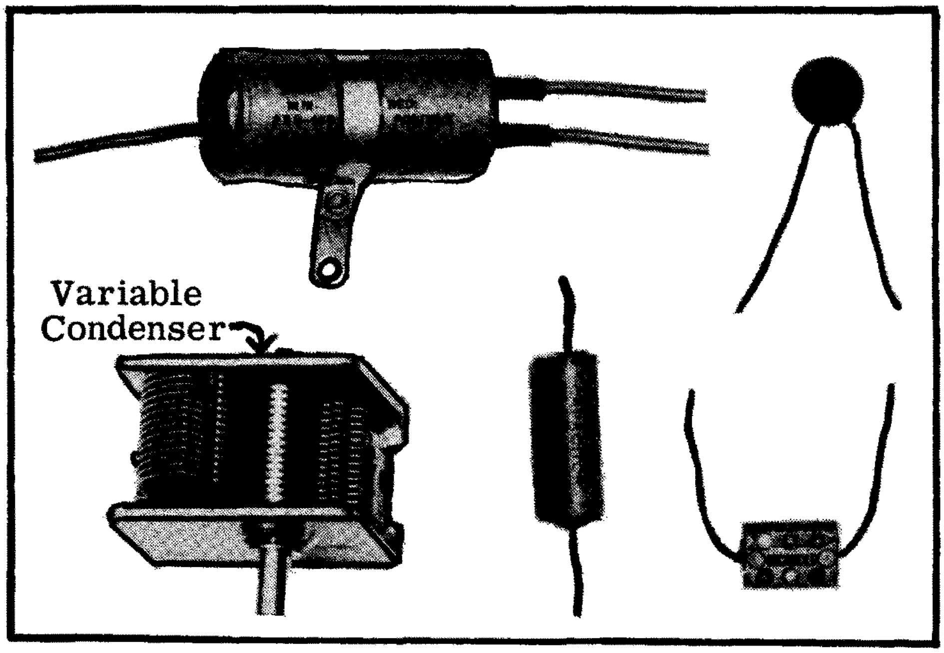


Fig. 3-16. Various types of condensers used in radio.

THE DIELECTRIC

The dielectric is nothing more than the name for the insulating material between the plates of a condenser. Examples of dielectrics used in condensers are mica, ceramic, glass, oil, waxpaper, etc. Condensers with different dielectric materials will have different capacities. For example, a condenser with a mica dielectric will have a larger capacity than an air dielectric condenser of similar dimensions. The dielectric determines the ability of a condenser to hold more or less charge.

THE VARIABLE CONDENSER

Fig. 3-17 shows the schematic symbol of a condenser whose capacity can be varied. This condenser is known as a VARIABLE CONDENSER, and is used whenever the capacitance in a circuit must frequently be changed. The station selector in a radio receiver is a typical example of a variable condenser. A variable condenser is illustrated in figure 3-16.

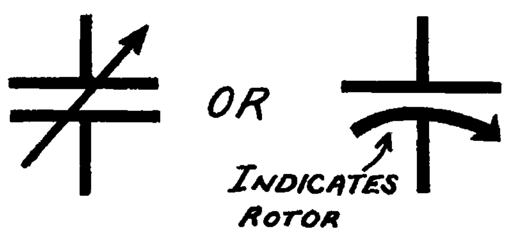
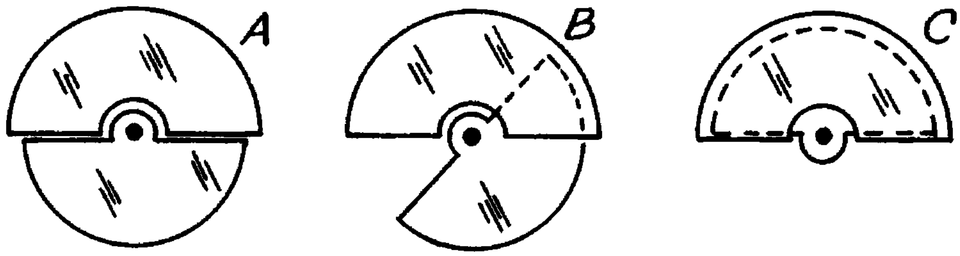


Fig. 3-17. Variable capacitor symbol.

Most variable capacitors are of the air dielectric type. A single variable capacitor consists of two sets of metal plates insulated from each other and so arranged that one set of plates can be moved in relation to the other set. The stationary plates are the stator; the movable plates, the rotor. As the rotor is turned so that its plates mesh with the stator plates, the capacity increases. Fig. 3-18 illustrates the rotor position of a variable condenser for minimum, intermediate, and maximum capacity. If several variable condensers are connected on a common shaft so that all may be controlled at the same time, the result is known as a ganged condenser. Figure 12-3 illustrates a three-gang condenser.



A. Minimum. B. Intermediate. C. Maximum.

Fig. 3-18. Variable condenser settings.

VOLTAGE RATING

Condensers are rated not only in capacity, but also for the maximum voltage they will stand before breaking down. If the voltage across a condenser is too high, the electrical pressure will force electrons to jump from the negative plate to the positive plate. This will puncture the dielectric and, in most cases, will ruin the condenser.

A typical condenser would be rated as follows:

Capacity - 8μfd.

d-c working voltage - 450 v

"d-c working voltage" indicates that the condenser may be used in any circuit as long as the d-c voltage or the a-c peak voltage across it does not exceed 450 v.

CONDENSERS CONNECTED IN SERIES COMBINATION

When two or more condensers are connected end to end as shown in figures 3-19 and 3-20, the condensers are said to be connected in series.

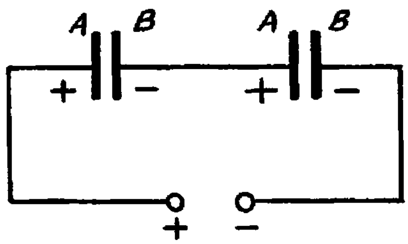


Fig. 3-19. Condensers in series.

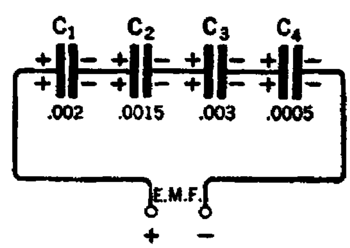


Fig. 3-20. Problem.

THE EFFECT OF CONNECTING CONDENSERS IN SERIES IS TO DECREASE THE TOTAL CAPACITY OF THE CIRCUIT, just as the total resistance of a circuit is decreased when resistors are connected in parallel.

The total capacity of condensers connected in series can be computed by using the following formula:

$$3\text{-}5)\quad C_T = \cfrac{1}{\cfrac{1}{C_1} + \cfrac{1}{C_2} + \cfrac{1}{C_3} + \text{etc.}}$$

Problem: If four condensers with capacities as shown in fig. 3-20 are connected in series, what is the total capacity?

Solution: Substitute in formula 3-5 the capacity values of the four condensers shown in fig. 3-20.

$$C_T = \cfrac{1}{\cfrac{1}{.002} + \cfrac{1}{.0015} + \cfrac{1}{.003} + \cfrac{1}{.0005}}$$

Dividing .002 into 1, we get 500, etc.

$$2)\quad C_T = \frac{1}{500 + 667 + 333 + 2000}$$

$$3)\quad C_T = \frac{1}{3500} = .00029\,\mu\text{fd.}$$

From the above example it should be clear that in a series arrangement of condensers the total capacity of the series combination (bank) is always less than the capacity of any individual condenser in the bank.

CONDENSERS CONNECTED IN PARALLEL COMBINATION

Figure 3-21 illustrates 3 condensers hooked together in parallel. Connecting condensers in parallel has the effect of greatly increasing the effective plate area. Since the effective plate area is increased, the effective capacity is also increased, as shown in fig. 3-21.

When condensers are connected in parallel, the resulting capacity is equal to the sum of the individual ca-

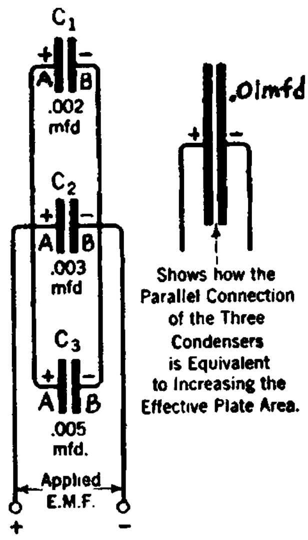


Fig. 3-21. Condensers in parallel.

pacities. The total capacity can be computed by using the following formula:

3-6) $C_T = C_1 + C_2 + C_3$, etc.

Problem: If three condensers of .002 μfd, .003 μfd, and .005 μfd are connected in parallel, what is the total capacity?

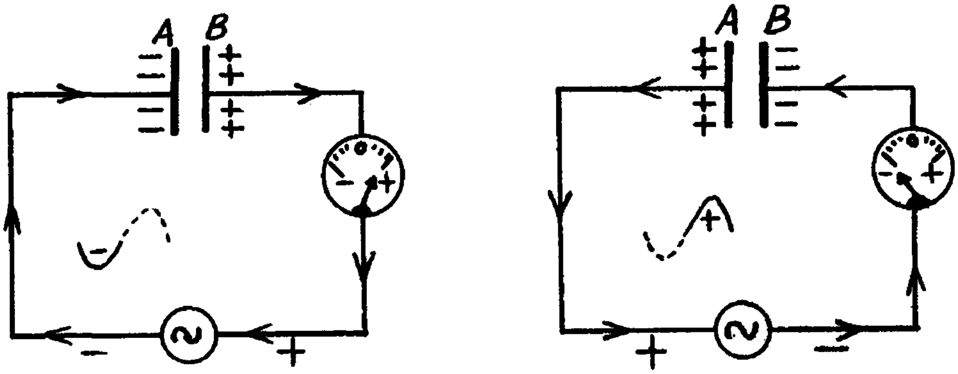
Solution: Use formula 3-6.

1) $C_T = C_1 + C_2 + C_3$

2) $C_T = .002 + .003 + .005 = .01\ \mu$fd.

THE CONDENSER IN AN ALTERNATING CURRENT CIRCUIT

If a condenser is placed across an a-c generator in series with an a-c ammeter, (as shown in figure 3-22A) the following action occurs: When the left side of the generator is negative, electrons flow from the negative terminal of the generator to condenser plate A. At the same time, electrons flow off plate B and through the ammeter to the right side of the generator. When the polarity of the a-c generator reverses, as in figure 3-22B, the electrons reverse in direction and flow from the left plate through the generator and ammeter onto the right plate. This reversal of current flow occurs many times in one second, depending upon the frequency of the generator.



A. Negative alternation. B. Positive alternation.

Fig. 3-22. Condenser across an a-c generator.

The ammeter registers a reversal of current flow since electrons flow through it first in one direction and then in the other. In other words, although an electric current does not flow through the condenser itself, it does flow in and out of the plates of the condenser, and therefore flows back and forth through all the components connected in series with the condenser. When it is said that a-c flows through a condenser, what is actually meant is that the current is flowing in and out of the plates of the condenser. As far as the other components in the circuit are concerned, the a-c might just as well be flowing through the condenser.

CAPACITIVE REACTANCE

Fig. 3-22A shows a condenser connected across an a-c generator. At the instant shown, (left side of generator is negative, right side is positive) electrons rush from the left side of the generator to the left plate of the condenser. At first, only a few electrons will have reached the condenser plate A. However, these few electrons will attempt to repel the electrons that are approaching this condenser plate. This same action occurs on the plate B when the polarity of the generator reverses itself. (see fig. 3-22B) The first few electrons to reach the right plate of the condenser will oppose the electrons that are approaching this plate. Every time the polarity of the generator reverses, the first few electrons that pile up on the condenser will repel the remaining electrons. Thus we see that a condenser offers a certain amount of opposition to alternating current. This opposition is actually a COUNT-

ER-E. M. F., since the original charge on the condenser plates represents an opposition voltage to the generator voltage. This counter-e. m. f. will vary inversely with the capacity of the condenser and the frequency of the a-c generator. The higher the frequency of the generator, the less time there will be for electrons to charge the condenser. The condenser counter-e. m. f., therefore, decreases with increase in generator frequency. As the capacity of the condenser increases, the charge will be distributed over an effectively larger plate area, decreasing the counter-e. m. f. The counter-e. m. f., therefore, decreases with an increase in condenser capacity.

The opposition or resistance that the condenser offers to a-c is called CAPACITIVE REACTANCE. The symbol for capacitive reactance is X_C, and its unit is the OHM.

In order to compute the capacitive reactance of a condenser in an a-c circuit, the following formulas are used:

1. - when the capacity is given in farads;

$$\text{3-7)} \quad X_C = \frac{1}{2\pi fC}$$

where: X_C = capacitive reactance in ohms
2π = 6.28
f = frequency of a-c in cycles
c = capacity in farads

2. - when the capacity is given in microfarads;

$$\text{3-8)} \quad X_C = \frac{1,000,000}{2\pi fc}$$

where: X_C = capacitive reactance in ohms
2π = 6.28
f = frequency of a-c in cycles
c = capacity in microfarads

Problem: Find the capacitive reactance of a 15 μfd condenser in an a-c circuit where the frequency of the generator is 1 kilocycle.

Solution: Use formula 3-8.

$$\text{1)} \quad X_C = \frac{1,000,000}{2\pi fc}$$

$$2)\ X_C = \frac{1,000,000}{6.28 \times 1000 \times 15}$$

$$3)\ X_C = \frac{1,000,000}{94,200} = 10.6\,\Omega$$

In an a-c circuit, a condenser acts somewhat differently than a coil. The inductance of a coil OPPOSES CURRENT CHANGES by means of a self-induced e. m. f.; a condenser OPPOSES VOLTAGE CHANGES by means of the counter-e. m. f. developed on its plates.

THE PHASE ANGLE

In an inductive circuit we found that the current lags the impressed voltage. In a capacitive circuit the opposite is true; THE CURRENT LEADS THE IMPRESSED VOLTAGE. This can be analyzed as follows: When a voltage or battery is first placed across a condenser, there cannot be any back e. m. f. across the condenser because its plates are initially uncharged. A condenser can only have a voltage across its plates provided there is a charge on its plates. If the charge is initially zero, then the counter voltage must be initially zero. Since the condenser offers no initial back e. m. f., the initial current into it is at maximum. Therefore, the current is at a maximum when the voltage is still zero; or, the current leads the voltage. When the current falls to zero, the voltage just reaches its maximum value.

The current leads the source voltage by 90° in a pure capacitive circuit (see fig. 3-23). If we introduce

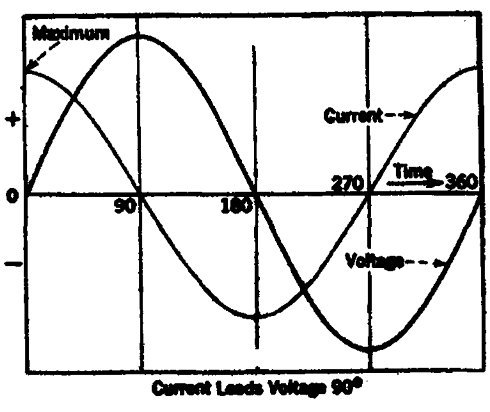


Fig. 3-23. Pure capacitive circuit.

some resistance into the circuit, the current will lead the voltage by less than 90°. When the resistance and capacitive reactance are equal, the current will lead the voltage by 45°. The greater the resistance in the circuit, the smaller is the phase angle.

IMPEDANCE OF SERIES CIRCUITS

In a previous paragraph we discussed the impedance of a series circuit containing resistance and inductive reactance. We learned that the total impedance of the circuit was not the simple sum of the resistance and the inductive reactance. The same is true for the impedance of a circuit containing resistance and capacitive reactance. The formula that is used to determine the impedance of an inductive

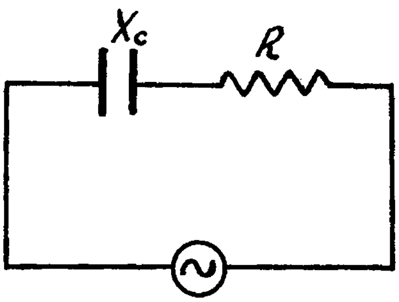


Fig. 3-24. R-C circuit.

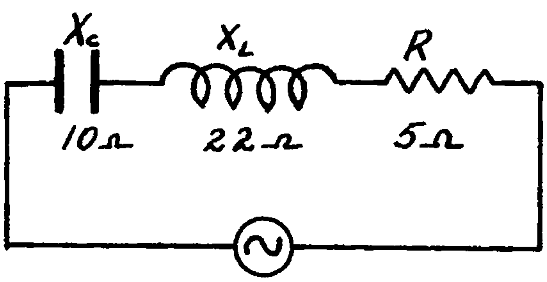


Fig. 3-25. R-L-C circuit.

circuit is; $Z = \sqrt{R^2 + X_L^2}$. To determine the impedance of a capacitive circuit, we use the same formula except that we substitute X_C for X_L. The formula now becomes:

$$3\text{-}9)\quad Z = \sqrt{R^2 + X_C^2}\ \text{ohms}$$

where: R = series resistance in ohms
X_C = capacitive reactance in ohms

Problem: If in a resistive-capacitive circuit X_C=4 ohms, and R=3 ohms, what is the total impedance?
Solution: Use formula 3-9.

1) $Z = \sqrt{R^2 + X_C^2}$

2) $Z = \sqrt{3^2 + 4^2}$

3) $Z = \sqrt{9 + 16}$

4) $Z = \sqrt{25} = 5$ ohms

IMPEDANCE OF SERIES R-L-C CIRCUITS

Observe the series circuit of fig. 3-25. Notice that this circuit contains resistance, inductance and capacitance. What is the relationship of X_L to X_C, and how can we figure out the impedance of such a circuit? The effects of X_L and X_c on the current in a series a-c circuit can be understood by considering the game "Tug - of-war". The rope represents the current, and the men pulling on the rope in opposite directions represent the actions of X_L and X_c on the current. X_L and X_c act on the current in opposition. If X_L and X_c are equal, they will have no effect on the current since their effects will cancel. If X_L is larger than X_c, it will be the difference between X_L and X_c which will effect the current. Conversely, if X_c is larger than X_L, it will also be the difference between X_c and X_L which will affect the current. Before we can determine the impedance of the circuit we must calculate the total reactance. The total reactance of the circuit is the difference between the two reactances, X_L and X_c. This difference is then added to the resistance in a manner similar to that of formula 3-9.

The following formula is used to find the impedance of a circuit containing Resistance, Inductance and Capacitance.

3-10) $Z = \sqrt{R^2 + (X_L - X_c)^2}$

where: Z is the total impedance in ohms
R is the resistance in ohms
X_L is the inductive reactance in ohms
X_c is the capacitive reactance in ohms

Problem: Find the impedance of a circuit which contains a resistance of 5 ohms, an inductive reactance of 22 ohms, and a capacitive reactance of 10 ohms. (fig. 3-25)

Solution: Use formula 3-10.

1) $Z = \sqrt{R^2 + (X_L - X_c)^2}$

2) $Z = \sqrt{R^2 + (22 - 10)^2} = \overline{25 + (12)^2}$

3) $Z = \sqrt{25 + 144} = \sqrt{169} = 13$ ohms

SERIES RESONANCE

In the previous paragraph we studied a series a-c circuit containing resistance, inductance and capacitance.

In order to find the impedance of such a circuit we had to use formula 3-10.

Let us assume that the values of L, C and the frequency of the a-c generator are so chosen that X_L and X_C are equal. In this case the quantity, $(X_L - X_C)$ in formula 3-10 would be equal to zero. The two reactances are equal and cancel each other. (recall the analogy of the game of tug-of-war) The only opposition that remains in the circuit is the resistance, R. Therefore, the IMPEDANCE IN A CIRCUIT, CONTAINING EQUAL AMOUNTS OF INDUCTIVE AND CAPACITIVE REACTANCE, IS EQUAL TO THE RESISTANCE IN THE CIRCUIT. The current flowing in the circuit is at its maximum value; and the impedance of the circuit is at its minimum value. The condition where the inductive reactance is equal to the capacitive reactance in a circuit is known as RESONANCE. Since the components of this circuit are in series, the circuit is known as a SERIES RESONANT CIRCUIT. The frequency of the generator at resonance is called the RESONANT FREQUENCY.

If the frequency of the a-c generator is increased, the inductive reactance will go up, and the capacitive reactance will go down. The difference between the reactances is a number larger than zero. Our circuit is therefore no longer resonant. The impedance of the circuit has increased since the resistance is no longer the sole opposition to current flow. The impedance of the circuit is now determined by formula 3-10. Since the circuit impedance has increased, the current will now decrease below its resonance value.

If the generator frequency is decreased, the inductive reactance goes down, and the capccitive reactance goes up. The reasoning in the preceding paragraph applies here as well. In this case, the current also decreases below its resonance value. We can therefore conclude that the current is a maximum at resonance, and decreases on either side of the resonant frequency.

THE RESONANCE CURVE

If we were to draw a curve of the variations of current with changes in generator frequency, we would obtain a curve known as a RESONANCE CURVE. This is illustrated in fig. 3-26. The vertical direction represents the amount of current flowing in the circuit for different frequencies. The horizontal direction represents the different generator frequencies. As the frequency of the generator is varied above and below the resonant frequency, the current will vary in the manner indicated. Notice that the

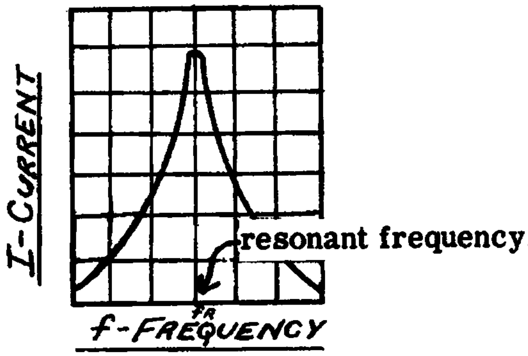


Fig. 3-26. The resonance curve.

current reaches a peak only at resonance, and decreases in value at either side of resonance.

RESONANT FREQUENCY OF A SERIES CIRCUIT

For every value of inductance and capacitance in a series circuit, there is ONE frequency at which the inductive reactance equals the capacitive reactance. This frequency is referred to as the resonant frequency. The resonant frequency can be calculated by using the following formula:

$$\text{3-11)} \quad f_R = \frac{1}{2\pi\sqrt{LC}}$$

where: f_R is the resonant frequency in cycles
2π is 6.28
L is the inductance in henries
C is the capacitance in farads

In order to find the resonant frequency, when L and C are given in more common units such as microhenries and microfarads, the above formula is modified as follows:

$$\text{3-11A)} \quad f_R = \frac{1,000,000}{2\pi\sqrt{LC}}$$

where f_R is the resonant frequency in cycles
2π is 6.28
L is the inductance in microhenries
C is the capacitance in microfarads

It is important to remember that the resonant frequency of a circuit goes up when either the inductance or capacitance goes down. This becomes apparent if we inspect the above formula.

PARALLEL RESONANCE

Fig. 3-27 illustrates a coil and condenser connected in parallel across an a-c generator. Note that R_L represents the d-c resistance of the coil. If the frequency of the generator is adjusted so that X_L is equal to X_C, we would have a condition of resonance known as PARALLEL RESONANCE. In a parallel resonant circuit, there are two different currents flowing; first, there is the line current (I_{Line}) which flows from the generator through the resonant circuit, and back to the generator. At resonance the line current is very low in value. The line current increases in value above and below resonance. At resonance, the line current supplies just enough energy to the parallel circuit to overcome the losses in the resistance of the coil. Secondly, there is the current which flows back and forth between the coil and condenser. This current, I_C, is called the INTERNAL CIRCULATING CURRENT. At resonance, the internal circulating current is very high compared to the line current. Since the reactances of the coil and condenser are equal and cancel each other, the only opposition to the internal circulating current at resonance is the resistance of the coil "R_L".

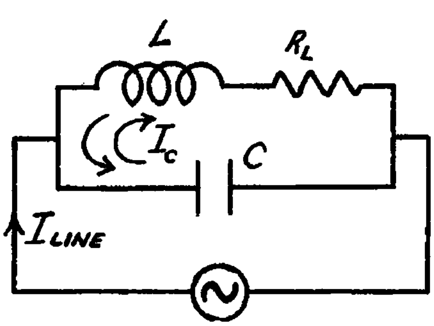


Fig. 3-27. Parallel Resonance.

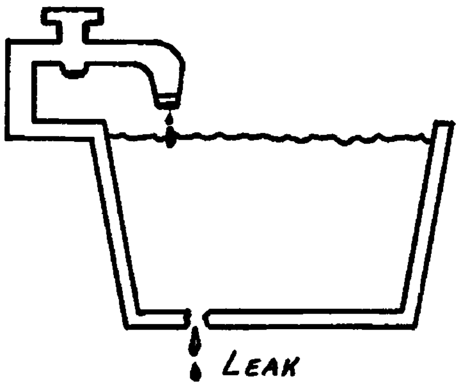


Fig. 3-28. Water tank.

To understand the operation of the parallel resonant circuit more clearly, we can compare it to a water tank with a small leak in its bottom. See fig. 3-28. The small leak represents the resistance of the coil. The tank represents the circuit of the coil and condenser in parallel. (The parallel combination of a coil and condenser is actually given the name TANK CIRCUIT). The water in the tank represents the energy present in the tank circuit due to the internal circulating current flowing between the coil and condenser. The faucet represents the generator and the water flowing from the faucet into the tank represents the line current.

If there were no leak, the water tank would not lose any water, and there would be no need to add water from the faucet. Similarly, if the electronic circuit had no resistance, no energy would be dissipated as the internal circulating current flows back and forth between the coil and condenser. (Energy can only be dissipated in a resistance) Therefore, the generator would not have to supply any energy since none would be lost in the circuit. Consequently, the line current would be zero. Practically speaking, there will always be some resistance present in the tank circuit. Energy will necessarily be dissipated in the tank circuit since the internal circulating current must flow through the resistance of the coil. In order to replenish this lost energy, the generator will have to supply energy by way of the line current flowing into the tank circuit.

IMPEDANCE OF THE PARALLEL RESONANT CIRCUIT

The average tank circuit encountered in radio has a very low coil resistance. The energy dissipated will therefore be very low, and the line current will also be very low. Since the line current is small, the impedance (opposition to the line current) of a parallel resonant circuit must be very high. Compare this with the low impedance of a series resonant circuit. We will also find that the impedance of the parallel resonant circuit decreases as the frequency of the energy that is injected into the tank circuit varies above and below the resonant frequency.

SUMMARY OF CHARACTERISTICS OF SERIES AND PARALLEL RESONANT CIRCUITS

	Series Resonant Circuit	Parallel Resonant Circuit
Impedance	low.	High.
Current	high.	line current - low. Internal circulating current - high.
E across Circuit	low.	high.

A-C POWER

In a previous paragraph we learned that the power loss in a d-c circuit is determined by using the following formulas:

1) $P = EI$ 2) $P = I^2R$ 3) $P = \frac{E^2}{R}$

where: R is the total resistance in the circuit.

This power is dissipated in the form of heat and is considered to be wasted energy.

The power loss in a pure resistive a-c circuit is similarly determined using the same formulas where E and I are in effective values.

3-12) 1) $P = E_{eff.} \times I_{eff.}$ 2) $P = I^2_{eff.} \times R$

where P is the power in watts 3) $P = \frac{E^2_{eff.}}{R}$

In an a-c circuit containing either inductance or capacitance, the voltage and current are out of phase. (They are not acting together at the same instant.) Therefore, the above formulas cannot be used to determine the TRUE POWER loss in a reactive circuit. The product of $E_{eff.}$ and $I_{eff.}$ would in this case be known as the APPARENT POWER loss. This power is actually larger than the true power consumed in the circuit. The true power is the heat dissipated in the circuit. The electric company charges you for the true power consumed over a period of time. Power can only be dissipated or used up in a resistive element. Power cannot be dissipated in a pure capacitive or pure inductive circuit.

The apparent power can be determined from the readings of a voltmeter and ammeter placed in the circuit as illustrated in fig. 3-29. The product of these readings, volts times amperes or VOLT-AMPERES, is the apparent power. The true power dissipated will always be indicated by an instrument called a WATTMETER.

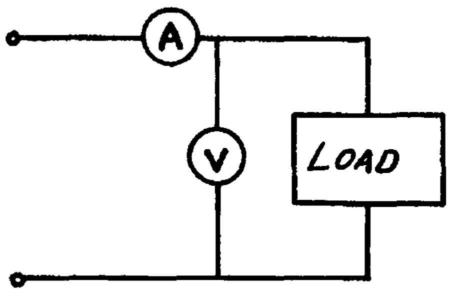


Fig. 3-29. Determining apparent power.

The one formula which can be used to determine the true power consumed in both d-c and a-c circuits is:

$$P = I^2R$$

Where: I is either the d-c current or the effective a-c current, and R is the resistance in the circuit.

THE TRANSFORMER

The voltage supplied to most communities in the United States is the standard 110 volts a-c. Practically all television sets and most radios require a voltage higher than 110 volts in order to operate satisfactorily. To fill this need, a device is incorporated in these sets to step-up the line voltage from 110 volts to a higher voltage. The device which can increase or decrease the value of an a-c voltage is called a TRANSFORMER.

PRINCIPLE OF THE TRANSFORMER

You will recall from our earlier discussion of a-c voltage, than an e. m. f. will be induced in a loop of wire which cuts a magnetic field. As long as there is relative motion between the loop and the magnetic field, a voltage will be generated. If the loop is kept stationary and the magnetic field cuts across the loop of wire, the result obtained will be the same as if the loop were in motion instead of the magnetic field. In either case, a voltage will be induced in the conductors of the loop. The transformer operation is based upon a varying magnetic field inducing a voltage in a stationary coil of wire.

OPERATION OF THE TRANSFORMER

Every time current flows through a conductor, a magnetic field builds up around the conductor. The magnetic field is in phase with the current at all times. Therefore, if an alternating current flows through a coil of wire, an alternating magnetic field will exist about this coil. This alternating magnetic field expands outwardly away from the coil and collapses back into the coil periodically. If a second coil with a lamp across it is placed in the vicinity of coil #1, as illustrated in fig. 3-30, the alternating magnetic field will cut across coil #2 and induce an a-c voltage in it; this voltage will cause the lamp to light. Notice that no electrical connection exists between the coils.

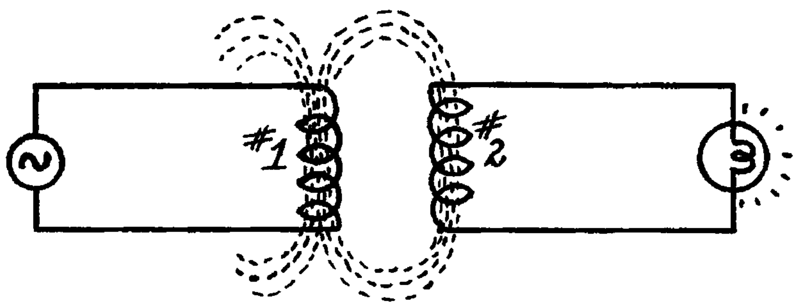


Fig. 3-30. Magnetic coupling.

Energy is transferred from coil #1 to coil #2 by means of the varying magnetic field. We say that the coils are MAGNETICALLY COUPLED. This method of transferring energy from one coil to another is known as TRANSFORMER ACTION. The entire device consisting of two coils magnetically coupled is known as a TRANSFORMER. Coil #1 which is connected to the voltage source is called the PRIMARY. Coil #2, in which the induced voltage is developed, is called the SECONDARY.

THE POWER TRANSFORMER

The transformer in Fig. 3-31B is known as an air-core transformer. Its use is confined to radio frequencies and it will be considered later on. A transformer which is used to transfer a-c power at power frequencies is known as a POWER TRANSFORMER.

In order for a power transformer to operate efficiently, the primary and secondary are wound on an iron core as illustrated in fig. 3-31A.

Power transformers can only be used on a-c because an alternating magnetic field is required to induce an

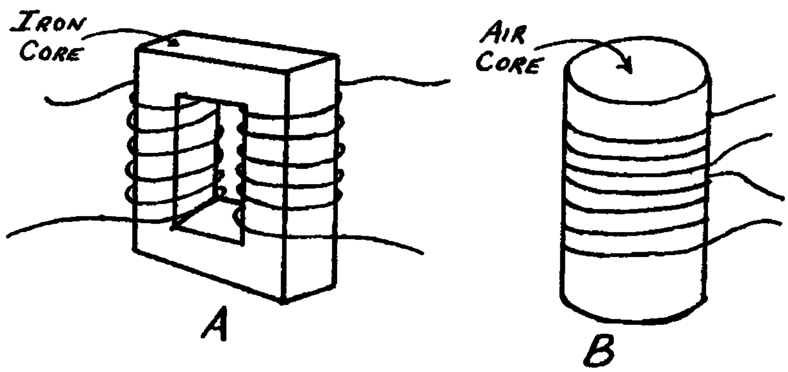


Fig. 3-31. Iron core and air core transformers.

e.m.f. in the secondary. It is dangerous to apply d-c to the power transformer primary. The primary has a low d-c resistance and, therefore, a high d-c current will flow through it. This high current will either blow a line fuse or damage the transformer beyond repair.

VOLTAGE AND TURNS RATIO

One of the most common uses of a transformer is to step-up the 110 volts a-c that is supplied to the average home. All a-c radios and television sets require several hundred volts to operate. They must therefore incorporate a transformer which will step-up the 110 volts. A fundamental principle of transformer action states that the voltage ratio between the secondary and the primary varies directly as the turns ratio. An example will clarify this point. If there are three times as many turns on the secondary as on the primary, the voltage of the secondary will be three times the voltage that is applied to the primary. Figure 3-32 illustrates this principle. Notice that the transformer secondary has three times as many turns

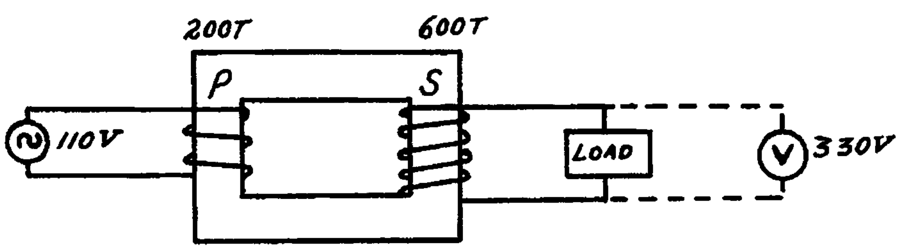


Fig. 3-32. 1 to 3 step-up transformer.

as its primary. If the primary voltage is 110 volts, the secondary voltage which appears across the load will be 330 volts. If there are ten times as many turns on the secondary as on the primary, the secondary voltage will be ten times as great as the primary voltage. A transformer whose secondary voltage is greater than the primary voltage is known as a STEP-UP TRANSFORMER.

Fig. 3-33 shows a transformer where the turns on the secondary are less than the turns on the primary. In this case the voltage will be stepped down from the primary to the secondary. This transformer is known as a STEP-DOWN TRANSFORMER. If 100 volts were applied to the primary winding, the secondary voltage would be 50 volts.

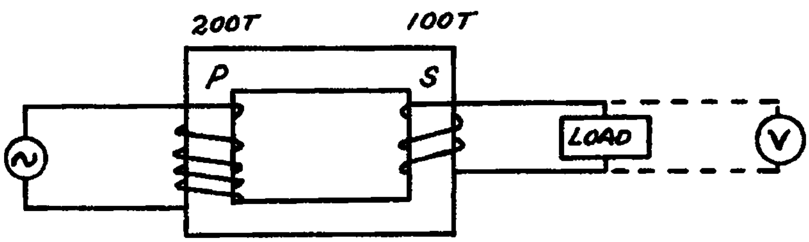


Fig. 3-33. 2 to 1 step-down transformer.

TRANSFORMER SYMBOLS

Fig. 3-34 shows the schematic symbols of typical transformers used in radio circuits.

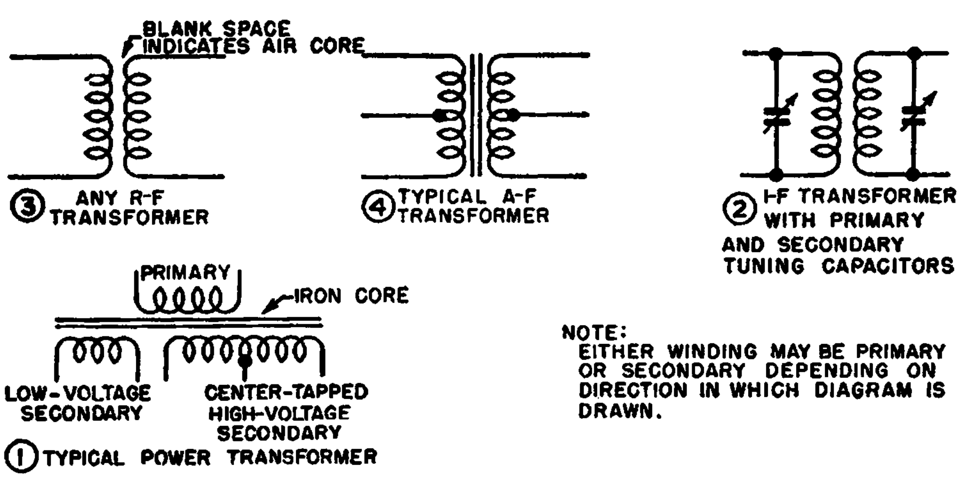


Fig. 3-34. Schematic symbols of typical transformers.

TRANSFORMER LOSSES

There are three types of losses which are encountered in the operation of a transformer. They are

1. - EDDY CURRENTS
2. - HYSTERESIS LOSSES
3. - COPPER LOSSES

EDDY CURRENTS are wasted currents induced in the iron core of the transformer by the varying magnetic field. These currents take a circular path through the core material as shown in fig. 3-35A. Since the resistance in the path of the eddy currents in a solid core material is low, the eddy currents will be large. Eddy currents serve only to heat up the iron core and therefore represent a power loss. Eddy current losses can be reduced by having the core made up of LAMINATIONS (thin insulated iron sheets) instead of solid iron. See fig. 3-35B. The laminations limit the eddy currents by increasing the resistance in their path of flow.

HYSTERESIS LOSSES represent the energy that is used up in forcing the iron core to reverse the direction of its magnetic field every time the current reverses its direction. Hysteresis losses can be minimized by using cores made of special materials. Hystersis losses together with eddy current losses are known as IRON-CORE LOSSES.

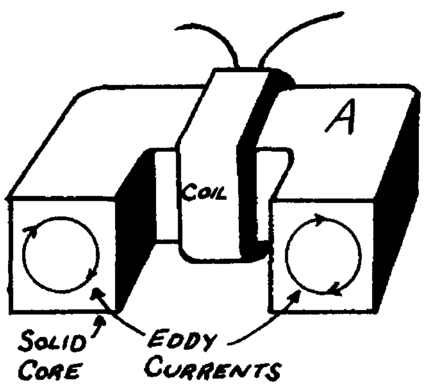


Fig. 3-35A. High eddy-current flow in solid core.

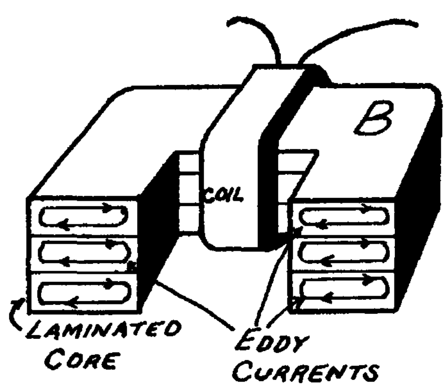


Fig. 3-35B. Low eddy-current flow in laminated core.

The third type of loss encountered in transformers is called COPPER LOSSES. Copper losses are caused by the resistance of the wire which makes up the turns of the windings. Current flowing through the resistance of the winding develops an I^2R power loss in the form of wasteful heat. Copper losses can be minimized by using a heavier wire for the windings; a thicker wire will have a lower resistance, and therefore, a lower I^2R loss.

MAXIMUM POWER TRANSFER

In order that there be a maximum transfer of energy from a generator to a load, the impedance of the load should equal the internal impedance of the generator. This law applies to all circuits in radio and electricity.

Sometimes a load, such as a speaker, may have a very low impedance compared to the very high internal impedance of the vacuum tube which is to energize the speaker. In order that there be maximum energy transfer between the vacuum tube (generator) and the speaker (load), a matching transformer (output transformer) is interposed between the two. The transformer steps up the impedance. We say that the transformer MATCHES the load to the generator, thus effecting maximum power transfer. Impedance matching is an important function of a transformer.

CHAPTER 4

THE DIODE VACUUM TUBE

THE DEVELOPMENT OF THE VACUUM TUBE

Thomas A. Edison was one of the great pioneers in the development of the vacuum tube. Edison invented the incandescent light bulb whose basic principles were later put to use by men, such as Fleming and DeForest, in the development of the modern vacuum tube.

Edison's incandescent electric lamp which was the forerunner of the modern electric bulb, consisted of a resistance wire called a filament enclosed within a glass envelope. The air within the glass envelope had been removed to create a vacuum. The ends of the resistance wire protruded through the glass as illustrated in fig. 4-1. If a current was passed through the resistance wire, it heated up and glowed. We can then say that the filament was heated to INCANDESCENCE.

While working with his electric light, Edison discovered that the incandescent wire emitted, or boiled off, electrons. These electrons remained around the wire in the form of an electron cloud or SPACE CHARGE. This phenomenon of electron emission is known as the EDISON EFFECT, and is the basis of the operation of all vacuum tubes.

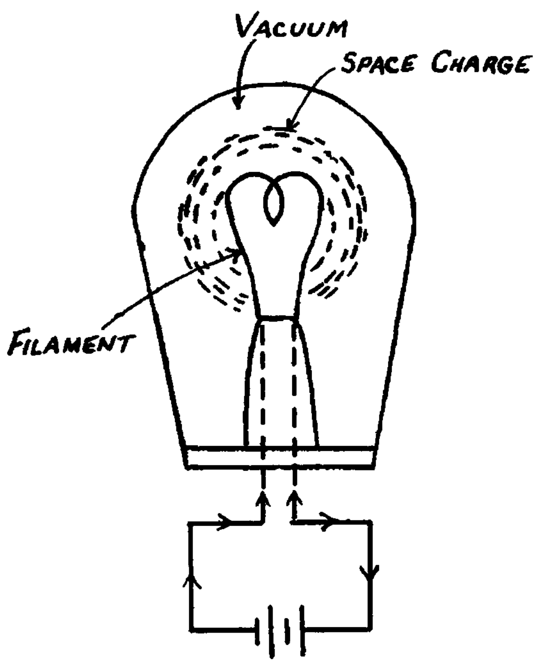


Fig. 4-1. The electric lamp.

ELECTRON EMISSION

Many metallic substances will emit electrons when heated to incandescence. For instance, the resistance wire in the light bulb emits electrons. These emitted electrons are wasted since they serve no useful purpose.

The vacuum tube is similar to the light bulb in that it also contains a resistance wire which emits electrons when heated. The vacuum tube, however, is designed to make use of the emitted electrons. In addition to the resistance wire, the vacuum tube has a positively charged collector of electrons called the PLATE. The positive plate attracts the emitted electrons. This is illustrated in fig. 4-2.

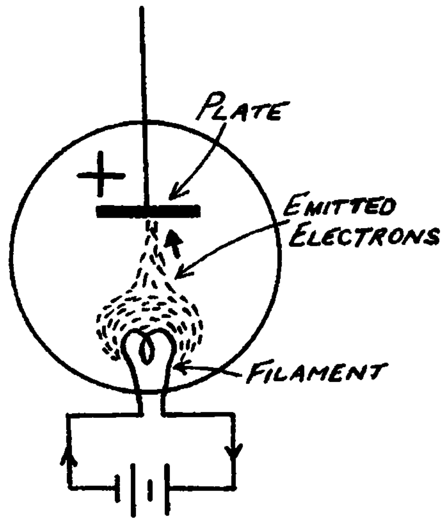


Fig. 4-2. Positive plate attracting electrons.

The purpose of the battery in fig. 4-2 is to force current through the filament, thereby heating it.

THE CATHODE

The element in the vacuum tube which supplies the electrons for the tube's operation is known as the CATHODE. The cathode emits or boils off electrons when energy in the form of heat is supplied to it. There are two different types of cathodes used in vacuum tubes. They are the directly heated and the indirectly heated types. We will now discuss these two types in detail.

1.- The directly heated cathode. This type is also known by the name FILAMENT-CATHODE. An example of a filament-cathode is illustrated in fig. 4-3. The heating current is passed directly through the cathode wire which is made of tungsten. The current heats up the cathode wire which then emits electrons from its surface. Directly heated filament-cathodes usually require very little heating power. They are therefore used in tubes designed for portable battery operation because it is necessary to

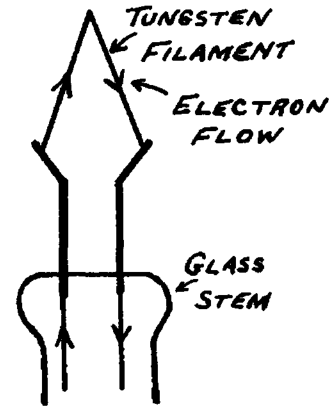
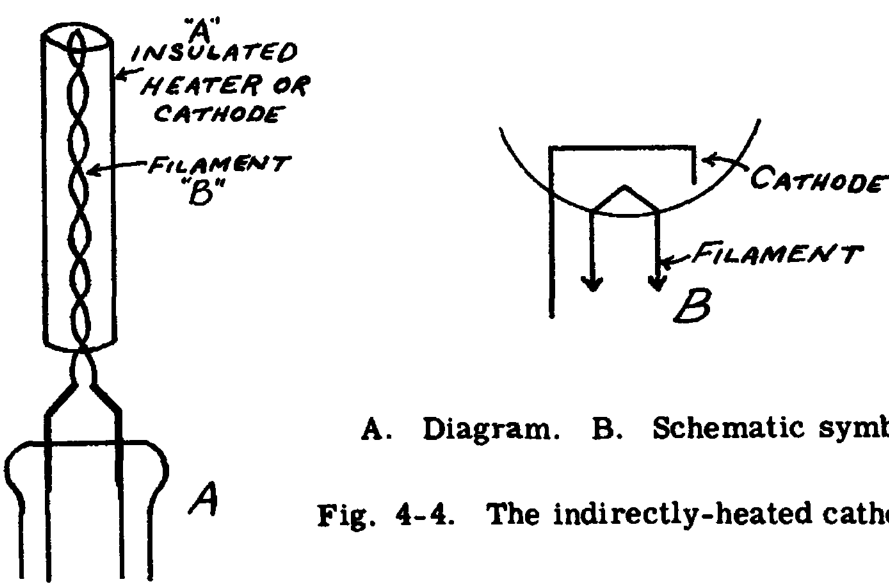


Fig. 4-3. Directly-heated cathode.

impose as small a drain as possible on the batteries. Examples of battery-operated filament-cathode tubes are the 1A7, the 1R5 and the 1U4.

2.- The indirectly-heated cathode. This type is also known as the HEATER-CATHODE and is illustrated in fig. 4-4A.



A. Diagram. B. Schematic symbol.

Fig. 4-4. The indirectly-heated cathode.

The heater-cathode consists of the following two parts:

1.- A thin metal sleeve or cylinder coated with electron-emitting material; this sleeve is the cathode.

2.- A heater wire which is insulated from the sleeve. The heater is usually made of a tungsten material. Current flows through the filament and heats it up. The cathode, being close to the filament, also heats up. Since the cathode has an electron emitting surface, the heat will cause it to emit electrons. Note that the heater function in this case is not to emit electrons but merely to heat the cathode. The heater wire is known as the filament. Fig. 4-4B shows the schematic symbol for the heater-cathode.

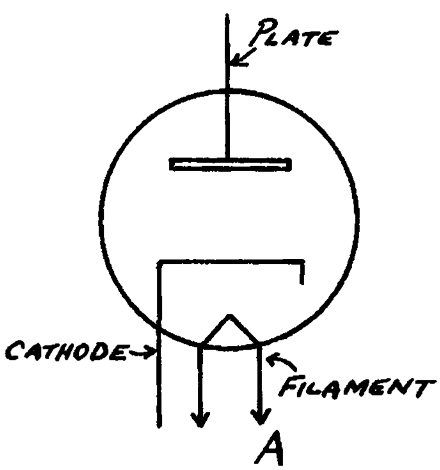
Almost all present day receiving tubes designed for a-c operation are of the indirectly-heated cathode type.

FILAMENT OPERATING VOLTAGE

The first number in a tube designation usually indicates the proper filament operating voltage. For example, a 6H6 tube should have its filament operated at 6.3 volts. All filaments should be operated at their designated operating voltages which are determined by the manufacturers. If the filament is operated above its rated voltage, the excessive current will shorten the filament life. Operating the filament below its rated voltage will decrease electron emission and lower the tube operating efficiency. The proper filament voltage for a particular tube, as well as other tube characteristics, can be found in a Tube Manual.

THE DIODE

Let us see how electrons emitted from the cathode can be collected and made to do useful work. Electrons are negatively charged and will be attracted by a positively charged object. Therefore, if a positively charged object called a PLATE is put into the vacuum tube, it will serve as a collector of electrons. A vacuum tube which contains a plate and a cathode is known as a DIODE. The schematic symbol for the diode is shown in fig. 4-5. B is a directly heated diode and A is an indirectly-heated diode.



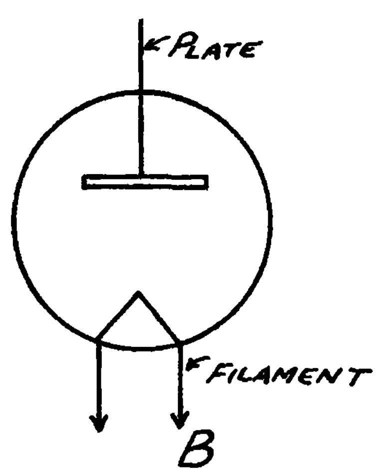


Fig. 4-5A. Indirectly-heated diode. Fig. 4-5B. Directly-heated diode.

The plate and the cathode are known as the ELEMENTS of the vacuum tube. The diode is therefore a two element tube. The heater of the indirectly-heated tube is not counted as a separate element.

THE DIODE AS A CONDUCTOR

Fig. 4-6 illustrates a simplified schematic of a diode with the plate connected to the positive terminal of a battery; the cathode is connected through a switch to the negative terminal. The instant the switch is closed, the ammeter in the circuit will register a current flow indicating that electrons are flowing from the cathode to the plate. The diode is said to be CONDUCTING. The diode conducts because the plate is positive with respect to the cathode.

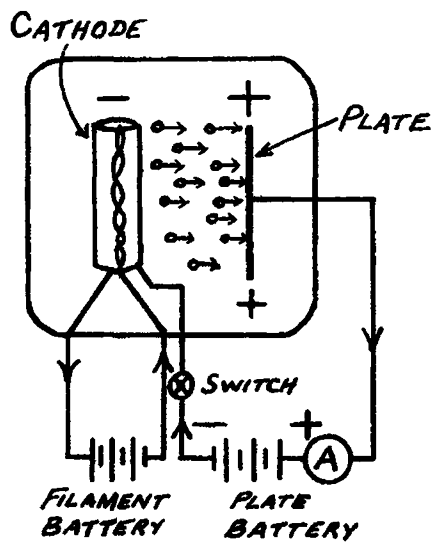


Fig. 4-6. Electron flow plate is positive.

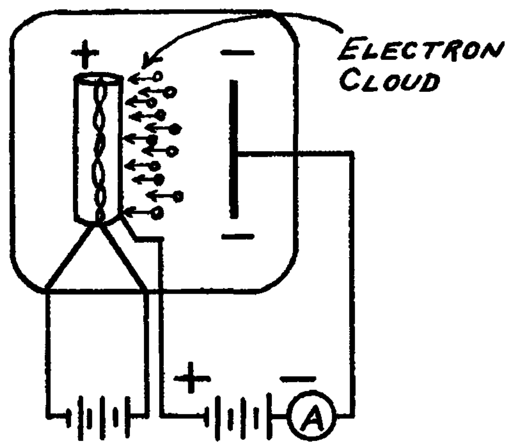


Fig. 4-7. Diode action when plate is negative.

The plate therefore attracts the negatively charged electrons emitted by the cathode. The electrons flow from the plate to the positive terminal of the battery. They then flow through the battery and back to the cathode, where they once more can be emitted to the plate. If the battery voltage is increased, the plate will become more positive and will therefore attract more electrons. The ammeter will consequently register a larger current flow. Conversely, if the plate battery voltage is decreased, the plate will attract less electrons, and the ammeter will register a smaller current flow.

When the diode conducts, it represents a very low resistance path between the cathode and plate. For all practical purposes, we can consider a conducting diode as a closed switch between the cathode and plate.

THE DIODE AS A NON-CONDUCTOR

If we reverse the battery connections as shown in fig. 4-7, the plate becomes negative and the cathode positive. Since the negative plate will not attract electrons, the diode will NOT CONDUCT. The diode, therefore, acts like an open switch and permits no current to flow. The ammeter will consequently read zero amperes. The emitted negatively-charged electrons are repelled by the negative plate and remain close to the cathode where they form an ELECTRON CLOUD. The cloud of electrons around the cathode is known as a SPACE CHARGE. If the plate were to become positive once again, the space charge would be rapidly reduced since its electrons would be attracted to the plate. The cathode is free once again to emit electrons.

Let us now summarize the operation of the diode:

1) electrons flow in one direction only, - from cathode to plate.

2) Electron flow to the plate will take place only when the plate is positive with respect to the cathode.

3) The current flow will vary with the plate to cathode voltage.

4) The diode acts as a conductor (short circuit) when the plate is positive;

5) The diode acts as a non-conductor (open circuit) when the plate is negative.

THE DIODE CHARACTERISTIC CURVE

Fig. 4-8 illustrates a diode connected to a source of variable voltage. The heater circuit has been omitted for the purpose of simplicity. "A" is a milliammeter connected in series with the tube. The voltage applied to the plate of the diode can be varied by changing the position of the plate tap from position #1 to position #8. As the tap is moved from position #1 to position #8, the plate to cathode voltage increases. For every value of plate voltage there will be a different value of diode plate current as measured by the milliammeter. The table in fig. 4-9 is a tabulation of plate current readings for various values of plate voltage. If we plot these readings on the graph in fig. 4-9, and then draw a line through the different points, we obtain a curve known as the DIODE CHARACTERISTIC CURVE. I_p is the electronic symbol for plate vurrent; E_p

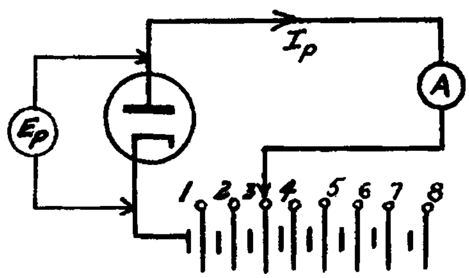


Fig. 4-8. Diode with variable voltage supply.

E_p	I_p
22.5	1.0
45	1.5
67	3.0
90	6.0
112	9.0
135	12.0
157	13.0
180	13.0+

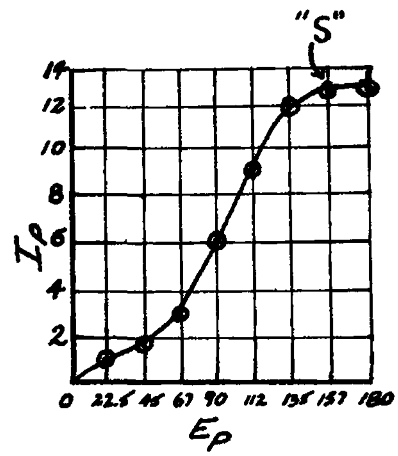


Fig. 4-9. Diode characteristic curve.

is the electronic symbol for plate to cathode voltage, or simply plate voltage. The plate-current-plate-voltage curve shows the amount of current that a particular diode will conduct for a given plate voltage. The curve indicates that, as the plate voltage increases, the plate current also increases up to the point "S". Beyond point "S" the curve becomes practically horizontal. In other words, as the plate voltage increases beyond point "S", the plate current remains essentially constant and will not increase regardless of plate voltage increases. The point "S" is known as the saturation point. It is the point at which the plate is collecting all of the electrons that the cathode is capable of emitting.

The characteristic curve is important because it tells us at a glance what the plate current will be for any particular plate voltage. This information is useful if we are designing a diode circuit for a certain application. Characteristic curves for diodes, as well as all other tubes, are found in tube manuals.

SUMMARY OF FILAMENTS AND DIODE TUBES

1) The emission of electrons from a filament is the principle upon which all electron tubes are based.

2) Electrons are negatively charged particles which are attracted to a positively charged plate.

3) A diode consists of an emitting surface called the cathode and a receiver of electrons called the plate. These elements are placed within an evacuated (vacuum) glass or metal bulb to prevent the hot filament from burning up, and to provide a clear path from the cathode to the plate for the fast-moving electrons.

CHAPTER 5

POWER SUPPLIES

RECTIFICATION

Vacuum tubes in receivers and transmitters will only operate when connected to a direct current source of power. Portable radios, for example, are energized by batteries which are in themselves a source of direct current. As noted previously, the electrical power that is delivered to most homes throughout the country today is alternating current. If we were to connect the tubes in our radios directly to the a-c wall outlet, the radio would not operate because a radio tube needs a source of d-c power. We all know that our radios do operate when we plug them into the a-c socket. Obviously, there must be something in the radio which converts the alternating current into direct current. The device in a radio which converts the alternating current into direct current is known as a RECTIFIER. The process of conversion is called RECTIFICATION.

THE DIODE AS A HALF-WAVE RECTIFIER

The ability of the diode vacuum tube to pass current in only one direction makes it possible to convert alternating current into direct current. Let us see how this is done. Fig. 5-1 illustrates a simple diode rectifier circuit. When

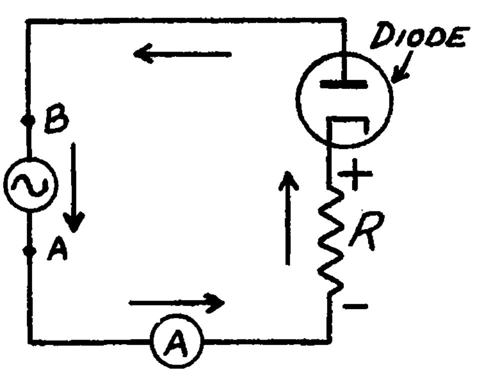


Fig. 5-1. Diode used as half-wave rectifier.

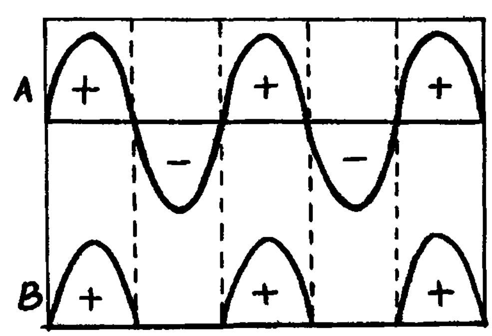


Fig. 5-2. Half-wave rectifier wave-forms.

terminal "B" of the a-c generator is positive with respect to terminal "A", the diode plate becomes positive with respect to its cathode. The diode therefore conducts current in the direction indicated by the arrows. The d-c milliammeter will deflect to the value of the current flow.

On the next half of the alternating current cycle, the polarity of the generator will be reversed, making the plate negative with respect to the cathode. The diode will stop conducting because a negative plate will repel the electron flow. The current in the circuit will therefore cease flowing during the negative half of the cycle. When the polarity of the a-c generator again reverses itself and makes the diode plate positive, current will again flow through the circuit. Fig. 5-2 is a graphic explanation of what is happening. Fig. 5-2A shows the sine wave which is generated across the terminals of the a-c generator. Fig. 5-2B shows the wave which is obtained across the load resistor R_L. In figure 5-2B, we see the positive halves of the cycle when the plate of the diode is positive with respect to the cathode. At that time, the diode conducts and acts as a short circuit. The positive half cycles are therefore impressed directly across the resistor R_L. During the negative half of each a-c cycle, the tube does not conduct and is an open circuit. During these times there is no voltage developed across the resistor since there is no current flow. The current through the resistor is therefore a pulsating direct current, and the voltage across the resistor is a pulsating direct voltage. Even though the current flows in spurts or pulses through the resistor, the current is still d-c because it flows in ONE direction only. This action of the diode in passing only one-half of the a-c input wave to the load resistor is known as HALF-WAVE RECTIFICATION.

The ends of the load resistance have been marked with a polarity because electrons are entering and emerging from this resistance. The end at which they enter becomes more negative than the end from which they emerge. The pulsating direct-voltage, if properly filtered, can be utilized to operate a radio receiver.

We can replace the a-c generator of fig. 5-1 with a transformer as shown in fig. 5-3, without altering the operation of the circuit. The transformer merely steps up the a-c voltage and the action is the same as in fig. 5-1.

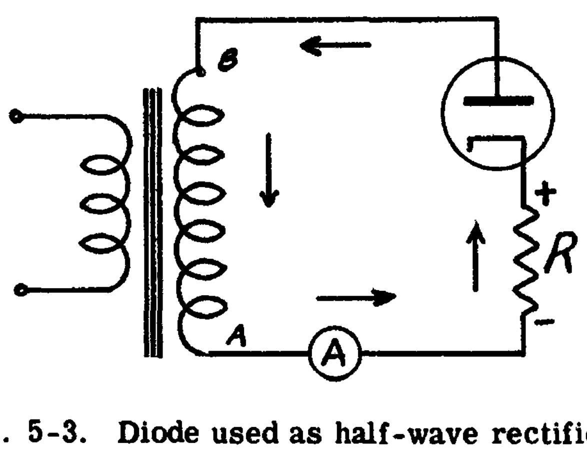


Fig. 5-3. Diode used as half-wave rectifier.

THE DIODE AS A FULL-WAVE RECTIFIER

In half-wave rectification, only the positive half of the a-c input is used. The negative alternations are completely cut off and wasted. If we could somehow utilize the negative as well as the positive alternation, we would be operating our rectifier system more efficiently. This is accomplished in full-wave rectification.

We can modify the half-wave rectifier circuit of fig. 5-3 by adding another diode and center-tapping the transformer secondary. The resulting circuit is illustrated in fig. 5-4. The cathodes of the diodes are connected together, and the circuit is known as a FULL-WAVE RECTIFIER. The operation of a full-wave rectifier is as follows;

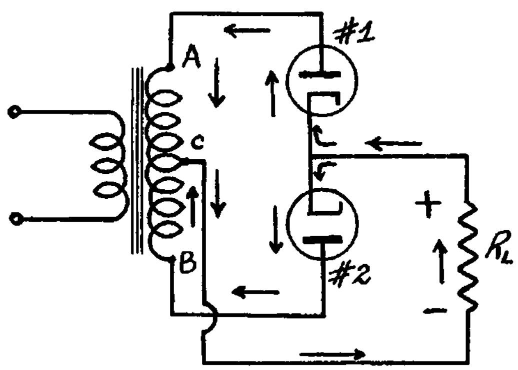
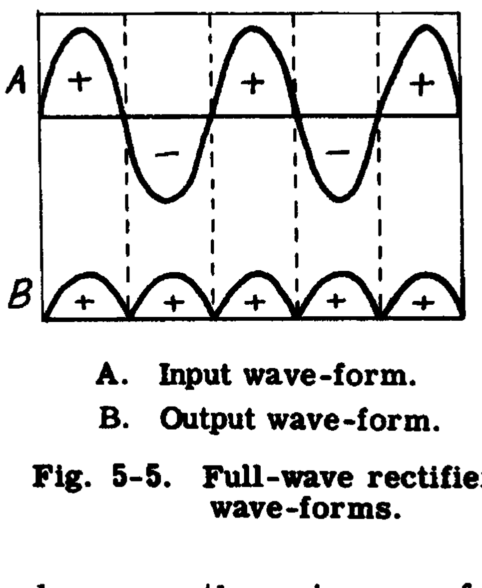


Fig. 5-4. Full-wave rectifier.



A. Input wave-form.
B. Output wave-form.

Fig. 5-5. Full-wave rectifier wave-forms.

When an a-c voltage is impressed across the primary of the transformer, an a-c voltage will be induced in the secondary. When point "A" is positive with respect to point "B", the plate of diode #1 is positive and the tube conducts. The electrons flow through the transformer, from A to C, out of C into the load resistance R_L. From R_L, the electrons flow to the cathode of diode #1. Since the tube is conducting (because of its positive plate), the current flows to the plate and back to point A to complete its circuit. During all this time the plate of diode #2 is negative and does not conduct.

On the next half of the a-c cycle, the bottom of the transformer, point "B", goes positive while the top, point "A", goes negative. The plate of diode #2 is now positive and the plate of diode #1 is negative. Diode #2 will now conduct, and diode #1 will not. The electrons flow through the transformer from B to C, into the load resistor R_L, and back to the cathode of diode #2. They then flow to the plate and back to point B. Notice that the current flows through the load resistor in the same direction as it did previously. Notice also, that the current flows through the resistor in the same direction during both the positive and negative halves of the input cycle. We have very definitely used both halves of the a-c input cycle, and have accomplished full-wave rectification. Fig. 5-5A shows the a-c across the transformer secondary. Fig. 5-5B shows the pulsating d-c flowing through the load. Compare this output with the rectified wave picture of fig. 5-2B.

VOLTAGE OF HALF-WAVE AND FULL-WAVE RECTIFIERS

In the half-wave rectifier, the entire transformer secondary delivers voltage to the tube. In the full-wave rectifier, only one half of the transformer secondary delivers voltage to a conducting tube at any one time. This is because the full wave system used a center-tapped transformer. For example; If the full transformer secondary voltage (A to B) is 400 volts (see figures 5-3 and 5-4), the full 400 volts will appear across the load of the half-wave rectifier; whereas only 200 volts will appear across the load in the full-wave rectifier.

SUMMARY OF RECTIFICATION

1) A single diode is used as a half-wave rectifier for converting a-c to d-c. Only half of the input a-c wave is used, and the full voltage of the secondary of the power transformer is obtained as useful d-c output.
2) A double diode is used as a full-wave rectifier. Both halves of the a-c wave are used, and greater efficiency is obtained. The output voltage is only half of the total transformer secondary voltage.

FILTERING

Fig. 5-6 illustrates the output voltage waveform of a battery. Notice that the voltage output remains constant. It does not vary with time. The output voltage of the battery is pure d-c. Remember, this is the type of voltage that the vacuum tubes of a radio require in order to operate properly. Now, look back to figs. 5-2B and 5-5B which show the output wave shapes of a half-wave and full-wave rectifier system. Compare these wave shapes to that of the battery output waveshape.

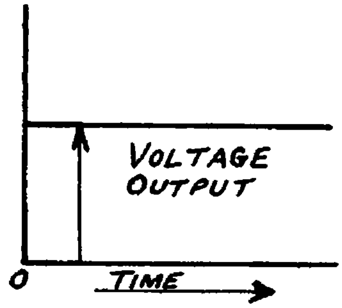


Fig. 5-6. Pure d-c.

It is evident that the output of the rectifier systems is far from being pure d-c. The output is actually a pulsating d-c, or a d-c with a superimposed a-c wave called a ripple. If we could somehow remove, or filter out, the a-c component or ripple from the pulsating d-c, we would end up with a straight line or pure d-c. Since we are striving to get a pure d-c output from our rectifier systems, it is obvious that we are going to have to remove the ripple from the output waveform. The method of removing the ripple from the d-c output is known as FILTERING. The device which does the filtering is called a FILTER.

The output waveform of the rectifier is actually a combination of direct current and an a-c ripple. The direct current and the a-c ripple are called the COMPONENTS of the pulsating wave.

RIPPLE FREQUENCY

The ripple has a very definite fundamental frequency. Examination of fig. 5-2 should indicate to you that the ripple frequency for a half-wave rectifier is the same as the line frequency or 60 CYCLES per second. Recall the definition of frequency which is the number of times a wave shape repeats itself in one second. Examination of fig. 5-5 should also indicate to you that the ripple frequency for a full-wave rectifier is twice the line frequency or 120 cycles per second.

THE FILTERING SYSTEM

Filtering out the ripple component is accomplished by connecting a filter system to the output of the rectifier tube. A filter system is a circuit consisting of condensers and inductors. The condensers are called filter condensers, and the inductors are known as filter chokes.

There are 2 different types of filter arrangements that are being used in transmitters and receivers. One is the condenser input type and the other is the choke input type. Both of these filters will now be discussed.

CONDENSER INPUT FILTER

Fig. 5-7 shows a condenser input filter system connected to the output of a full-wave rectifier. The filter is enclosed within the dotted line. The filter is recognized as a condenser input type because the filter component nearest to the rectifier is a condenser (C_1). The complete filter is given the name π filter. π is a greek letter pronounced pi. The π filter is the one most commonly found in radio receivers today.

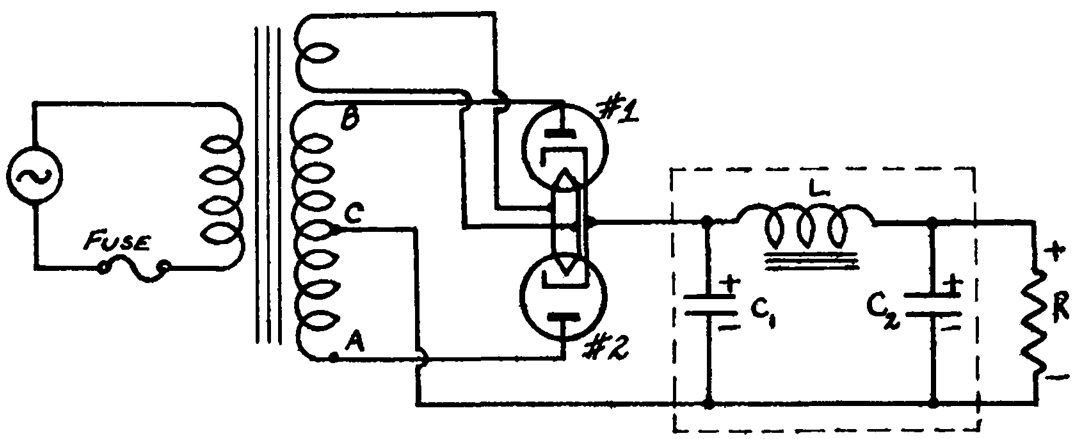


Fig. 5-7. Full-wave rectifier with condenser input filter.

The filter operates to remove the a-c component in the following manner. Poing B in fig. 5-8 illustrates the

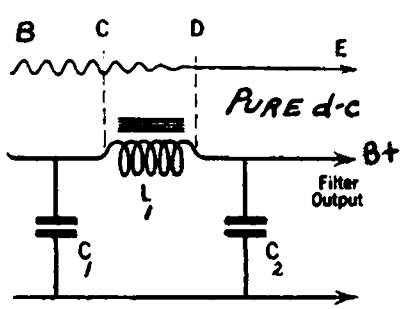


Fig. 5-8. Filtering.

rectified wave shape at the input to the filter. Remember, that this wave is a combination of a d-c voltage and an a-c ripple. Now, C_1 is a very high capacity condenser of about

20 μfd. A 20 μfd condenser has a very low reactance to a 120 cps. ripple component. It will, therefore, short-circuit, or by-pass most of the ripple component. The d-c voltage, on the other hand, is not affected by the presence of condenser C_1. Remember that a condenser acts like an open-circuit to a d-c voltage. We say that a condenser blocks d-c. Point C shows the resulting wave shape after it is acted upon by condenser C_1. Notice that some of the ripple still remains superimposed on the d-c wave. The choke, L_1, has a very low d-c resistance. The d-c will, therefore, pass right through L_1 without any opposition. However, the choke will generate a very strong counter e.m.f. to oppose the a-c ripple. The result is that practically all of the remaining ripple will be prevented from passing through the choke. The wave shape appearing on the other side of the choke is shown at point D. The wave shape is practically pure d-c with just a very slight ripple remaining. Condenser C_2 acts in exactly the same manner as C_1. It will short out the remaining ripple, leaving just the pure d-c as illustrated at point E. The pure d-c voltage can now be satisfactorily applied to the vacuum tubes for their proper operation. The d-c voltage which is applied to the vacuum tubes is called the B+ voltage.

THE CHOKE INPUT FILTER

Figure 5-9 illustrates a CHOKE INPUT filter. We call it a choke input filter because the first filter component after the rectifier is a choke. The filtering action

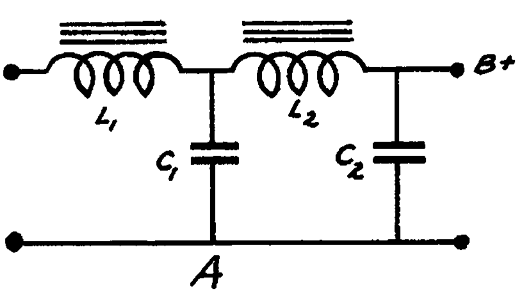


Fig. 5-9. Choke input.

of the choke input filter is similar to that of the condenser input filter. However, it has an advantage and a disadvantage when compared to a condenser input filter. The choke input filter has better voltage regulation than a condenser input filter (the subject of voltage regulation will be fully discussed in a later paragraph). On the other hand, the condenser input filter provides a higher output voltage than the choke input filter.

THE ELECTROLYTIC CONDENSER

The average value of filter condenser for a receiver lies in the range between 4 and 50 μfd. At these high values of capacity, the ordinary paper or mica condenser would be too large in physical size for practical use. A special type of condenser called an ELECTROLYTIC CONDENSER, was designed to have a large value of capacity in a small size container. The electrolytic condenser depends on a chemical action to produce a very thin film of oxide which forms the dielectric.

All electrolytic condensers are polarized; that is, they have a positive and negative terminal. The positive terminal must always be connected to the positive d-c voltage point in the circuit, and the negative terminal must similarly be connected to the negative d-c point. If these rules are not observed, the condenser will short-circuit under operation and will have to be replaced. The short-circuit may also damage the rectifier tube.

The principle disadvantages of the electrolytic condenser are its short life (compared to other condensers) and its high leakage current. A condenser is said to have leakage when a small value of d-c current flows through its dielectric. In other words, the dielectric is not an absolutely perfect insulator. A good electrolytic condenser will have a low value of leakage current never exceeding 3 or 4 ma. at its rated working voltage. Electrolytic condensers are used chiefly in power supplies where leakage current is not important.

The working voltage of an electrolytic condenser should never be exceeded under actual operation as the condenser may break down and short-circuit.

THE SHORT-CIRCUITED FILTER CONDENSER

If condenser C_1 of fig. 5-7 shorts, the rectifier tube will conduct excessive current. As a result, the safety fuse in series with the primary of the power transformer will blow. The fuse acts as a protective device for the components in the rectifier circuit. If there is no fuse, the plates of the vacuum type rectifier tube will become red hot due to the bombardment of the plate by the large electron flow. The tube may become damaged and will have to be replaced. The primary or secondary windings of the transformer may also burn out due to the excessive current.

If condenser C_2 in fig. 5-7 were to short, the rectifier tube would conduct very heavily through the choke coil. The choke coil might burn out in addition to the above mentioned components.

If either C_1 or C_2 shorts, there obviously will be no B+ voltage, and the radio or transmitter will not function.

THE FILTER CHOKE

Filter chokes in a receiver power supply run from 4 to 30 henries. Chokes are designed to have as low a d-c resistance as possible. As a result, the d-c voltage drop across the choke will be low; and the remaining B+ voltage will be as high as possible.

SUMMARY OF FILTERING ACTION

1) Filtering smooths out the ripple in a rectified d-c wave.

2) A condenser input filter is used when a high output voltage is desired, and where regulation is not too important. Receiver power supplies almost always use condenser input filters.

3) A choke input filter is used where regulation is of first importance - as in a transmitter power supply.

4) The output ripple frequency of a half-wave system is equal to the line frequency of 60 cps. The ripple frequency for the full-wave rectifier is double the line frequency, or 120 cps. For equal filtering action, the filter condensers in a half-wave power supply should have a greater capacity than the filter condensers in full-wave power supply.

VOLTAGE REGULATION

The load current is the current that is drawn from the power supply by the vacuum tubes of the receiver or transmitter. If the load current varies, the B+ voltage will also vary. The B+ voltage is at a maximum when the load current is zero. As the load on the power supply increases, the B+ voltage drops. At full load current, the B+ voltage is at a minimum. A good power supply is one whose B+ voltage varies very little under varying load conditions. We say that such a power supply has good VOLTAGE REGULATION. A power supply with poor voltage regulation is one whose B+ voltage varies considerably with changes in load conditions.

The vacuum tubes in a radio receiver draw a constant load current from the power supply. A receiver power supply is therefore not required to have good voltage regulation characteristics. A transmitter, on the other hand, presents a varying load to the power supply. The transmitter power supply should therefore have good voltage regulation characteristics.

In order to improve the voltage regulation of a power supply, a resistor is often bridged across the output condenser. (resistor R in fig. 5-7) This resistor is known as a BLEEDER RESISTOR. A bleeder resistor improves the voltage regulation by providing a minimum load on the power supply. It also serves to discharge the filter condensers when the power is turned off.

The bleeder resistor may also be used as a voltage divider to supply different voltages for use in the receiver or transmitter.

ADVANTAGES OF FULL-WAVE OVER HALF-WAVE RECTIFICATION

The output of a full-wave rectifier is easier to filter than a half-wave rectifier. The reason for this is as follows:

You will recall that the formula for capacitive reactance is:

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

From this formula, we see that the higher the frequency the lower the reactance of the filter condenser to the a-c component. The ripple frequency of a full-wave rectifier (120 cps.) is twice that of half-wave rectifier (60 cps.). Because of this, the reactances of the filter condensers will be 1/2 as much at 120 cps. as they would be at 60 cps. The filter condensers will therefore more effectively by-pass or get rid of a 120 cps. ripple than a 60 cps. ripple.

Also note that the counter e.m.f. or opposition of the choke is twice as great at 120 cps. as it is at 60 cps. This is because the reactance of an inductor is directly proportional to the frequency. ($X_L = 2\pi fL$)

Thus, we see that the a-c ripple of a full-wave rectifier is more easily squelched than the a.c. ripple of a half-wave rectifier.

Another advantage of full-wave rectification over half-wave rectification is better voltage regulation.

INVERSE PEAK VOLTAGE

A rectifier tube does not conduct during one-half of the input a-c cycle. This is when the plate is negative with respect to the cathode. During this non-conducting time there will be a high negative voltage on the plate. Fig. 5-10 illustrates this condition. The voltage across the

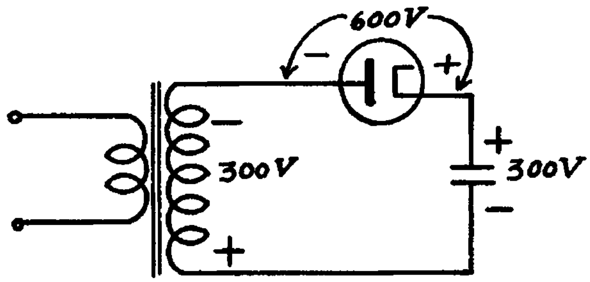


Fig. 5-10. Inverse-peak voltage.

transformer secondary is 300 volts peak, and the input condenser is charged up to 300 volts from the previous alternation. Notice that the two voltages are in series and in phase across the rectifier tube. The maximum voltage between plate and cathode during non-conduction is 600 volts. This voltage is called the INVERSE PEAK VOLTAGE. If this inverse peak voltage exceeds the rating given by the manufacturer, there is a great danger of damage from an arc-back between the two elements.

CHAPTER 6

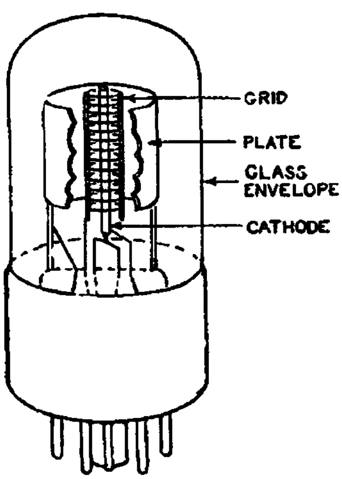
VACUUM TUBES

INTRODUCTION

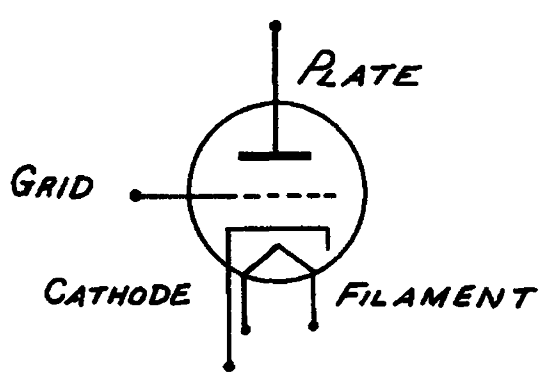
In chapter 4, we studied the construction of a diode vacuum tube In chapter 5, we studied the action of the diode vacuun tube as a rectifier in changing alternating current to direct current We will now deal with the operation of the vacuum tube when used as an amplifier. An amplifier increases the amplitude of small voltages or currents. The vacuum tubes that are used for amplification purposes are three, four, and five element tubes. The three element tube is called a TRIODE; four and five element tubes are called TETRODES AND PENTODES respectively We shall now proceed to study each one of these tubes in detail.

THE TRIODE

The TRIODE is different from the diode in that it contains one more element. This new element is called the CONTROL GRID. The control grid is a thin piece of wire wound in the form of a spiral mesh. It surrounds the cathode. Electrons emitted by the cathode can easily pass through the grid structure and onto the plate. Fig. 6-1A shows the actual physical arrangement of the cathode, grid, and plate structure in a typical triode. Notice that the grid is placed much closer to the cathode than to the plate.



A. Cut away section of a triode.



B. Schematic symbol.

Fig. 6-1. The triode.

Fig 6-1B illustrates the schematic representation of the triode The grid is shown by means of a dotted line between the cathode and plate.

OPERATION OF A TRIODE

Fig. 6-2 shows a triode circuit which is used to study the effect of grid voltage variations upon the plate current. The plate current is measured by placing an ammeter in series with the plate circuit. All tube voltage

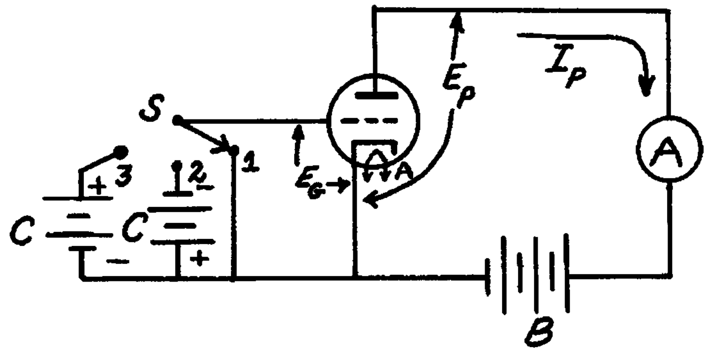


Fig. 6-2. Effect of grid voltage on plate current flow.

measurements are taken with the cathode as a reference point.

Notice the letters A, B and C beneath the battery sympols in fig. 6-2. These letters indicate the voltages that are applied to the different elements in the tube. The "A" voltage is applied to the heater, or filament. The "B" voltage is applied to the plate; the "C" voltage is applied to the grid. "S" is a three-position switch in the control grid circuit. With the switch in position #1, the control grid is connected directly to the cathode. With the switch in position #2, the control grid is connected to the negative terminal of a battery. With the switch in position #3, the control grid is connected to the positive terminal of a battery. Let us see how changes in the control grid voltage affect the operation of the triode. With the switch in position #1, and the plate positive, electrons will flow from the cathode through the grid structure to the plate. Since the grid is connected directly to the cathode, it will not affect the flow of plate current.

If the switch is thrown to position #2, the grid becomes negative with respect to the cathode. The negatively charged grid will repel many of the negatively charged electrons back into the area surrounding the cathode. Hence, the number of electrons which are able to reach the plate is reduced. This effect is illustrated in fig. 6-3. The milliammeter in the plate circuit will show a reduction in plate current when the grid voltage is changed from a zero voltage to a negative voltage.

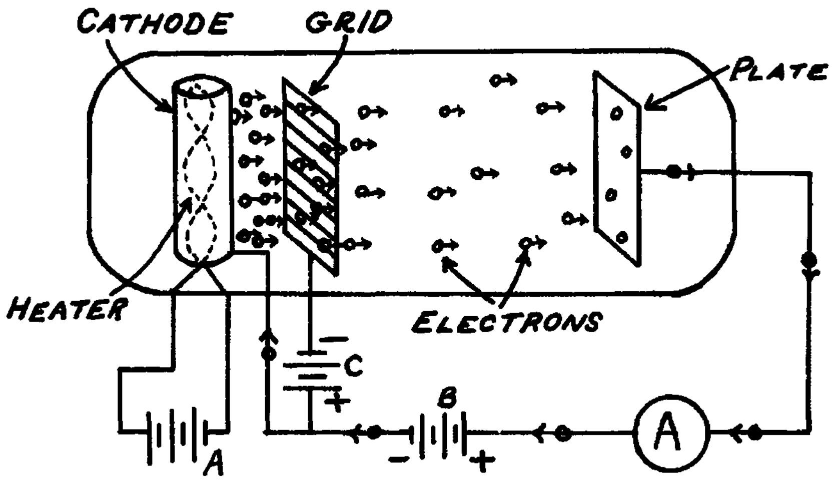


Fig. 6-3. Effect of negative grid on plate current flow.

If the switch is thrown to position #3, the grid becomes positive with respect to the cathode. The plate current will increase since the positive control grid attracts the negative electrons and allows many more electrons to be drawn to the plate than it did in switch position #1 and #2. A positive grid actually pulls electrons from the cathode to the plate. Thus, we see how the control grid acts as a control valve for plate current flow. As we vary the voltage on the grid, the plate current varies. THE CONTROL GRID, THEREFORE, CONTROLS THE FLOW OF ELECTRONS TO THE PLATE.

PLATE CURRENT - GRID VOLTAGE CURVE

In order to further study the relationship between the plate current and the grid voltage, let us take measurements to see exactly how the plate current varies with changes in the grid voltage. Fig. 6-4 illustrates a schematic of a triode whose grid voltage can be varied by means of a potentiometer placed across the "C" battery. Let us plot the milliammeter plate current readings for different values of grid voltage on a graph. Fig. 6-5 illustrates the resulting graph. The horizontal line represents the grid voltage in volts, and the vertical line represents the plate current in milliamperes. The plate current measurements are taken with the plate voltage kept constant at 150 volts. If we draw a line through the points that represent the various plate current readings, we obtain a curve known as the E_g - I_p characteristic curve. Notice that if the grid is made sufficiently negative (minus 10 volts), the plate current drops to zero. At this point, the highly negative grid repels all electrons back to the

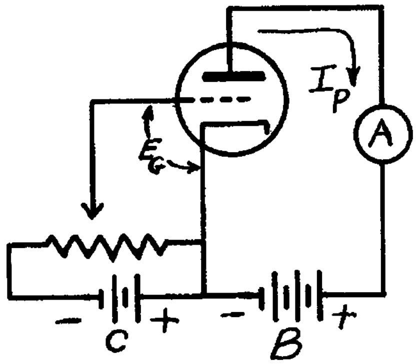


Fig. 6-4. Obtaining data for EG-Ip curve.

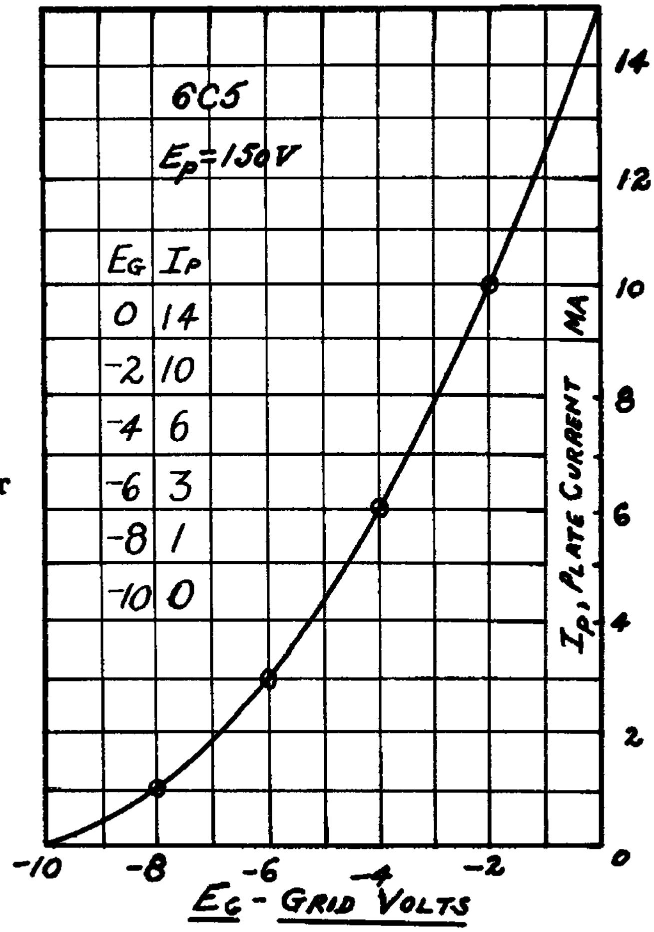


Fig. 6-5. Grid voltage, plate current curve.

cathode area. As the grid voltage is made less negative (more positive), the electrons begin to flow to the plate. If we continue to make the grid voltage less negative, the plate current will continue to increase. When we make the grid positive with respect to the cathode, the plate current keeps on increasing. As the grid voltage is made more positive, the plate current continues to rise. A point is soon reached (Not shown in fig. 6-5) where the plate current can no longer increase regardless of further increases in positive grid voltage. This point is called the SATURATION POINT.

The voltage that is applied to the grid is called GRID BIAS VOLTAGE, or simply BIAS. The BIAS that cuts the plate current to zero is called the CUT-OFF BIAS. In fig. 6-5, the cut-off bias is -10 volts. Whenever the voltage on the grid prevents current from flowing, we say that we have a BLOCKED GRID.

The curve of fig. 6-5 was obtained with the plate voltage held constant. We can also take data of grid voltage and plate current readings for different values of plate voltage. The result of plotting all these points is a series of curves called a FAMILY OF CURVES. This is illustrated in fig. 6-6. Each curve is plotted with the grid voltage varied while the plate voltage is kept constant. Notice that for a given grid voltage, the plate current increases with increase in plate voltage. This is to be expected since an increase in plate voltage should result in an increase in plate current.

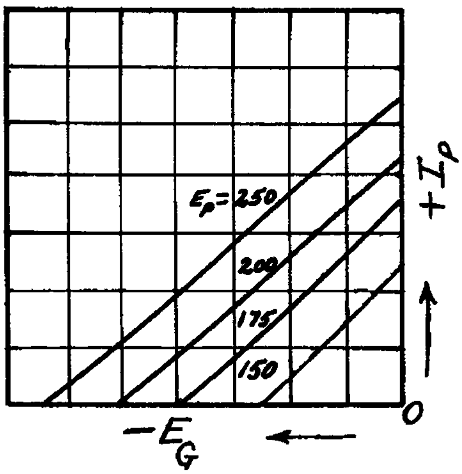


Fig. 6-6. Family of E_G-Ip curves.

THE E_p - I_p CHARACTERISTIC CURVE FOR THE TRIODE

In fig. 6-5, the plate voltage was kept constant and plate current readings were plotted as we varied the grid voltage. Another popular characteristic curve is the E_p-I_p curves of fig. 6-7. Here, the grid voltage is kept constant and plate current readings are plotted as we vary the plate voltage. Notice that the plate current rises as the plate voltage increases. The E_p - I_p curves are the ones that are usually found in tube manuals.

THE TRIODE AS AN AMPLIFIER

In a previous paragraph it was stated that multi-element tubes are used to amplify weak signals. We will now proceed to study the exact manner in which a triode amplifies a signal voltage that is applied to its grid.

The control grid is physically much closer to the cathode than the plate is. The grid voltage will therefore have a greater effect on the plate current than will the plate voltage. A small change in grid voltage will cause a large change in plate current; whereas, a small change in plate voltage causes a small change in plate current. Let us see, graphically, how a changing voltage (such as an a-c signal), on the grid of a triode, causes the plate current

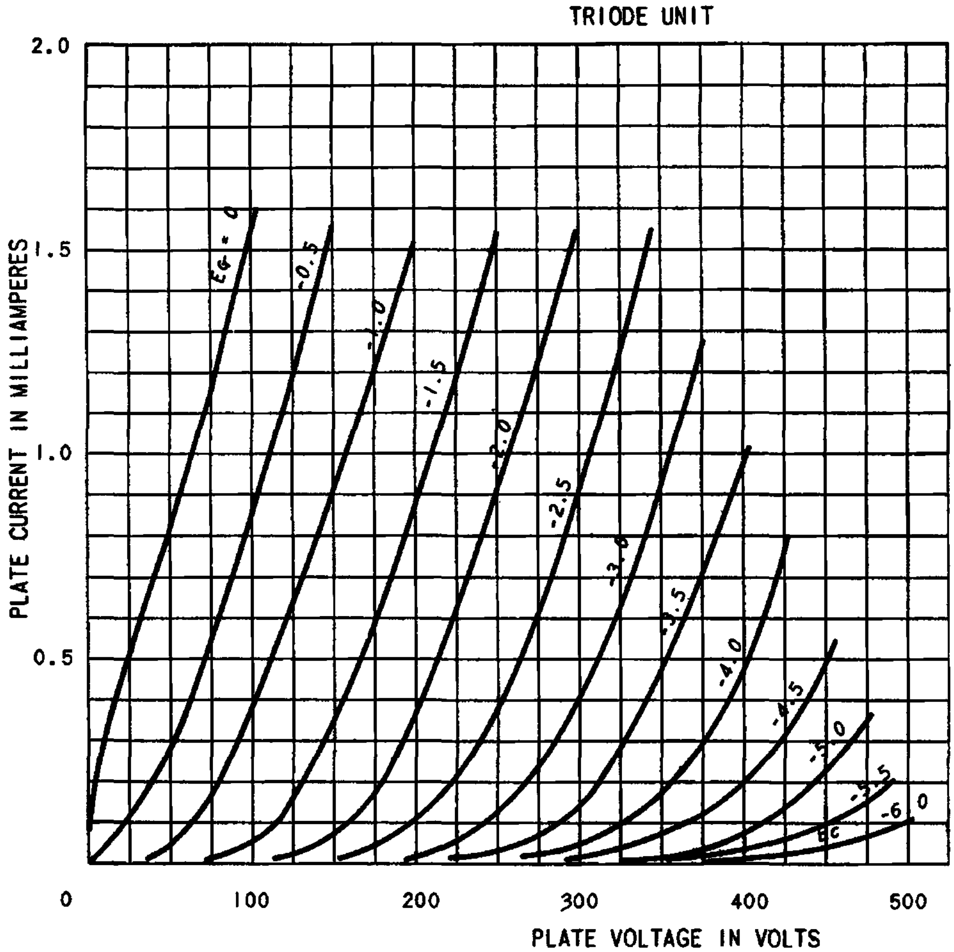


Fig. 6-7. Family of Ep-Ip curves.

to vary. Fig. 6-8 illustrates a triode whose plate is connected to a fixed B+ voltage. The grid is in series with an a-c generator and a fixed bias voltage. The total voltage between the grid and cathode will always be the sum of the generator or signal voltage and the bias voltage.

We will assume that the signal voltage is 1 volt peak and that the battery bias voltage is 3 volts. From the I_p-E_g curve of figure 6-9, it can be seen that when the a-c signal applied to the grid is zero, the plate current will be 8 ma. This is due to the 3 volts of bias supplied by the bias battery. The value of 8 ma. is obtained from the graph by working vertically from the -3 volt point on the grid voltage line until the curve is reached. From this point we go straight across until we hit the vertical plate current line. In this case we reach the vertical line at 8 ma.

Let us see what happens on the positive half of the a-c signal, when +1 volt is being applied to the grid. Since the signal voltage of +1 volt and -3 volts of bias are in ser-

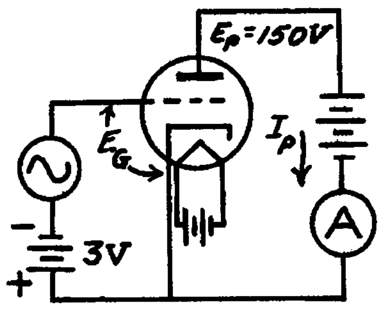


Fig. 6-8. Triode with an a-c signal on the grid.

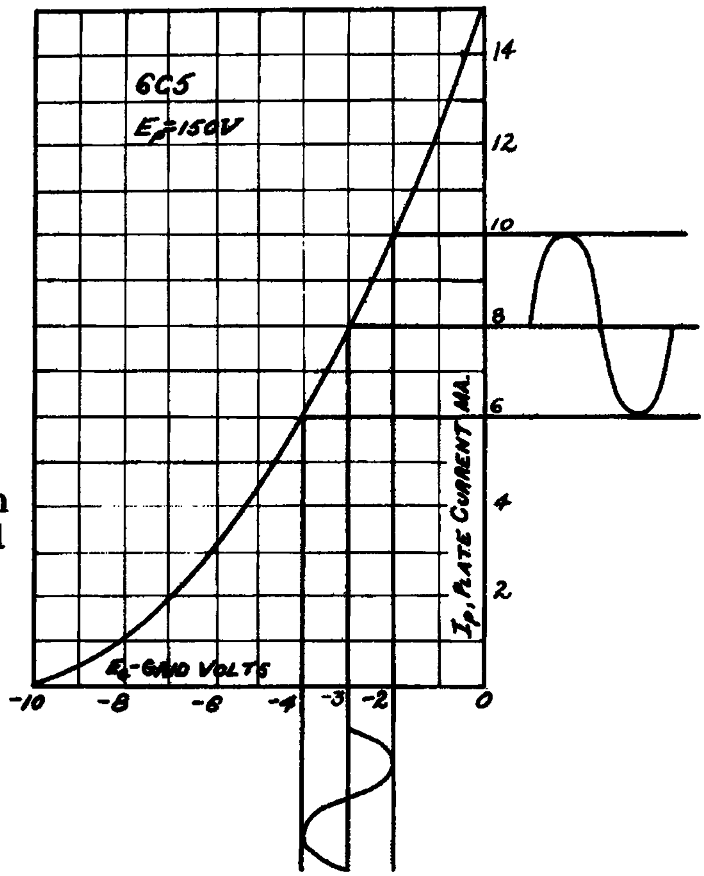


Fig. 6-9. Plate current wave form resulting from an a-c grid voltage.

ies, the resultant voltage between the grid and cathode will be -2 volts (the sum of +1 and -3 is -2). By looking at figure 6-9, we see that -2 volts on the grid causes a plate current of 10 ma. Thus, when the incoming signal reaches its positive peak value of +1 volt, the plate current rises to 10 ma.

On the negative half of the incoming signal, -4 volts will appear between the grid and cathode. This is because the sum of the -1 volt of signal and the -3 volts of bias is -4 volts. By looking at the graph, it can be seen that -4 volts on the grid causes a plate current of 6 ma. Thus, when the incoming signal reaches its negative peak value of -1 volt, the plate current drops to 6 ma.

From the above, we can see that the plate current rises and falls in step with the signal on the grid. As a matter of fact, the waveform of the plate current variation is an exact reproduction of the signal that is applied to the grid.

Thus far we have converted grid voltage variations into plate current variations. In order to make use of these plate current variations, some device must be placed in the plate circuit to act as a load across which the varying plate current will develop a varying voltage. The plate load may be a resistor, an inductor, or a tuned circuit. Fig. 6-10 shows a resistor used as a plate load in a triode amplifier circuit. Except for the plate load resistor, this circuit is the same as that in fig. 6-8. From figure 6-9,

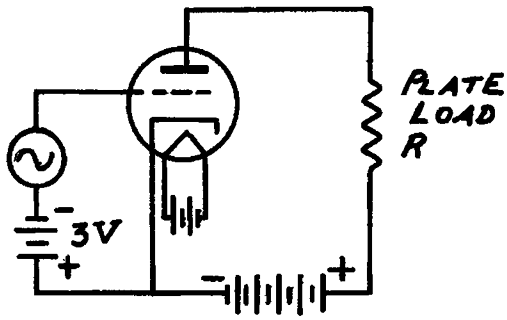


Fig. 6-10. Triode using a resistor as a plate load.

we can see that a 1 volt signal caused a total plate current variation of 4 milliamperes (from 6 to 10 ma.). This 4 ma. variation will cause a total voltage variation of 40 volts to be produced across the 10,000 ohm resistor. This can easily be proven by Ohm's law. One form of Ohm's law states that:

$$E = I \times R$$

$$E = .004 \times 10,000$$

$$E = 40\ V$$

Thus it can be seen that a 2 volt a-c signal variation (from -2 volts to -4 volts peak to peak) can produce a 40 volt variation in the plate circuit. In other words, the original signal or variation that was applied to the grid has been AMPLIFIED twenty times.

$$(\frac{40}{2} = 20)$$

From fig. 6-9 it can be seen that the voltage variation in the plate circuit is not only amplified, but it is also a faithful reproduction of the grid signal. The circuit in fig. 6-10 is therefore the basis for all amplification circuits in radio and television.

VACUUM TUBE CHARACTERISTICS

Since many different types of vacuum tubes are used in radio and television circuits, it is important to classify tubes according to the performance which may be expected of them. The three most important factors by which tubes are classified are the AMPLIFICATION FACTOR, the TRANSCONDUCTANCE, and the PLATE RESISTANCE.

1. Amplification Factor - The AMPLIFICATION FACTOR of a tube is the maximum voltage amplification which can be expected from the tube. It is a theoretical value never reached in actual circuit use. Stated mathematically, it is the ratio of the change in plate voltage to the change in grid voltage that produces the same change in plate current. For example, Let us assume that a certain tube is operating with a plate voltage of 250 volts, a grid voltage of -10 volts and a plate current of 18 ma. Let us assume that if we should change the plate voltage to 280 volts and leave the grid voltage constant, the plate current would go up to 23 ma. This means that a plate voltage change of 30 volts results in a plate current change of 5 ma. Suppose that a grid voltage change from -10 volts to -13 volts returns the plate current from 23 ma. back to 18 ma. We can say that a grid voltage change of 3 volts has the same effect on the plate current as a plate voltage change of 30 volts. The amplification factor would therefore be the plate voltage change (30 volts) divided by the grid voltage change (3 volts) or 10.

The amplification factor is commonly designated by the Greek letter μ. The formula for the μ, or mu, of a tube is:

$$\text{6-1)}\quad \text{Amplification factor } (\mu) = \frac{\Delta E_p}{\Delta E_g}$$

The terms ΔE_p and ΔE_g mean a small change in plate voltage and a small change in grid voltage respectively.

2. Transconductance -The TRANSCONDUCTANCE, or MUTUAL CONDUCTANCE, of a tube is the figure of merit of the tube. It tells us how much of a plate current variation we can get for a certain amount of grid voltage variation. Transconductance is defined as the ratio of a small change in plate current to the change in grid volt-

age that produced it. The formula for transconductance is:

$$6\text{-}2)\quad \text{Transconductance } (G_m) = \frac{\Delta I_p}{\Delta E_g}$$

where: ΔI_p is a small change in plate current

ΔE_g is the small change in grid voltage that caused ΔI_p.

G_m is the symbol for transconductance

The basic unit of the transconductance of a tube is the MHO. The mho was previously mentioned in chapter 1 as the unit of conductance. We use the same unit because the transconductance of a tube is similar to the conductance of a circuit.

3. Plate Resistance - The PLATE RESISTANCE of a tube is the internal resistance between the cathode and plate to the flow of varying plate current. Mathematically speaking, it is the ratio of a small change in plate voltage to the change in plate current that this voltage change produces. The formula for plate resistance is:

$$6\text{-}3)\quad \text{Plate Resistance } (R_p) = \frac{\Delta E_p}{\Delta I_p}$$

A tube may be considered to be a variable resistor in its operation as an amplifier. If the grid is made positive, the current flow from cathode to plate is increased. This means that the resistance from the cathode to the plate is now less than it was before. On the other hand, if the grid is made more negative, the plate current will decrease. This means, of course, that the plate resistance has become greater.

EFFICIENCY OF VACUUM TUBES

We often use the term EFFICIENCY when we speak about the performance of a certain device or machine. Efficiency refers to the amount of power that can be gotten out of a device as compared to the amount of power that has been put into it. For instance, if 100 watts of electrical power is used up in a light bulb and only 2 watts of equivalent light power is produced, we can say that the electric bulb is a low efficiency device. The bulb generates into light only 2% of the power that is put into it. (the other 98 watts are dissipated inside the bulb in the form of heat.) On the other hand, an electric motor may draw 100 watts of electric power and produce 75 watts of equivalent mechanical power. We can say that the motor is a high efficiency device. The motor produces, in the form of useful work, 75% of the power put into it.

In radio, we classify vacuum tubes according to their efficiency in delivering useful power to a load.

The plate efficiency of a vacuum tube is defined as the ratio of the a-c plate power output to the d-c plate power input. It is given in a percentage, and its mathematical formula is:

$$\text{6-4)} \quad \text{Plate Efficiency} = \frac{\text{a-c output power}}{\text{d-c input power}} \times 100$$

For example, if the a-c power output of a vacuum tube is 150 watts, and the d-c power input is 200 watts, the efficiency is 150 divided by 200 or 75%.

The a-c power output of a tube is the power in watts that the tube delivers to its load. The load may be the loudspeaker or the grid of a following tube. The d-c power input, on the other hand, is the product of the d-c plate voltage applied to the tube and the d-c plate current. For instance, if the plate voltage is 750 volts, and the plate current is 150 milliamperes, then the power input is 112.5 watts. The power input is derived in the following manner:

$$\text{Power input in watts} = E_p \times I_p$$

$$P \text{ input} = 750 \times .15$$

$$P = 112.5 \text{ watts}$$

Note that the 150 milliamperes was changed to amperes by moving the decimal three places to the left.

MAXIMUM PLATE DISSIPATION

In the above problem concerning the plate efficiency of a vacuum tube, it is apparent that only a certain percentage of the applied power (input power) appears as output power. What happened to the remainder of the input power? The remainder of the input power is wasted in the form of heat within the tube, exactly as in a light bulb. Remember that the tube represents a resistance between the cathode and plate. Power loss applies to the resistance of a tube as well as any ordinary resistor. The plate current in flowing through the plate resistance dissipates heat. The power dissipated on the plate in the form of heat is equal to $I_p^2 R_p$, where I_p is the plate current and R_p is the plate resistance.

There is a limit to the amount of power that a tube can dissipate in the form of heat without damaging itself. This limit is known as the MAXIMUM PLATE DISSIPATION and it is expressed in watts. To find the maximum plate dissipation for any particular tube we simply look it up in the tube manual.

LIMITATIONS OF A TRIODE

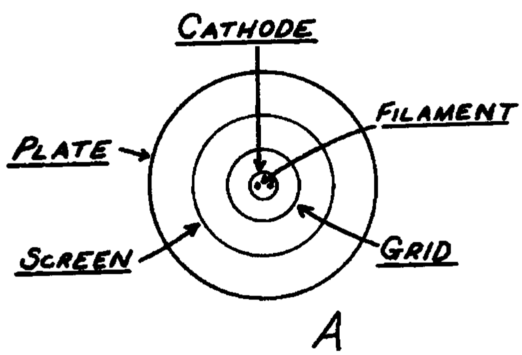
In the early days of radio, triodes were used exclusively in radio receivers and transmitters. Later on the tetrodes and pentodes made their appearance and replaced the triode in many applications. The reason for this change was that the triode had certain characteristics which limited its application in radio work. Before we discuss the tetrode and pentode, we shall first examine in detail the limitations of the triode.

In chapter 3, we learned that two conducting surfaces separated by an insulator form a condenser. Since the plate and grid of a tube are two conducting surfaces separated by a vacuum dielectric, there exists a capacitance between the plate and grid. By the same reasoning, a capacitor is formed between the grid and cathode, and between the plate and cathode. These internal tube capacitances are called INTERELECTRODE CAPACITANCES. The interelectrode capacitance between the plate and the grid exerts a detrimental effect upon the action of a triode amplifier. This capacitance gives rise to a condition known as OSCILLATION which is extremely undersirable. Oscillations come about in the following manner: A varying grid voltage causes a varying plate voltage which is then passed on to the next stage. However, because of the undesirable grid to plate capacitance, the voltage variations from the plate circuit are FED BACK to the grid circuit and are reamplified until oscillations or howling takes place. This is especially true at radio frequencies. In a later chapter, we will discuss this condition of oscillation in greater detail.

Another defect of the triode results from the fact that the plate current depends not only upon the grid voltage but also upon the plate voltage. Because of this, the gain of a triode, used as an amplifier, is kept down. For example, a positive grid signal will cause the plate current to go up; the increasing I_p will increase the voltage across the load resistor. The voltage across the load resistor and the voltage between plate and cathode are in series and therefore must always add up to the fixed B+ voltage value. If the voltage across the load resistor goes up, the plate voltage must go down. The decreased plate voltage, in turn, will cause the plate current to decrease somewhat, counteracting the effect of the signal on the plate current. Thus the amplification is kept down. The way to circumvent this defect would be to make the plate current independent of the plate voltage. Variations in plate voltage would then have no effect on the plate current. This is achieved in the tetrode and pentode.

THE TETRODE

In an effort to reduce the grid-plate capacitance within the tube, a fourth element was added to the conventional triode. This fourth element is called a SCREEN GRID; the screen grid is placed between the control grid and the plate. The top view of a tetrode is shown in Fig. 6-11A; the schematic symbol of a tetrode is shown in Fig. 6-11B. The screen is wound in the form of a spiral grid, similar to the control grid. The screen grid shields the control grid



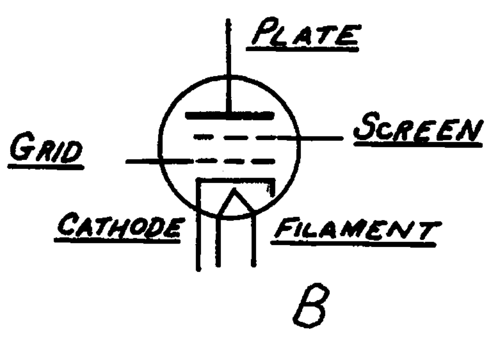


Fig. 6-11A. Top view of a tetrode. **Fig. 6-11B. Schematic symbol for a tetrode.**

from the plate and thereby reduces the grid-plate capacitance.

In order for the screen grid to act as an effective shield, it must be grounded for a-c. But, as we shall soon see, the screen grid must at the same time be kept at a high positive d-c potential. The way to satisfy both conditions is to ground the screen grid through a condenser (c of fig. 6-12).

A typical screen grid, or tetrode (four elements) tube connected in a circuit is shown in fig. 6-12. The

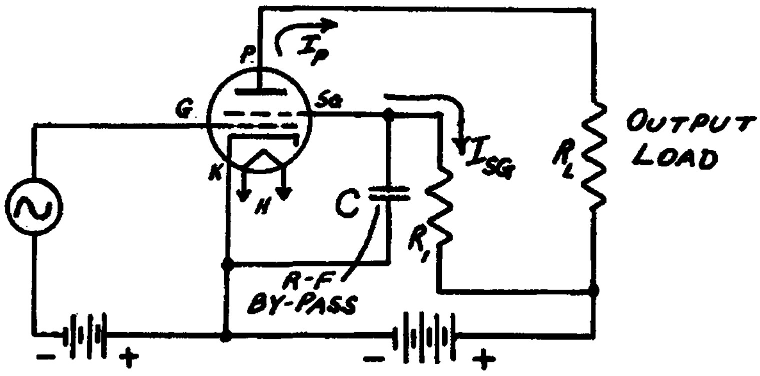


Fig. 6-12. Tetrode amplifier circuit.

screen grid is operated at a d-c potential somewhat lower than that of the plate. The positive screen grid acts like the plate of a triode in attracting electrons emitted by the cathode. A few of the electrons will hit the screen grid resulting in screen current flow. The screen current flows through resistor R_1. R_1 is called the screen voltage dropping resistor. The screen current that flows through R_1 causes a voltage drop across it. The screen grid voltage is therefore the B+ voltage minus the voltage drop across the resistor R_1. The screen voltage is measured from the screen grid to the cathode.

Since the screen grid is similar to the control grid in construction, most of the electrons will pass through the screen and reach the plate. Since the plate is a solid element and more positive than the screen grid, it will receive most of the electrons emitted by the cathode.

INCREASED AMPLIFICATION OF TETRODE

Because the screen grid is closer to the cathode than the plate, the screen grid has practically complete control over the plate current. The plate current is therefore not influenced by plate voltage variations. Since the screen is at a-c ground potential, there will be no variation in the screen voltage when an a-c signal is being applied to the grid. The screen grid therefore exerts a constant pull on the electrons that make up the plate current. The only element in the tetrode that causes the plate current to vary is the control grid. The control grid no longer shares its control over the plate current with the plate, as it did in the triode. Small variations of voltage on the control grid will cause the plate current to vary without any counteraction from a varying plate voltage. As a result the plate resistance and the amplification factor of the tetrode are much greater than they are in a triode.

THE PENTODE

The introduction of the screen grid in the tetrode successfully reduced the plate-grid capacitance and increased the amplification factor. The tetrode, however, suffers from one important defect. This defect is known as SECONDARY EMISSION. The Pentode (five element tube) was developed to overcome the effects of secondary emission.

Secondary emission is the condition that arises when the high velocity electrons strike the plate. The force of the impact causes additional electrons to be knocked out of the atomic structure of the plate. For every electron that strikes the plate, two or three electrons will be knocked out of the plate. In a triode, these secondary emission electrons normally find their way back to the highly positive plate and cause no interference in the operation of the tube. In the tetrode, as long as the plate voltage is much higher than the screen voltage, the secondary emission electrons fall back to the plate, and tube operation will be normal. However, if a large signal voltage is applied to the control grid, the plate voltage will drop below the screen voltage at the positive peak of the input signal. The result of this lowered plate voltage is to cause the secondary emission electrons to flow to the positive screen grid instead of returning to the plate. Thus, the number of electrons reaching the plate drops, while at the same time, the screen current is increased. This results in a reduction in the amplification of the tube and distortion in its output.

In the pentode, a third grid is placed between the screen grid and the plate. (see fig. 6-13) The third grid is similar in physical construction to the screen grid and the control grid. This third grid is connected to the cathode so that it will be highly negative with respect to the plate and will force the secondary emission electrons back to the plate. Because it suppresses secondary emission, the third grid is called the SUPPRESSOR GRID. The negative suppressor grid will not interfere with the flow of electrons from the cathode to the plate even though it does suppress the secondary electrons coming from the plate. The reason for this is that the electrons from the cathode

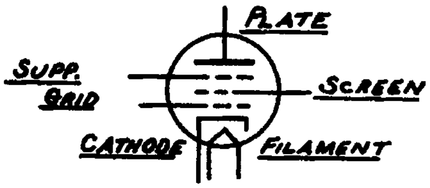


Fig. 6-13. Schematic symbol for pentode.

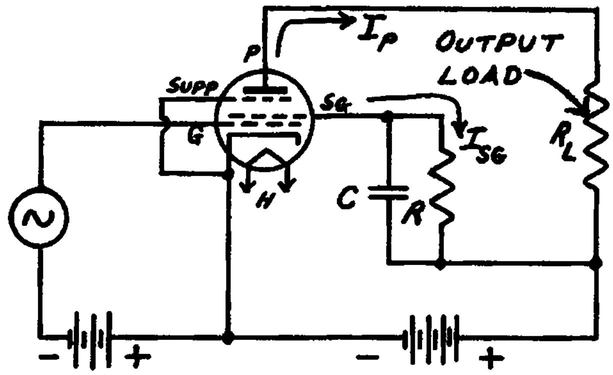


Fig. 6-14. Pentode amplifier circuit.

are traveling at such a high velocity when they reach the vicinity of the suppressor grid, that they go right on through to the highly positive plate. On the other hand, the secondary electrons coming from the plate are moving at a rather low velocity and are easily pushed back to the plate. Fig. 6-14 illustrates a pentode hooked up as an amplifier. Note that the only difference between this circuit and the tetrode amplifier circuit of fig. 6-12 is the addition of the suppressor grid.

THE BEAM POWER TUBE

A beam power tube is a pentode with special construction features. A beam power tube has greater power handling ability than the ordinary tetrode or pentode. With very small grid voltages, a beam power tube can develop large amounts of power in its plate circuit. The tube is therefore said to have high power sensitivity. The beam power tube is constructed so that the wire turns of the control grid and screen grid line up with each other horizontally. This means that every turn of the screen grid mesh is directly behind a turn of the control grid mesh. Thus, electrons flowing from the cathode travel through the control grid and onto the plate without striking the screen grid. The screen grid current is therefore very low and, since the plate gets the electrons which would normally have gone to the screen grid, the plate power output is increased. Because of the physical alignment of the control grid and the screen grid, the electrons flow to the plate in sheets, or beams. This is illustrated in fig. 6-15. To further concentrate and form the heavy beams of plate current, deflecting plates are incorporated

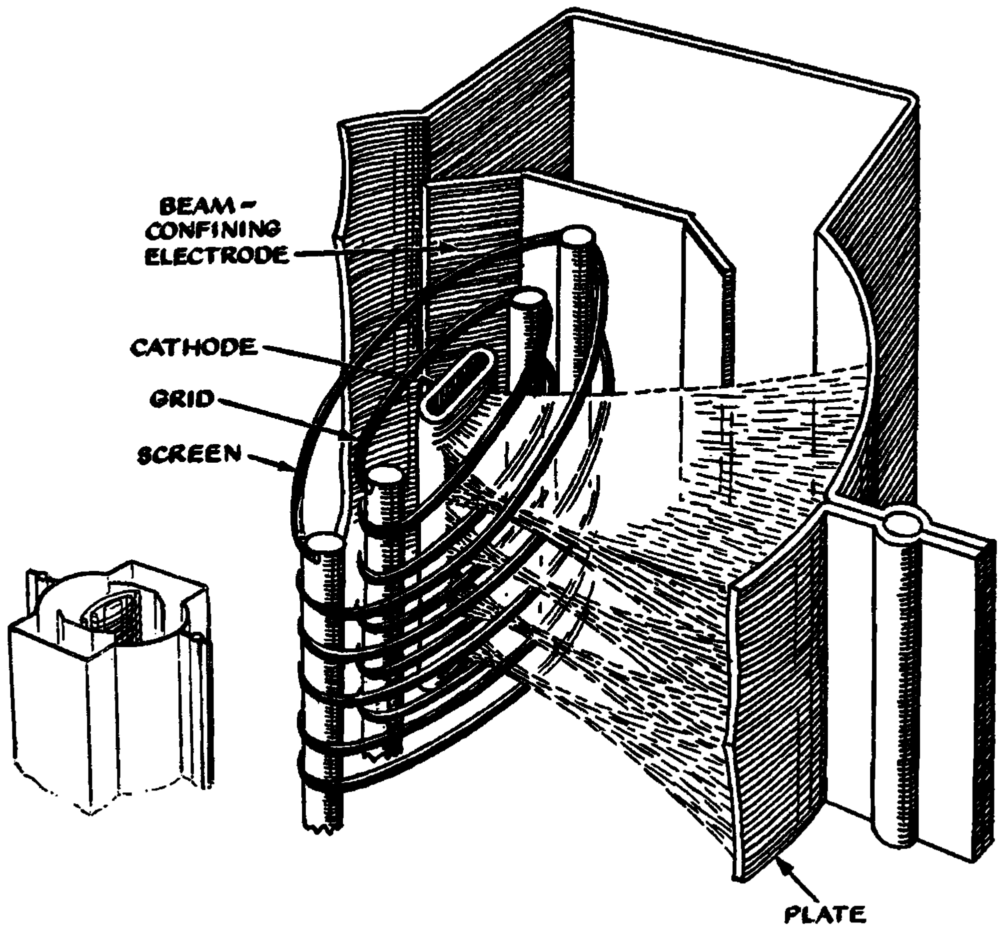


Fig. 6-15. The beam power tube (courtesy RCA).

into the tube structure. These deflecting plates are placed between the screen grid and the plate, and extend partway around the tube. These beam forming deflecting plates are internally connected to the cathode and therefore acquire a negative charge with respect to the plate. As a result, the deflecting plates repel the electrons into concentrated heavy beams of plate current.

No actual suppressor grid is necessary because secondary emission from the plate is suppressed by the space charge which forms between the plate and screen grid. This space charge has been indicated by the heavier dashes in fig. 6-15. The space charge of the electron beam is caused by the slowing up of electrons in the area between the screen grid and the plate. By operating the plate of the beam power tube at a lower potential than the screen grid, the plate is made negative with respect to the screen. The electrons are therefore slowed down when they pass through the screen on their way to the plate. Stray secondary emission electrons cannot return to the screen grid outside of the beam area because of the beam forming plates. Some beam power tubes use an actual suppressor grid in place of the space charge effect.

To summarize, we can say that the beam power tube has:

1. high power sensitivity
2. high power output
3. high plate efficiency

GAS IN A VACUUM TUBE

The ordinary vacuum type tube is supposed to be free of any gas or air. If a vacuum tube does contain gas which was not excluded during the manufacturing process, it is called a SOFT tube. The visible indication of a soft tube is a blue or purple haze, sometimes accompanied by a reddened plate. The plate current of a soft tube is excessively high. A soft tube is often erratic in its operation and should be replaced.

THE GETTER

Most vacuum tubes contain a GETTER. A getter is a small piece of metal made of barium or some similar chemical. This chemical removes or destroys stray gases that remain in the vacuum tube after the evacuation process.

CHAPTER 7

AUDIO AMPLIFICATION

INTRODUCTION

At this point, we understand that when a small amplitude signal is applied to the grid of a triode or pentode, it will be amplified and will appear many times larger in the plate circuit. This property of grid-controlled vacuum tubes makes possible their use as AMPLIFIERS. An amplifier may be defined as a device which transforms a small input signal into a large output signal.

AMPLIFIER APPLICATION

Amplifiers find many practical applications. For example, the signal that is developed in the crystal pickup of a record player is much too weak to be applied directly to a loud speaker. This weak signal must first be amplified (made larger) before it can properly drive a loud speaker. A lecturer addressing an audience in a large auditorium must have his voice amplified in order for him to be heard by everyone in the hall. The amplifier that accomplishes this is called a PUBLIC ADDRESS SYSTEM. Amplifiers are also extensively used in fields such as motion pictures, electrical recording and photo-electronics. Since amplifiers find such a wide application, it is important that we thoroughly understand their operation.

AMPLIFIERS USED IN RADIO RECEIVERS

The modern radio receiver uses two types of amplifiers in its operation; they are:

1.- The radio-frequency (r-f.) amplifier: This amplifier amplifies the weak radio-frequency signals picked up by the aerial of the receiver. A radio frequency signal is a high frequency radio wave (usually above 400 kilocycles (kc.) which is sent out into space by the radio transmitter. R.f. amplifiers will be discussed in a later chapter.

2.- The audio-frequency (a.f.) Amplifier: This amplifier amplifies the sound frequencies or audio frequencies before they are applied to the loud speaker. Audio frequencies are in the range between 16 and 16,000 cps.

CLASSIFICATION OF AMPLIFIERS

Amplifiers are classified according to the work they are intended to perform and the manner in which they are operated. The classification is determined by the grid bias of the amplifier which in turn determines the manner in which they will operate. Amplifiers are classified into general categories, class A, class B, and class C. The audio amplifier is invariably operated either class A or class B. The class C amplifier is generally found in a transmitter and will be discussed fully in the chapter on transmitters There is also a class AB amplifier which has characteristics midway between those of a class A amplifier and a class B amplifier.

CLASS A AMPLIFICATION

A graphical illustration of Class A amplification is shown in figure 7-1. Figure 7-1 is actually a platecurrent-grid voltage characteristic curve of the Class A amplifier. The bias voltage or operating point is at the mid-point of the straight line portion of the curve. Because the tube is

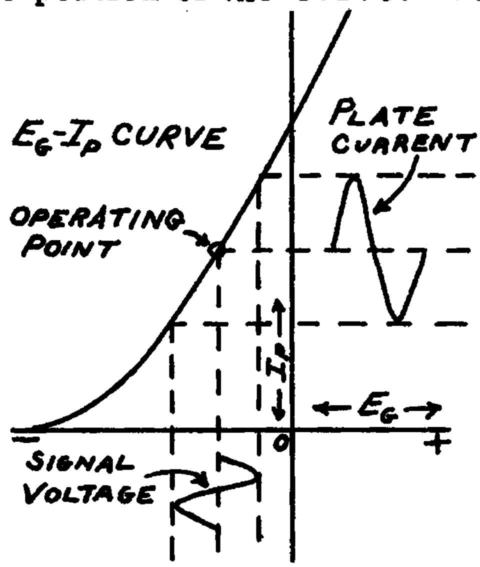


Fig. 7-1. Class A operation.

operated on the straight line portion of the curve, the PLATE CURRENT VARIATIONS ARE AN EXACT REPRODUCTION OF THE INPUT SIGNAL. Thus, we see that Class A operation gives us excellent fidelity.

From figure 7-1, you will notice that plate current flows for the entire cycle of the input signal. In other words, the tube conducts current continuously. Because of this, there is plate dissipation all the time. This results in POOR EFFICIENCY AND LOW POWER OUTPUT.

Other characteristics of a Class A amplifier are:

1. The signal never drives the grid negative enough to cut the tube off.

2. The signal never drives the grid positive with respect to the cathode. A positive grid would result in grid current flow which would cause distortion. Thus, there is no grid current flow in a Class A amplifier.

THE BIAS VOLTAGE SUPPLY

Practically all amplifiers operate with a certain amount of bias voltage. The two methods of obtaining bias voltage for an a-f amplifier are:

1.- fixed bias
2.- self-bias, or cathode bias

Fig. 7-2 illustrates an amplifier with fixed bias. The fixed bias in this case is obtained from a source called a "C" battery. The fixed bias voltage can also be obtained from a negative d-c voltage point in the power supply. The bias viltage is of constant value and cannot vary. The dis-advantage of fixed bias operation is that an external source of power is required.

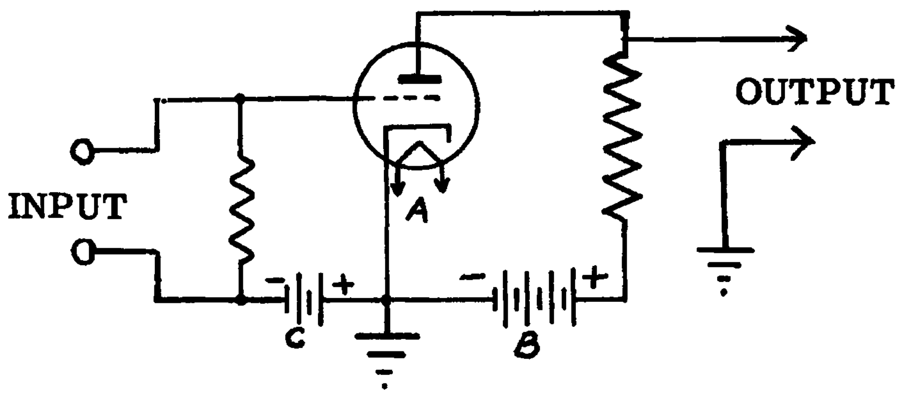


Fig. 7-2. Amplifier stage using fixed bias.

Fig. 7-3 illustrates an amplifier with cathode bias. The biasing circuit consists of the resistor, R, and the condenser, C, connected from cathode to ground. The bias voltage is developed by the d-c plate current flowing from ground through the resistor to the cathode. Since the current flows into the resistor from ground, this side of the resistor is negative with respect to the cathode side. The purpose of the condenser, C, is to by-pass the a-c component of plate current around the resistor. If the a-c component of current were allowed to flow through the biasing resistor, a varying bias voltage would be developed. Under normal amplifier operation this is not desirable. The a-c component of plate current therefore flows through the bypass condenser, C, while the d-c component of plate current flows through the biasing resistor, R, establishing a source of bias voltage. The advantage of cathode bias is that it eliminates the need for a separate source of bias voltage. Most receiver circuits use this self-biasing principle.

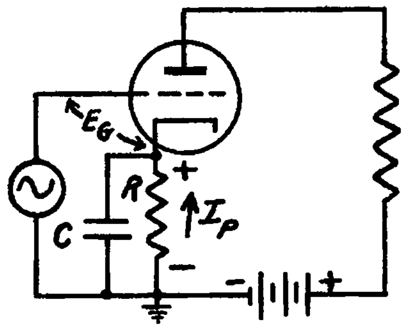


Fig. 7-3. Cathode-bias.

It may sometimes be necessary to compute the value of the biasing resistor, R. For example: Suppose we wish to operate a certain tube as a class A amplifier. The tube manual states that for class A operation, the bias for that tube is -3 volts and the plate current will be 10 ma. (.01A) Since we know the voltage across the resistor and the current through it, we can easily find the value of the cathode resistor by using ohm's law:

$$R_k = \frac{E}{I} = \frac{3}{.01} = 300 \text{ ohms}$$

COUPLING SYSTEMS IN AMPLIFIERS

Audio amplifiers are usually classified according to the method of coupling the signal from one stage to another. There are two common types of a-f coupling used in receivers and transmitters. One is transformer coupling and the other is resistance-capacity coupling.

TRANSFORMER COUPLED AMPLIFIER

A simple transformer coupled audio-amplifier is shown in fig. 7-4. V_1 and V_2 are the voltage amplifiers. T_1 is a special type of matching transformer known as an audio interstage transformer. For maximum power transfer from the plate of V_1 to the grid of V_2, the transformer is so designed that its primary impedance approximately matches the plate circuit impedance of V_1, and its secondary impedance matches the grid circuit impedance of V_2. The turns ratio for this type of fransformer is usually 1 to 3 step up from plate to grid. The secondary therefore has about three times as many turns as the primary.

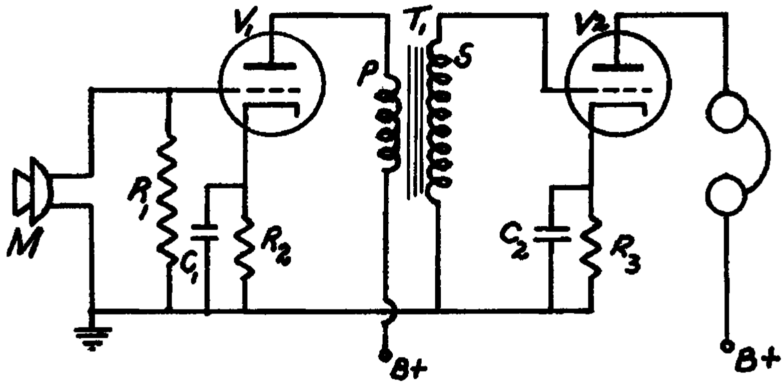


Fig. 7-4. Two-stage transformer-coupled amplifier.

Coupling is accomplished in the following manner. The varying plate current of V_1 (which is a replica of the audio signal) generates a varying magnetic field about the primary of transformer T_1. This varying magnetic field in turn induces a voltage in the secondary of T_1 which is applied as a signal voltage to the grid of V_2. This signal is then amplified by V_2 and applied to the headphones.

Let us now discuss the functions of the other parts of fig. 7-4.

"M" is the microphone which supplies the input signal to the grid of V_1.

"R_1" is the grid load resistor which serves two purposes:

a) Microphone current flowing through the resistor establishes a necessary alternating current voltage drop between the grid and cathode. This voltage drop is the signal which is to be amplified.

b) Electrons which collect on the grid can leak off to ground through the resistor. These electrons might otherwise accumulate sufficiently on the grid to cause the tube to cut-off. This condition is known as a blocked grid.

"R_2" is a cathode biasing resistor chosen to provide the correct tube bias for class A operation.

"C_1" is a cathode by-pass condenser. It provides a very low-impedance path around the bias resistor for the audio currents.

"T_1" is the interstage audio transformer.

"R_3" is a bias resistor.

"C_2" is a by-pass condenser.

ADVANTAGES OF TRANSFORMER COUPLING

The advantages of transformer coupling are:

1) High gain due to step-up ratio of transformer

2) Low d-c resistance of transformer primary permits the use of a low B+ voltage.

DISADVANTAGES OF TRANSFORMER COUPLING

The disadvantages of transformer coupling are:

1) Distortion of the signal due to the transformer characteristics. - An amplifier which reproduces faithfully and amplifies equally the band of audio frequencies which is applied to its input is said to have low distortion or HIGH FIDELITY. The average transformers used in a transformer-coupled amplifier introduce some distortion into the signal. As a result, the amplifier is said to have POOR FIDELITY. High fidelity transformer-coupled amplifiers are very difficult to design and therefore are quite expensive.

2) The transformers are large and expensive.

3) The transformers must be magnetically shielded to prevent pick-up of hum.

4) Transformer coupling is usually limited to triode amplifiers with the result that the high gain of pentodes cannot be realized.

RESISTANCE-CAPACITY COUPLED AMPLIFIER

The disadvantages of the transformer-coupled amplifier are overcome in the design of a resistance-capacity coupled amplifier. The major difference between the two amplifiers is that the interstage coupling transformer is replaced with a resistance-capacity coupling network. The elimination of the transformer allows us to use pentode tubes with a consequent increase in the overall gain of the amplifier. The elimination of the audio-coupling transformer also does away with the distortion associated with its use. Generally speaking, the R-C amplifier is the superior of the two amplifiers because of its simplicity, compactness, lower cost, and higher fidelity.

Fig. 7-5 illustrates a two stage, resistance-coupled amplifier. The coupling between the plate of V_1 and the grid of V_2 consists of a resistance-capacity network (R_4, C_3 and R_5). Condenser "C_3" is the COUPLING condenser. Its function is to pass the audio from the plate of V_1 to the grid of V_2 while, at the same time, blocking the positive plate voltage of V_1 from being applied to the grid of V_2. If the coupling condenser becomes shorted, the d-c plate voltage of V_1 would be applied directly to the grid of V_2. The positive voltage on the grid of V_2 would result in excessive grid and plate current flow, and would cause the audio signal to become distorted. The capacity of C_3 is determined

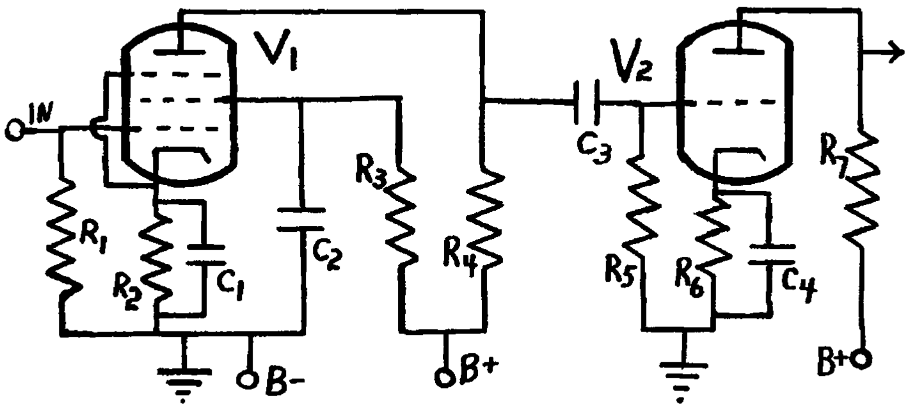


Fig. 7-5. Two stage resistance-coupled amplifier.

by the reactance it should have for the lowest audio frequency that it is to pass on to the grid of V_2. This reactance should be very low for the lowest audio frequency that is to be passed. The a-c signal from V_1 is developed across R_5.

The following is a review summary of the functions of the remaining components in fig. 7-5.

Parts	Function
R_1	. . . Grid load resistor
C_1,C_4	. . . Cathode by-pass condensers
R_2,R_6	. . . Cathode bias resistors
R_3	. . . Screen dropping resistor
C_2	. . . Screen by-pass condenser
R_7	. . . Plate load resistor; high impedance for audio

FREQUENCY RESPONSE

An amplifier is said to have a FLAT FREQUENCY RESPONSE if it amplifies all frequencies applied to the input grid equally. A frequency response curve is a graph which plots the amplifier voltage output in either volts or decibels over a frequency range. Fig. 7-6 illustrates the response curves for a transformer-coupled audio amplifier and a resistance-coupled audio amplifier. The R-C amplifier has the flatter curve and has, therefore, a flatter frequency response. A flatter response means better fidelity.

DISTORTION IN A CLASS A AMPLIFIER

Fig. 7-7a illustrates a pure sine wave of a certain

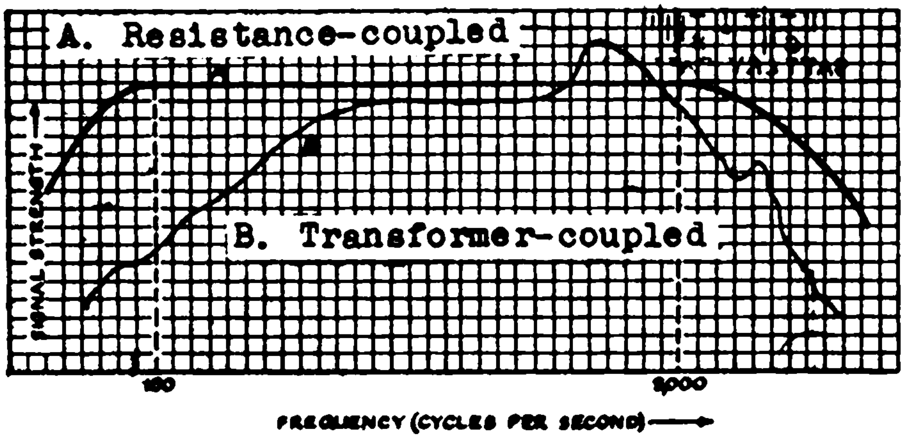


Fig. 7-6. Frequency response curve.

frequency. A pure sine wave is an a-c wave which is free of distortion. The ideal audio amplifier is one which will amplify a sine wave without changing its waveshape. The amplified plate signal must therefore be an exact duplicate

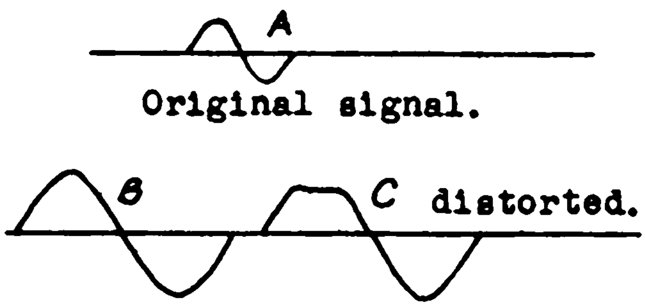


Fig. 7-7. Distortion in class A amplifier.

of the grid signal. Fig. 7-7B illustrates an amplified version of the sine wave of fig. 7-7A. It has the same waveshape as fig. 7-7A and therefore is still considered a pure sine wave (undistorted) even though it is amplified. Figure 7-7C illustrates a distorted sine wave. Note the flattening at the top of the positive portion of the wave.

CAUSES OF DISTORTION IN CLASS A AMPLIFIERS

Fig. 7-8 illustrates the E_g- Ip curve for a properly operated class A amplifier. The bias point, "A", is at the mid-point of the linear portion of the curve. The input signal is of the correct amplitude and the plate signal is an amplified and undistorted version of the input signal.

The causes of distortion in a Class A amplifier are as follows:

1) too strong a signal on the grid (signal overloading):- Excessive excitation voltage will drive the grid positive with respect to the cathode on the positive peaks of the signal. A positive grid draws grid current which results in distortion of the signal. The negative peaks of the signal may drive the grid so negative that the tube will cut-off. Cut-off condition results in distortion to the signal. See fig. 7-9.

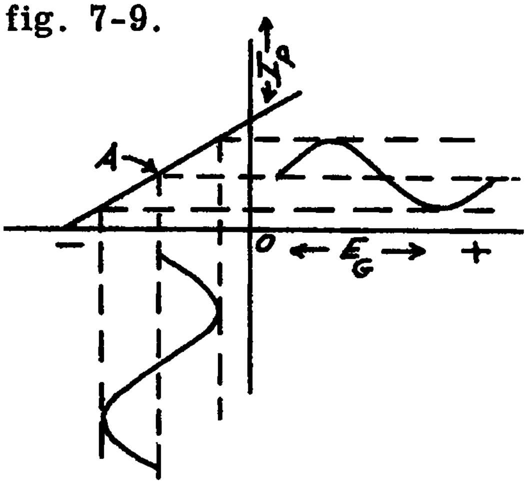


Fig. 7-8. Proper class A operation.

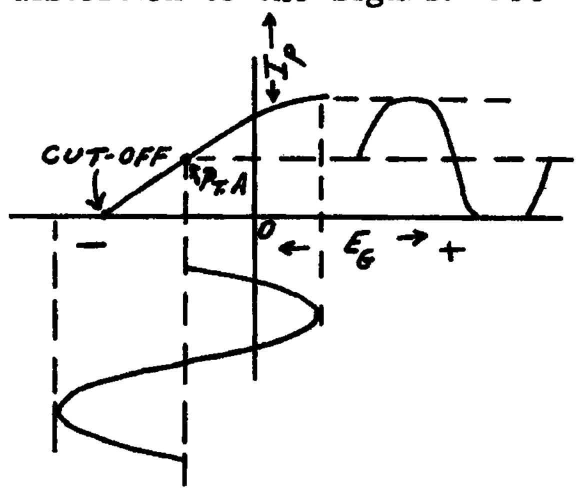


Fig. 7-9. Distortion due to excessive signal voltage.

2) Improper grid bias. The result of operating the amplifier with too little grid bias is shown in figure 7-10. Notice that the low bias places the operating point of the tube at the top of the curve instead of the middle of the curve. This causes the positive peaks of the signal voltage to drive the grid into the positive grid voltage region and draw grid current. The resulting distortion is a flattening or clipping of the positive peaks of the plate current output signal.

The result of operating the amplifier with an excessively negative grid bias is shown in fig. 7-11. The negative peaks of the signal drive the tube into cut-off. The resulting distortion is a clipping of the negative peaks of the plate current output signal.

THE CLASS A POWER AMPLIFIER

A class A voltage amplifier serves only to amplify weak voltage variations. A voltage amplifier is not required to supply a large power output. The average plate current of a voltage amplifier is therefore comparatively low in value. (a representative value would be about 5 ma) A loudspeaker, however, needs a comparatively large current variation through its voice coil in order to operate properly. The tube which is to drive the loudspeaker must be capable of handling a large amount of power. Such a tube is known as a POWER AMPLIFIER. The plate current of a receiver power amplifier tube may be about 50 ma.

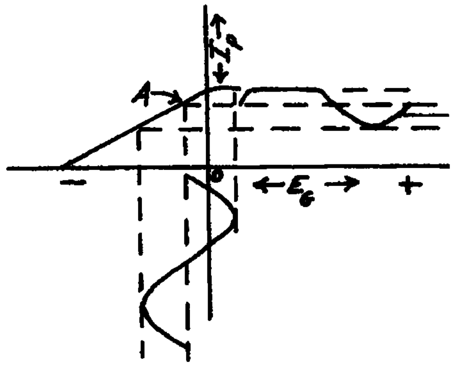


Fig. 7-10. Distortion in class A operation caused by too little bias.

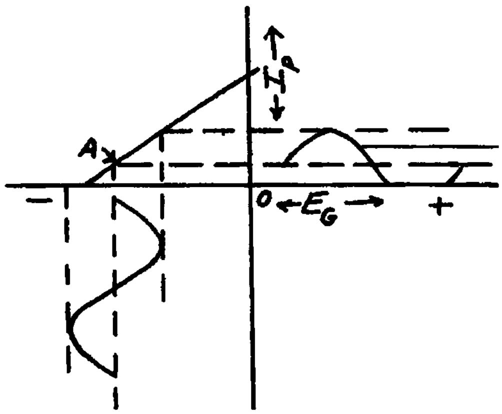


Fig. 7-11. Distortion in Class A operation caused by excessive bias.

The characteristics of a power amplifier tube are as follows:

1) A low plate resistance:- Since a power tube must be able to handle a relatively high power, it must be capable of conducting a large plate current. An amplifier tube acts like a resistor. A low plate resistance will enable a large plate current to flow. For example: The plate resistance of the 6SJ7 voltage amplifier is 700,000 ohms, and the plate current is 3.0 ma; whereas the plate resistance of the 6F6 power amplifier is 78,000 ohms, and the plate current is about 35 ma.

2) large signal handling ability: A large signal on the grid means a large plate current variation. The tube must be capable of handling a large signal without going into cut-off or drawing grid current. This means that the grid will normally operate with a comparatively large bias voltage. The bias voltage for the 6F6 power amplifier is -16 volts, as compared to -3 volts for the 6SJ7 voltage amplifier.

3) A low amplification factor: The amplification factor is directly related to the plate resistance. If the plate resistance is low, the amplification factor will be low. The 2A3 triode power amplifier has an amplification factor of only 4.2.

4) Large cathode structure: The cathode structure

must be large in order to be able to supply the large plate current requirements.

5) Large plate surface structure: The plate surface must be large to enable it to radiate the heat generated by the large plate current flow.

THE CLASS B POWER AMPLIFIER

A power amplifier operated class A has a comparatively poor operating efficiency. The reason for this is that the tube conducts plate current for the entire cycle of the input signal; this results in a continuous dissipation of heat by the plate. Consequently, the maximum power output possibilities of the class A amplifier are never fully realized.

The modulator stages of radio-telephone transmitters require power audio amplifiers capable of delivering large amounts of power. Class A power amplifiers would not be practical for such an application because of their poor operating efficiency. The class B power amplifier is therefore used because of its high operating efficiency. A class B amplifier is biased to cut-off so that plate current is practically zero without a signal. Fig. 7-12 illustrates class B operation on the E_g - I_p curve.

THE CHARACTERISTICS OF THE CLASS B AMPLIFIER

The characteristics of the class B amplifier are as follows:

1) Plate current flows only during the positive half of the signal period. The negative half of the signal cuts off the tube. (see fig. 7-12) The amplifier operates in a manner similar to that of a rectifier in that it conducts only

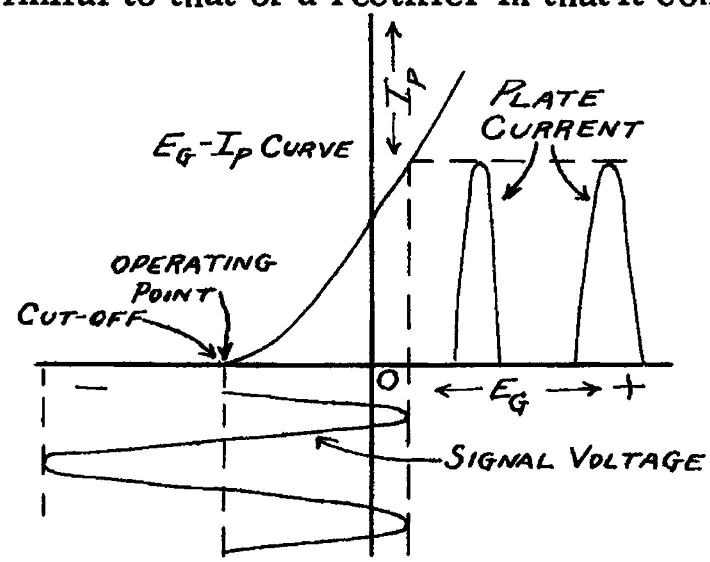


Fig. 7-12. Class B operation.

when the signal is positive.

2) The amplifier is operated over the entire length of its characteristic curve so that large plate current swings can be obtained. The large plate current swing is necessary if large power output is to be realized.

3) The efficiency for class B operation is much higher than that for class A for two reasons:

a. Plate current flows for half a cycle, so that the power wasted in heating the plate is very much reduced.

b. Efficiency of operation increases when a greater portion of the length of the characteristic curve is utilized. The class B amplifier uses a greater portion of its characteristic curve than a class A amplifier.

CLASS B PUSH-PULL POWER AMPLIFIER

A class B amplifier tube, when used alone, will distort the signal because only one half of the input cycle is amplified. Two tubes are therefore necessary, one to amplify the positive half of the input signal and the other to amplify the negative half. The plate output of each tube is combined with the other to form one continuous wave. This system of amplification is called PUSH-PULL amplification.

Figure 7-13 illustrates a basic class B push-pull amplifier. Its operation is as follows: We will assume that, during the positive half of the input cycle, the grid of V_1 goes positive and the grid of V_2 goes negative. V_1 will conduct current while V_2 will be cut-off. V_1 will therefore amplify the positive half of the signal. During the negative half of the input signal, the grid of V_1 goes negative while

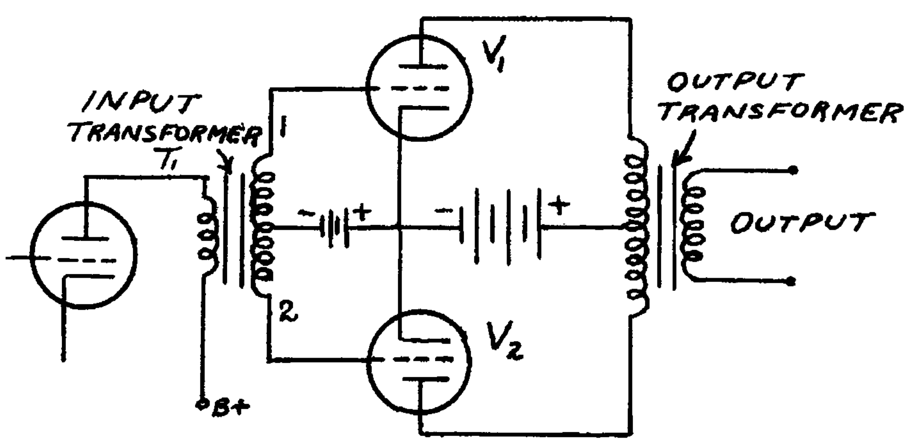
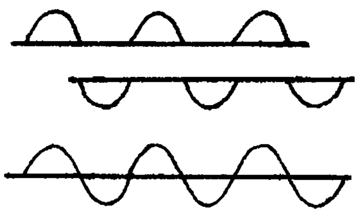


Fig. 7-13. Class B push-pull amplifier.

the grid of V_2 goes positive. V_1 will cut off and V_2 will conduct. V_2, therefore, amplifies the negative half of the input signal. The negative plate signal of V_2 and positive plate signal of V_1 combine in the output to form a complete amplified cycle. This is illustrated in fig. 7-14.



A. Output of tube 1.

B. Output of tube 2.

C. Resultant output.

Fig. 7-14. Output of a class B push-pull amplifier.

Push-pull operation has enabled us to utilize the high efficiency of a class B amplifier while at the same time eliminating the distortion inherent in class B operation.

SECOND HARMONIC DISTORTION

Any distorted waveform may be analyzed and found to consist of a fundamental frequency plus a number of harmonics. Harmonic frequencies are multiples of the fundamental frequency. For example; Let us suppose the original undistorted signal is a 1000 cycle wave. The second harmonic would be 2000 cycles; the third harmonic would be 3000 cycles, etc. This signal upon being amplified becomes distorted due to the addition of harmonic frequencies to the original waveform during the process of amplification. In our example, the amplified distorted waveform would be found to consist of the original fundamental frequency of 1000 cycles, plus a second harmonic conponent of 2000 cycles, plus a third harmonic component of 3000 cycles, etc. The fundamental and the harmonics all add together to give us a resulting distorted waveshape. The second harmonic is usually the most predominant of all the harmonics present. Fig. 7-15 illustrates a distorted resultant wave, which is the sum of a fundamental plus a second harmonic component.

In an audio amplifier, the distorted signal frequency is converted by the speaker into a distorted sound frequency which sounds unpleasant to the ear. If we could remove this second harmonic from the amplified signal before it reaches the speaker, we would end up with the original undistorted waveform.

Push-pull operation eliminates second harmonic distortion. Fig. 7-16 illustrates the distorted output of two class A amplifiers connected in push-pull. A class "A" push-pull amplifier differs from a class "B" push-pull amplifier in that both tubes in the class "A" push-pull amplifier conduct current continuously. Both tubes combine their output during both the positive as well as the negative cycles to give us the resulting waveshape. Notice that the two curves combine together, point by point, to produce the

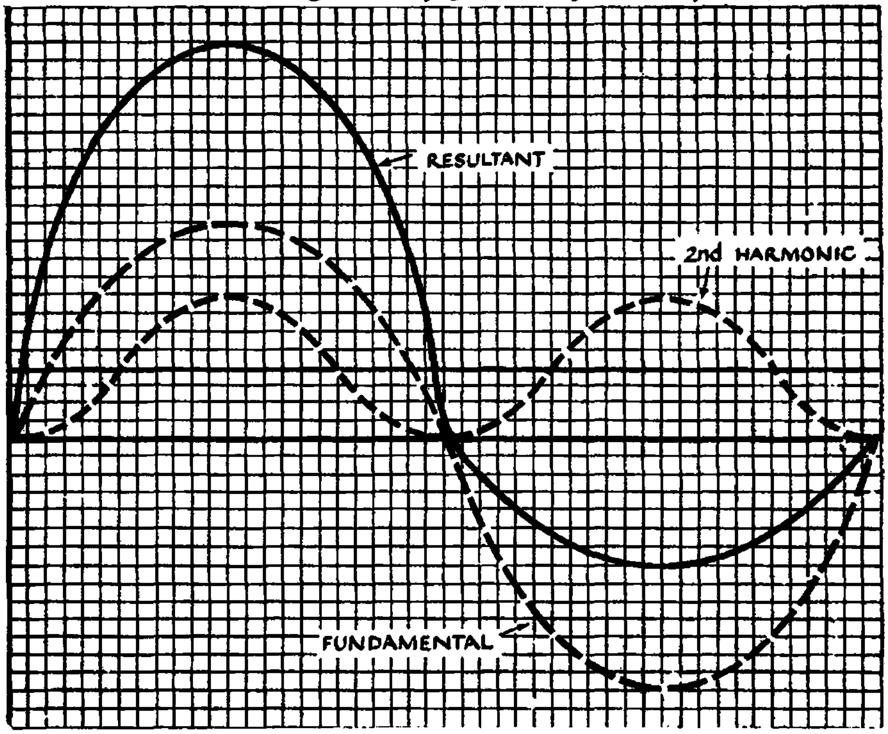


Fig. 7-15. Second harmonic distortion.

resultant undistorted output curve. The second harmonics of V_1 and V_2 are out of phase with each other across the transformer primary, and consequently cancel each other out.

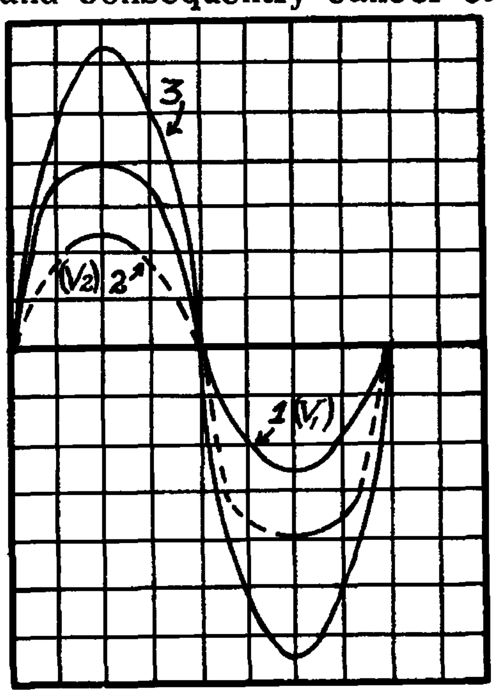


Fig. 7-16. Push-pull operation eliminating second harmonic.

By eliminating even (2nd, 4th, 6th, etc.) harmonic distortion, push-pull operation improves the fidelity of reproduction considerably over that obtainable from one tube (single-ended) operation. A good audio system always uses push-pull amplifiers in its last stage.

INVERSE FEEDBACK

Fig. 7-17 shows a circuit in which part of the output signal on the plate of the power tube is fed back to the grid through a resistor and condenser. Since the plate and

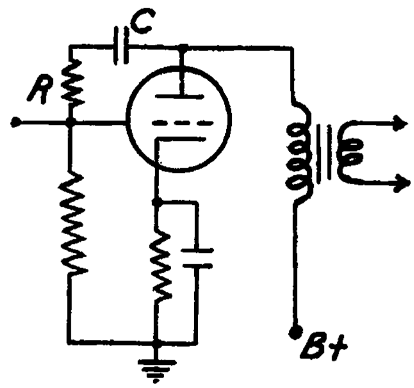


Fig. 7-17. Negative feedback.

grid voltages are out of phase, the feedback signal will be out of phase with the grid signal. If the amount of feedback is correctly adjusted, the harmonics causing distortion may be partially cancelled out. Since a portion of the original signal is also being fed back out of phase, the overall gain of the system is reduced. This disadvantage can be overcome by using either high mu tubes or another stage of amplification. As a result of inverse feedback, the distortion is reduced to a great extent.

Inverse feedback is also known as negative feedback and degenerative feedback.

SOUND

A class A audio amplifier is used to amplify the small signal output of a microphone. The action of a microphone depends upon certain characteristics of a sound wave. We have therefore reached a point in our discussion of amplifiers where a brief resume of the nature of sound becomes necessary.

SOUND is defined as a disturbance in a material medium caused by the vibration of any body at a certain definite frequency. A sound wave travels through a material medium such as air or steel in the form of a compressional wave. This compressional wave travels out from a region of disturbance in exactly the same manner as ripples do when a pebble is dropped into a pool of water. Vibrating objects, such as your vocal cords, cause regions of compressed air followed by rarefied air to move outward and away from them in the form of concentric spheres. These vibrations or disturbances reach the ear and cause the eardrum to move inward and outward according to the pressure exerted by compressions and rarefactions. The human ear is capable of hearing such disturbances only if they occur within the range from 16 to 16,000 cycles per second. The FREQUENCY RESPONSE of the ear is therefore said to be from 16 to 16,000 cps. This range of frequencies is designated by the term AUDIO FREQUENCIES. Although a frequency vibration of 30,000 cps will cause the diaghragm in the ear to vibrate, the nerves in the ear are incapable of detecting the vibration.

THE MICROPHONE

An amplifier can only amplify an electrical frequency. Therefore, a sound frequency such as music or voice must first be converted into an equivalent electrical frequency in order that it may be amplified.

A microphone is a device which translates or converts sound impulses into varying electrical potentials. These varying electrical potentials constitute the electrical signal and can be impressed between the grid and cathode of the first amplifier tube for purposes of amplification. There are many types of microphones in use today; we shall discuss a few of the common ones.

THE SINGLE-BUTTON CARBON MICROPHONE

Construction: The single-button carbon microphone consists mainly of a diaphram and a small compartment filled with carbon granules. The compartment is called a "BUTTON". One side of the button is movable and is attached directly to the diaphram. (See figure 7-18). A 6 volt battery and the primary of a transformer are connected in series with the button. Operation: When sound strikes the diaphram of the microphone, the diaphram vibrates at the frequency of the sound. This vibration causes the moveable side of the button to move in and out, thereby causing the packing of the carbon granules to vary. This, in turn, causes the resistance of the button to vary. The varying resistance will cause the current in the circuit to vary. The result is that an audio current, with the same frequency as the original sound, flows through the primary of the microphone transformer.

Connection:- The impedance of the button is about

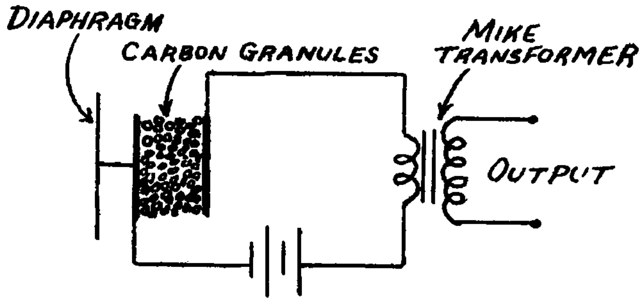


Fig. 7-18. Single-button carbon microphone.

100 ohms. A microphone transformer is used to match this low impedance to the high grid impedance of the first stage.

Frequency response:- The single button carbon microphone responds well to audio frequencies between 250 and 2700 cps. Since many of the tones of musical instruments lie above 2700 cps, the carbon microphone is suitable only for speech. The general range of speech frequencies is below 2700 cps.

OTHER CHARACTERISTICS:-

1. The carbon microphone is the most sensitive of all microphones in use at the present time. For a given level of sound input, this microphone will generate a higher signal voltage than any other microphone.
2. The carbon microphone is not directional; it picks up sound impulses equally well from all directions.
3. Constant current through the granules gives rise to an annoying background hiss.
4. Excessive current flowing through the carbon granules, or jarring of the microphone while the current is on, will cause the microphone to lose its sensitivity.

THE RIBBON OR VELOCITY MICROPHONE

Construction:- This microphone is activated by moving air particles. A thin, corrugated, metallic ribbon is suspended between the poles of a strong permanent magnet.

Operation:- Sound energy strikes the ribbon and causes it to move back and forth, thereby cutting the magnetic field. The cutting action induces an e.m.f. in the ribbon; this e.m.f. is the audio signal. The e.m.f. frequency is determined by the frequency of the sound wave which strikes the ribbon. The impedance of the short piece of ribbon may be as low as 0.5 ohms. A matching transformer is employed to match the low output impedance of the ribbon microphone to the high grid input impedance.

Frequency Response:- The frequency response is fairly flat from 30 to 12,000 cps. This wide frequency range is satisfactory for the transmission of music as well as sound.

Other Characteristics: 1) To prevent booming effect, the microphone should be placed at least 14 inches away from the source of sound.

2) This microphone is bi-directional; maximum pick-up occurs at the front and back of the head of the microphone.

3) It is desirable as a broadcast microphone because of its flat frequency response.

THE CRYSTAL MICROPHONE

Construction:- The active element in a crystal microphone is a crystalline material, usually Rochelle salts. Other crystals that may be used are quartz and tourmaline. There are two types of crystal microphones:

1) diaphragm type in which a thin diaphragm is rigidly fixed to one of the major faces of the crystal.

2) sound cell type in which a series of crystals are excited by sound pressure directly, without the use of a diaphragm. We shall examine the sound cell type of crystal microphone as it is the most commonly used of the two types of crystal microphones.

Operation:- Certain crystals, like Rochelle salts, develop a potential difference between two surfaces when a mechanical pressure is applied to their opposite surfaces. Sound pressure applied to a crystal surface will develop a varying electric potential across the opposite surface at the frequency of the sound wave. In this manner sound energy is converted into electrical energy. The varying potential that is developed is applied to the grid circuit of an amplifier for further amplification.

Connection:- The crystal microphone is about the simplest microphone to connect. It requires no battery, since it generates its own potential. The crystal microphone requires no transformer because it has a high impedance (over one megohm) and is therefore a perfect match to the high impedance of the grid circuit.

Frequency Response:- The frequency response of the crystal microphone is from 50 to 8000 cps. This is satisfactory for speech reproduction but not quite satisfactory for high fidelity music.

Other Characteristics:- 1) A crystal microphone should be handled with care because any shock is likely to impair its operation.

2) It should not be exposed to excessive temperature and humidity changes.

3) It is used in portable, mobile, and fixed station equipment.

4) A single sound cell type of crystal microphone is not directional: multiple cell types can be designed for directional use.

THE REPRODUCER

The process of amplification consists of three individual steps:

1) conversion of sound energy to electrical energy (by the microphone)
2) amplification of the converted electrical energy
3) conversion of the amplified electrical energy back into sound energy.

This last step is accomplished by means of a REPRODUCER. Of the many types of reproducers in use today, we will study the headphones, the electromagnetic dynamic loudspeaker and the permanent magnetic dynamic loudspeaker.

THE RADIO HEADPHONE

The radio headphone or telephone receiver is the simplest type of reproducer. It consists, basically of an iron core electromagnet and a metal diaphram. This is illustrated in figure 7-19. The diaphram is separated from the electromagnet by a few thousandths of an inch.

Audio currents are sent through the coils of the electromagnet. This causes the field of the coils to alternately weaken and strengthen. The diaphram vibrates in accordance with this varying field and sets the surrounding air into motion. This air motion constitutes the sound waves which travel to the ear of the listener.

The impedance of most electromagnetic headphones is about 2000 ohms. This value is high enough for the headphones to be used directly as a plate load for a voltage amplifier triode without the need of a matching transformer.

THE ELECTRO-DYNAMIC LOUD SPEAKER

The major parts of the electro-dynamic loud speaker are: (see fig. 7-20)

1) The Field Coil: The field coil is a powerful electromagnet which must be energized from a pure d-c source. The d-c is usually obtained from the same power supply that supplies power to the amplifier or radio.

2) The Voice Coil: This coil is one of few turns; it

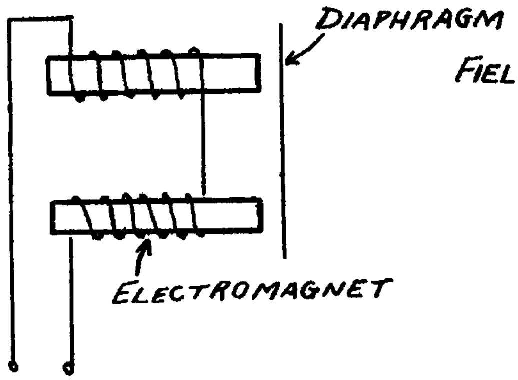


Fig. 7-19. Simplified diagram of headphone.

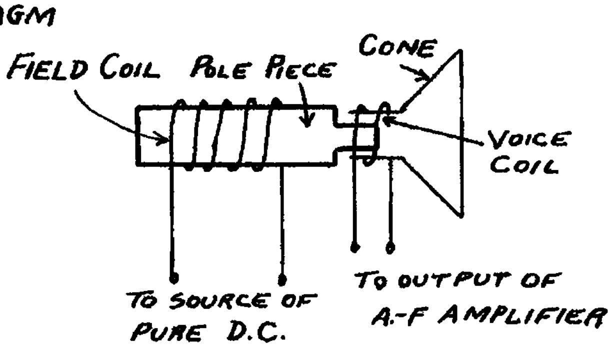


Fig. 7-20. The electrodynamic speaker.

has an impedance of from 2 to 20 ohms The coil is wound around a small cardboard cylinder which fits closely around the pole piece of the field magnet. The voice coil is the only part of the system which is free to vibrate.

3) The Spider: The voice coil is suspended around the pole piece by a very flexible support called the "spider".

4) The Cone: The cone of the speaker is firmly attached to the voice coil. The outer edges of the cone are secured to the metal frame of the speaker housing.

OPERATION OF THE ELECTRO-DYNAMIC LOUD SPEAKER

Since the voice coil impedance is low, the coil must be connected to the output tube through a matching transformer. The operation of the speaker is similar to the operation of the headphones. Audio currents flow through the voice coil and set up a varying magnetic field around the voice coil. The magnetic reaction between the voice coil and the field coil causes the voice coil, together with the cone, to vibrate at the audio frequency. The vibrating cone transmits its energy to the air in the form of sound wave.

PERMANENT MAGNETIC DYNAMIC SPEAKERS

With the development of powerful magnetic alloys, such as Alnico steel, the permanent magnet began to replace the electromagnetic field coil. The resulting speakers are called permanent magnetic dynamic speakers, or simply P.M. dynamic speakers. Except for the fact that a permanent magnet has replaced the electromagnetic field coil, the P.M. speaker operates in exactly the same manner as the electromagnetic speaker.

CHAPTER 8
INTRODUCTION TO TRANSMISSION AND RECEPTION

INTRODUCTION

The first seven chapters of this book were devoted to a study of vacuum tubes, fundamental radio theory, and basic circuits. These chapters gave us the background material for our discussion of transmitters and receivers. However, before we go into a detailed study of actual transmitter and receiver circuits, we will take a bird's eye view of a complete communications system. Instead of drawing out the individual circuits, we will draw a series of boxes, each box representing a stage. (A stage is a tube with its associated parts). The function of each stage will be printed inside the box. Such a diagram is known as a block diagram. Figure 8-1 illustrates a block diagram of a radio-telephone transmitter and figure 8-2 illustrates the block diagram of a receiver.

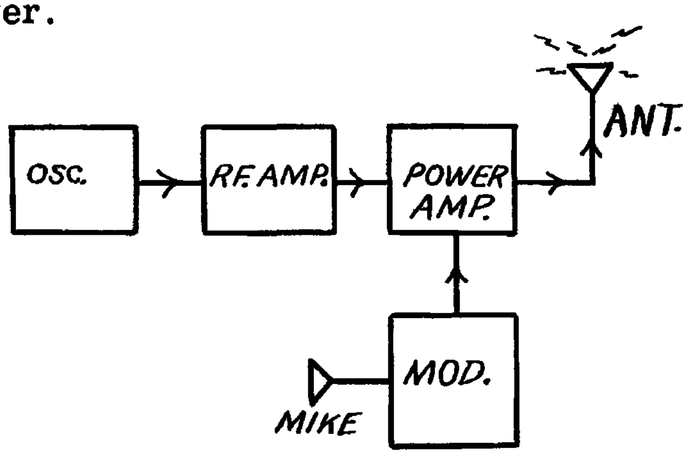


Fig. 8-1. The radio transmitter

THE TRANSMITTER

In the early development of radio it was found that the magnetic fields resulting from high-frequency currents were able to travel long distances through space. One of the primary functions of the transmitter is to develop this high frequency signal. This is accomplished in the OSCILLATOR stage. The oscillator stage is actually the heart of the transmitter.

The output of the oscillator is fed to the RADIO-FREQUENCY AMPLIFIER. The function of the radio-frequency amplifier is to amplify the output of the oscillator.

The output of the r.f. amplifier is then fed to the R.F. POWER AMPLIFIER. The r.f. power amplifier amplifies the r.f. in terms of power. The power amplifier then supplies the antenna with this amplified r.f. power.

Up to this point, we have only discussed the generation and transmission of a radio frequency wave that does not contain any speech. The three stages, discussed so far, can transmit only code. If we desire to transmit speech, we must add a microphone and one or more stages.

We have already studied the microphone in detail. Its function is to convert sound energy into electrical energy. The output of the microphone is applied to the modulator which is simply an audio amplifier. The modulator serves two functions: 1) It amplifies the weak audio output of the microphone. 2) It superimposes the audio on to the radio frequency energy that is present at the power amplifier stage. This process is called modulation. The audio waves are not capable of travelling through space and therefore must be combined with an r-f wave in order to be transmitted. Thus the r-f acts as the "carrier" for the audio; the r-f carries the audio from the transmitter to the receiver. The combined audio-r-f output of the power amplifier is fed to the antenna where it is radiated out into space in the form of electromagnetic waves.

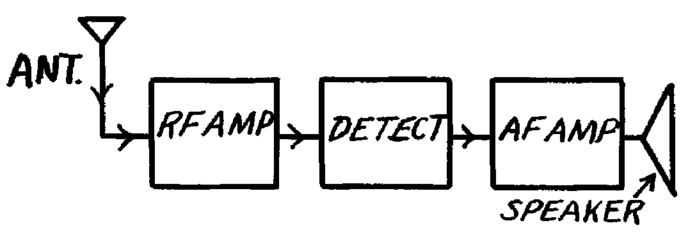


Fig. 8-2. The receiver

THE RECEIVER

At the receiving end of the communications system, the electromagnetic waves induce small signal voltages into the receiving antenna. These signal voltages are quite weak because the electromagnetic waves have travelled some distance before striking the receiving antenna. The signal voltages must therefore be amplified; this is the function of the r-f amplifier, the first stage in the receiver. The output of this stage is applied to the detector. Just as the oscillator is the heart of the transmitter, the detector is the heart of the receiver. The detector stage separates the audio from the r-f carrier. The carrier has now served its purpose in bringing the audio to the receiver. All that we are actually interested in is the audio. The audio output of the detector is then fed to an audio amplifier stage to be amplified. The amplified audio is applied to a speaker which converts the audio electrical variations back into the original sound that energized the microphone of the transmitter.

Thus, we have briefly described a modern communications system. The remaining chapters will go into the details of each stage of the communications system.

CHAPTER 9
OSCILLATORS

INTRODUCTION TO OSCILLATORS

Simply speaking, a vacuum tube oscillator is an electronic alternating current generator. It is a device used to generate an alternating current of any desired frequency. All transmitters, and practically all receivers, use a vacuum tube oscillator. Vacuum tube oscillators are also employed in various types of instruments used for testing and adjusting radio equipment. Because oscillators find so many applications, various types of oscillator circuits have been developed. The operation, however, of the different types of oscillators is fundamentally the same.

THE OSCILLATING TUNED CIRCUIT

The heart of an oscillator is a TUNED CIRCUIT which consists of a coil and condenser in parallel. In order to understand how a complete oscillator works, it is first necessary to see how a simple tuned circuit can produce alternating current oscillations. An elementary oscillatory circuit is shown in fig. 9-1. When the switch, "S", is thrown to the left, the condenser, "C", is placed across the battery. The coil, "L", is out of the circuit. "C" will

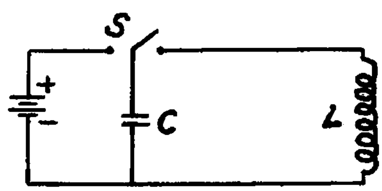


Fig. 9-1. An elementary oscillatory circuit.

immediately charge up to the voltage of the battery. The upper plate of "C" will become positive, and the lower plate will become negative. A certain amount of electrical energy is therefore stored up on the plates of the condenser by the charging process. If the switch is then thrown to the right, the condenser will discharge through the coil "L". The electrons will flow from the lower plate of "C", through the coil and back to the upper plate of "C". The flow of electrons will build up a magnetic field around "L" The energy which was stored in the condenser has now been transferred over to the magnetic field surrounding the coil. When "C" is discharged completely, the flow of electrons through "L" tends to cease, causing the magnetic field to start collapsing. The collapsing magnetic field induces a voltage of such a polarity across "L", that it maintains the flow of electrons to the upper plate of the condenser. This occurs because the magnetic field acts to prevent a change in the flow of current (Lenz's Law). The flow of electrons to the upper plate continues until the magnetic field has completely collapsed. The condenser now becomes charged with its top plate negative and its bottom plate positive. The energy which was in the magnetic field has now been transferred over to the condenser in the form of a stored charge. The condenser is now charged in the opposite polarity to its original charge. The condenser again discharges through "L", and the entire action as outlined above repeats itself. Thus we can see that the energy or current OSCILLATES back and forth between the coil and the condenser, alternately charging "C" first in one direction and then in the other. This alternating current will produce an alternating voltage across the tuned circuit. The frequency of this a-c voltage is determined by the values of "L" and "C".

THE DAMPED AND UNDAMPED WAVE

If there were no resistance in either the coil or the condenser, there would be no energy loss. The oscillations would therefore continue forever at a constant amplitude. A graph, illustrating this condition is shown in fig. 9-2A. The wave is called an UNDAMPED WAVE (continuous oscillations). However, such a situation is impossible in ac-

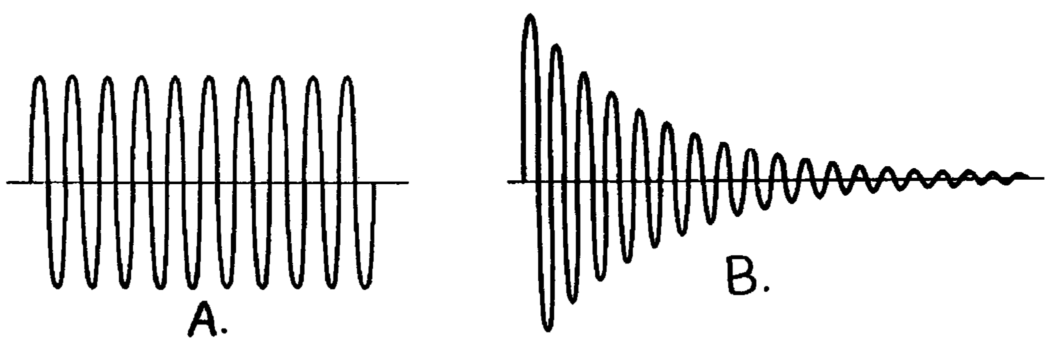


Fig. 9-2. Oscillations.

tual practice. Some resistance is always present in radio components, especially in a coil. This resistance causes some of the energy which oscillates back and forth in the tuned circuit to be transformed into heat. The heat, of course, is a loss of energy. Therefore, with each succeeding cycle, the amplitude of the oscillating voltage decreases until all of the energy has been dissipated in the form of heat. Fig. 9-2B illustrates the diminishing oscillations. We call this a DAMPED WAVE.

CONDITION FOR OSCILLATION

In radio, it is necessary that the tuned circuit oscillations continue at a constant amplitude, (just like the undamped wave of fig. 9-2A). If we want the oscillations to continue, we must make up for the resistance losses which occur in the L-C circuit. We must somehow inject electrical energy back into the L-C circuit to sustain the oscillations. Where is this energy to come from, and how do we inject it properly into the L-C circuit? To answer these questions we can compare the oscillations of energy in the tuned circuit to a child on a swing. In order that the child keep swinging to a constant height, it is necessary that someone give the swing a little push each time the child reaches the top of his swing. In other words, energy must be added to the swing at the right time to overcome the friction in the hinges. Otherwise the swing will gradually come to rest just like the damped wave oscillations. In radio, the answer to the question of how to maintain oscillation lies in the use of the amplifying ability of the electron tube.

When a vacuum tube is hooked up to a power supply, the a-c energy developed in the plate circuit is much greater than that applied to the grid circuit; this is due to the tube's amplification. If the oscillating circuit of fig. 9-1 were to be connected to the grid circuit of a vacuum tube, an amplified version of the oscillating voltage would appear in the plate circuit. If we could somehow continuously feed back some energy from the plate circuit to the grid circuit to compensate for the resistance losses in the L-C grid circuit, oscillations could continue like the undamped wave of fig. 9-2A. A simple method of doing this is shown in fig. 9-3. L_1 and C_1 represent the tuned circuit, sometimes

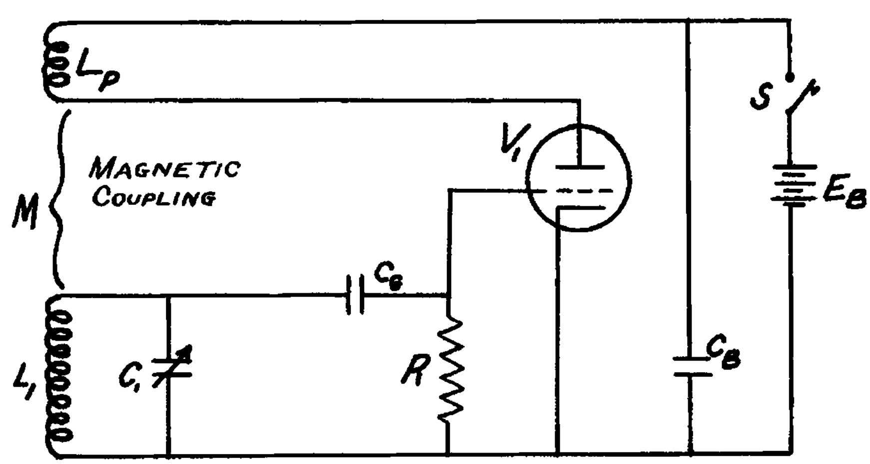


Fig. 9-3. Tickler-coil oscillator or Armstrong oscillator.

called the TANK CIRCUIT. V_1 is the triode amplifier tube. L_p is a coil of wire wound on the same form and placed next to L_1. Since L_p is in the plate circuit, it is easy to see that some of the amplified energy from the plate circuit is fed back to the grid circuit through the magnetic coupling between the two coils. If this energy can overcome the losses in the tank circuit, oscillations will be maintained.

The entire circuit of fig. 9-3 is called a vacuum tube oscillator. This particular oscillator has found wide practical use, especially in modern receivers. It is known by the names of the TUNED GRID OSCILLATOR, TICKLER COIL OSCILLATOR, or the ARMSTRONG OSCILLATOR. We shall now discuss, in more detail, the operation of this vacuum tube oscillator.

OPERATION OF A VACUUM TUBE OSCILLATOR

As soon as the switch "S" is turned on, a surge of plate current flows through the plate coil, L_p. This surging current builds up an expanding magnetic field around L_p. The expanding field cuts through L_1 and induces an e.m.f. in it. The induced e.m.f. across the coil will now charge the condenser of the tuned circuit. The condenser then discharges through L_1 and the oscillatory action, previously described, begins. The losses in the tank circuit are overcome by a feed-back of energy from the plate circuit to the grid circuit by means of magnetic coupling between L_p and L_1. In this manner the oscillations of the tuned circuit are maintained at a constant amplitude.

L_p, called the TICKLER COIL, must be wound in such a direction so that an expanding field about it induces a voltage in L_1 which causes the grid to go positive. A positive grid will cause the plate current and the field around L_p to further increase, and induce energy back into L_1. The process of transferring energy from L_p of the plate circuit to L_1 of the grid circuit is called INDUCTIVE FEEDBACK or MAGNETIC FEEDBACK. Since the energy fed back to the tuned circuit is sufficient to make up for the energy lost in the resistance of the tank circuit, the oscillations will continue and will not die down. If the tickler coil is wound in such a direction so as to make the grid negative, the oscillator will NOT start oscillating at all.

From the above explanation we realize that the vacuum tube itself does not oscillate. The oscillations actually take place in the tuned circuit. The vacuum tube simply functions as an electrical valve which automatically controls the release of energy back into the tuned circuit. The feedback energy overcomes losses and maintains oscillations. The above explanation of the operation of an oscillator is basic to all oscillator circuits that will be covered in this chapter.

GRID-LEAK BIAS

Efficient operation of an r-f. oscillator requires that it have a high negative bias. There are several ways of obtaining this large bias. One way is by means of a battery; another is by means of a negative voltage power supply. However, in the case of an oscillator, the only practical way of obtaining this high negative bias is by means of a resistor and condenser connected in the grid circuit, as shown in fig. 9-3. This type of bias is called GRID-LEAK BIAS Grid-leak bias is used in all oscillators. A simple explanation of grid-leak bias is as follows:

When the peaks of the oscillations in the tank circuit of fig. 9-3 drive the grid positive with respect to the cathode, grid current, I_g, flows in the grid circuit. A positive grid attracts electrons as does a positive plate. The grid current flow charges up condenser C_g in the manner shown in fig. 9-4A. During the remainder of the cycle, the grid does not conduct and the condenser discharges through R as shown in fig. 9-4B. Current flowing through R produces a voltage such that the top or grid side of R becomes negative

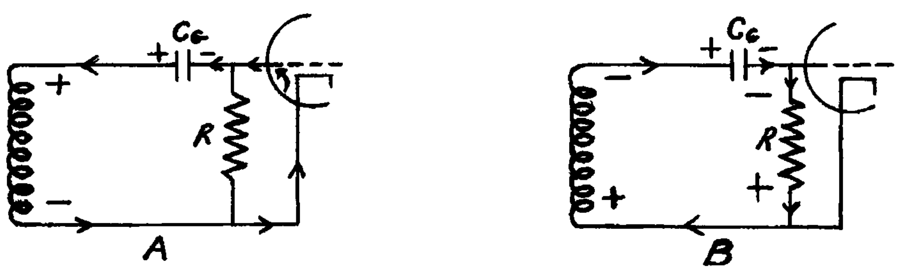


Fig. 9-4. Grid-lead bias.

with respect to the bottom or cathode side. This voltage is the grid-leak bias voltage which makes the control grid negative with respect to the cathode. Because of the heavy grid-leak bias, plate current flows only during the positive peaks of the oscillations. Since the plate current flows for only a small part of a cycle, the average power wasted inside the tube is reduced, and the efficiency of the oscillator is increased. The fact that the plate current does not flow continuously does not hinder oscillations because it is only necessary to feed back small pulses of energy in every cycle to sustain the oscillations.

FREQUENCY OF OSCILLATION

The larger the value of the inductance in the tuned circuit, the longer it will take for the condenser to discharge through the inductance. Likewise, the larger the capacitance, the longer it will take the condenser to charge or discharge. Since the time of a cycle of oscillation depends upon the charge and discharge time, it can be seen that the frequency of the oscillator goes down as the inductance or capacitance is increased. On the other hand, the frequency goes up if the inductance or capacitance is made smaller. The formula for the frequency of an oscillator is:

$$\text{9-1)} \quad F = \frac{1}{2\pi\sqrt{LC}}$$

where: F is the frequency in cycles
L is the tank inductance in henries
C is the tank capacitance in farads

In order to vary the frequency of the oscillator, it is necessary to vary the value of the inductance or the capacitance. In most receivers and transmitters a variable condenser is used in the tank circuit to vary the frequency of the oscillator.

THE HARTLEY OSCILLATOR

A popular oscillator that is frequently used in electronic circuits is the HARTLEY OSCILLATOR. Its principle of operation is very similar to that of the Armstrong Oscillator. Instead of having two separate plate and grid coils, the Hartley oscillator has a single coil which is tapped. The Hartley oscillator can always be recognized by its tapped coil. (see fig. 9-5) One part of the coil, (L_p), is in the plate circuit and the other part, (L_g), is in the grid circuit. Capacitor, C, is across the entire coil. The resonant frequency of this oscillator is determined by C and L_g and L_p in series. You will recall that in the Armstrong oscillator energy is fed back by the inductive coupling between the tickler coil and the grid coil. The feedback in the Hartley oscillator is also due to inductive coupling (between L_p and L_g). The tickler coil may be represented by L_p. The amount of feedback can be controlled by varying the position of the tap on the coil. The theory of operation of the Hartley oscillator is exactly the same as the Armstrong oscillator.

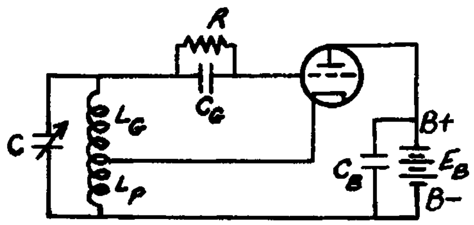


Fig. 9-5. Series-fed Hartley.

FREQUENCY STABILITY OF OSCILLATORS

If an oscillator remains in operation continuously, it will be found that the frequency of the oscillator drifts with time. For example, when an oscillator is first turned on, it may start to oscillate at a frequency of 1000 kc. After the oscillator warms up, the frequency may drift either above or below 1000 kc. Frequency drift is highly undesirable in a broadcast transmitter since it would cause fading of the signal at the receiver end. Similarly, oscillators in test equipment must have a minimum of frequency drift if the equipment is to serve any useful purpose. The causes of oscillator drift and its prevention are subjects of importance to all radio men.

Oscillator frequency drift may be caused by the following factors:

1.- improper design of the oscillator circuit
    a. choosing the wrong combination of L and C for the tank circuit
2.- poor voltage regulation of the oscillator power supply
    a. changes in B+ voltage will cause voltage variations at the screen and plate. This will vary the oscillator frequency. A well regulated oscillator power supply is therefore necessary for good frequency stability.
3.- changes in plate resistance and interelectrode capacitance of a tube will cause the frequency to vary.
4.- changes in temperature will cause the inductance and capacitance of the tank circuit to vary. A physical change in either L or C will change the oscillating frequency.
5.- changes in loading of the oscillator
    a. If the output of the oscillator is fed di-

rectly into a varying load, the frequency of the oscillator will be affected. The oscillator must be isolated from the varying load in order to maintain good frequency stability.

CRYSTAL-CONTROLLED OSCILLATORS

The most stable of all oscillators is the CRYSTAL-CONTROLLED OSCILLATOR. The most important difference between the oscillators studied so far and the crystal oscillator is that the oscillator tuned circuit, consisting of L and C, is replaced by a crystal substance. This crystal is usually made out of quartz, a mineral found in the earth. The quartz crystal has the following peculiar property. If a mechanical vibration is applied to the quartz crystal, an electrical voltage will be developed across its surfaces. On the other hand, if we apply an alternating voltage to the surfaces of the quartz crystal, it will vibrate mechanically. This property of quartz is known as the PIEZO-ELECTRIC EFFECT.

If we momentarily apply an a-c voltage to two parallel surfaces of the crystal, it will start to vibrate mechanically;this mechanical vibration will in turn generate an a-c voltage. This a-c voltage will again cause the crystal to vibrate, etc., etc.. This process will continue until all of the electrical energy which was injected into the crystal is used up. The crystal, from an electrical viewpoint, acts in the same manner as a tuned circuit. If energy is injected into a crystal, an electrical oscillation is generated across the crystal surface which continues until all of the energy has been used up. Since the vibrating crystal is similar to a tuned circuit, it can be placed in the grid circuit of an oscillator in place of the actual tuned grid circuit. A schematic of a triode crystal oscillator is shown in fig. 9-6. Energy from the plate tuned circuit is fed back to the grid circuit through the grid-plate capacitance of the tube. The energy that is fed back to the grid circuit keeps the crystal oscillating. The oscillations occur at the resonant frequency of the crystal, and the plate circuit is tuned approximately to this frequency. The resonant frequency of a crystal is mainly determined by its thickness.

The strength of the crystal's vibrations depends upon the voltage being fed back to the crystal. If the feed-back is too great, the vibrations may become strong enough to crack or shatter the crystal. The use of a tetrode or pentode overcomes this difficulty because the screen grid reduces the feed-back. However, the little energy that does get back is sufficient to sustain the crystal's oscillations.

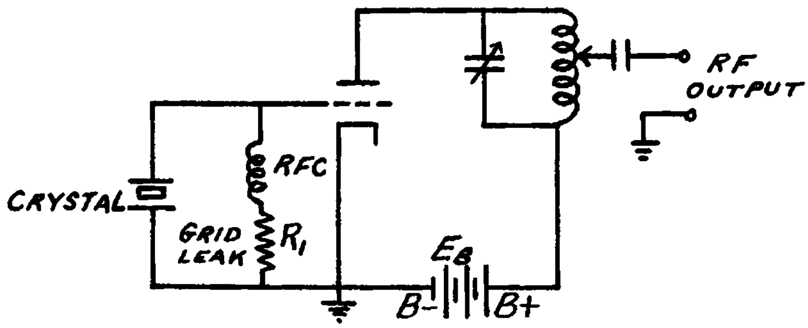


Fig. 9-6. Crystal-controlled oscillator.

Tetrodes and pentodes are also more sensitive than triodes and require less grid voltage for satisfactory oscillator operation. The purpose of the r-f choke in fig. 9-6 is to make sure that the feed-back energy gets to the crystal and is not by-passed to ground through R_1.

CHAPTER 10

TRANSMITTERS

Radio transmitters are divided into two types. One is the CONTINUOUS-WAVE type of transmitter;the other is the MODULATED type of transmitter. The continuous-wave type is used to transmit code signals, while the modulated type sends out sound such as speech, music, etc. We will first study the continuous-wave transmitter.

CONTINUOUS WAVES

Continuous waves, abbreviated C.W., are radio waves of constant amplitude. In the C.W. transmitter, continuous waves are radiated into space by simply coupling the output of a vacuum tube power oscillator to a suitable antenna system. The international Morse Code is used to convey intelligence by C.W. communication. In the Morse code, various combinations of dots and dashes represent the letters of the alphabet. In order to transmit code, the C.W. transmission must be interrupted in a dot and dash sequence. This type of emission is actually an r-f wave broken up into sections. An oscillator is made to stop and start oscillating by means of a telegraph key. By allowing the oscillator to operate for longer or shorter amounts of time, we can produce dots and dashes. Fig. 10-1 shows the output of an oscillator for the letter "D" (dash-dot-dot).

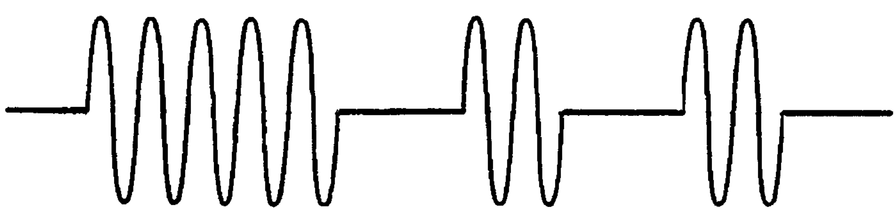


Fig. 10-1. Keyed output of an oscillator for the letter "D"

ONE-TUBE TRANSMITTER

In early type radio transmitters, the oscillator was directly coupled to the antenna system. In order to increase the power output of this type of transmitter, it was necessary to use a larger tube or to increase the operating voltages. There is a limit, however, to the amount of power that one can get from a one-tube transmitter. The power output of an oscillator depends upon r-f currents in the oscillator circuit. Since these currents are relatively weak, very little power can be delivered to the antenna. The radiated wave, therefore, will also be weak. Another defect of the simple oscillator type of transmitter is its poor frequency stability. Fig. 10-2 shows a one-tube transmitter. Condenser C_A represents the antenna capacitance to ground. This will vary as the antenna swings in the wind. This varying antenna capacitance will be coupled back to the tank circuit and will cause the oscillator frequency to vary. The disadvantage of poor frequency stability can be overcome to a great extent by the use of an r.f. amplifier stage which serves to isolate the antenna from the oscillator. Changes in antenna capacity will therefore not be reflected back into the oscillator tank circuit. At the same time, the r.f. amplifier amplifies the output of the oscillator and feeds a more powerful signal into the antenna.

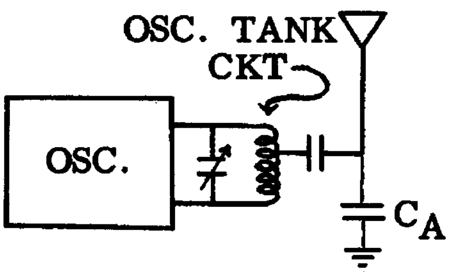
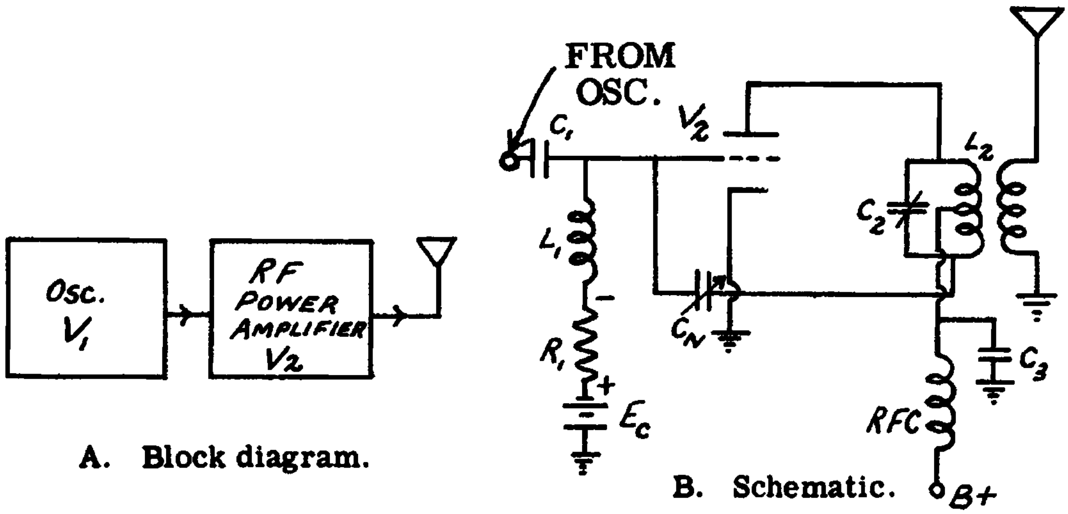


Fig. 10-2. One-tube transmitter.

MASTER-OSCILLATOR POWER-AMPLIFIER

A transmitter consisting of an oscillator and an amplifier (or a series of amplifiers) is called a MASTER-OSCILLATOR POWER-AMPLIFIER, MOPA for short. Such a transmitter is shown in fig. 10-3. The output of the oscillator is amplified by V_2. Condenser C_1 prevents the high d-c voltage on the plate of V_1 from being applied to the grid of V_2. At the same time, it allows the r-f energy to get through to the grid of V_2. The r-f choke L_1 prevents the r-f energy from flowing to ground through R_1. This is because an r-f choke opposes the flow of r-f currents.

The master-oscillator power-amplifier type of transmitter has a decided advantage over the simple oscillator transmitter, in that the frequency stability is greatly improved. High frequency stability is obtained in this system because the oscillator is not coupled directly to the antenna. The oscillator is therefore unaffected by any change in the antenna-to-ground capacitance. Changes in antenna-to-ground capacitance will merely react upon the r-f power



A. Block diagram. B. Schematic.

Fig. 10-3. Master-oscillator power-amplifier transmitter.

amplifier circuit resulting in a slight decrease in the radiated power output. The amplifier of fig. 10-3 may feed the antenna directly, or it may be the first of a series of r-f amplifiers, the last of which feeds into an antenna system.

HIGH EFFICIENCY CLASS C R.F. AMPLIFIER

In a previous chapter, we studied the biasing methods for audio amplifiers. You will recall that a-f amplifiers were operated as class A or class B amplifiers because we were interested in obtaining good fidelity of reproduction. The class A amplifier sacrifices efficiency for excellent fidelity. In the case of an r-f amplifier we are not interested in fidelity since we are not amplifying an audio signal. We are interested in efficiency of operation. An r-f amplifier operates most efficiently in a transmitter as a Class C amplifier. In order to operate the tube as a class C amplifier, the bias must be between one and one-half to four times the bias value necessary for cut-off. This condition is shown graphically in fig. 10-4. You will notice that with a pure sine wave applied to the grid, the plate current consists of small pulses which certainly do not resemble the input sine wave. Since the plate current wave does not resemble the grid signal, the fidelity of a class C amplifier is poor. The important point to notice is that the plate current flows for only a fraction of the period of the input signal. Compare this to a class A amplifier where the plate current flows continuously. Obviously, more power is wasted in plate dissipation in a class A amplifier than in a Class C amplifier.

Since the plate dissipation is decreased in the Class C amplifier, the useful power output is increased. The efficiency of a class C amplifier is therefore excellent. It is approximately 70% efficient.

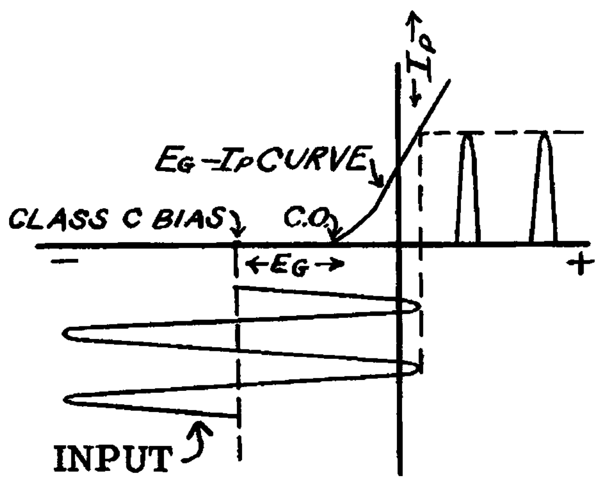


Fig. 10-4. Class "C" bias operation.

The question that always arises at this point is: Of what good are the plate current pulses if we are interested in obtaining an amplified version of the sine wave input. The answer lies in the ability of the plate tank circuit to reproduce a relatively pure sine wave from pulses of energy which are applied to it every cycle. This principle was fully discussed in the last chapter.

GRID-LEAK BIAS

It was mentioned above that a class C amplifier requires a bias of from one and one-half to four times the value of cut-off bias. There are several methods of obtaining class C bias. The first method that we shall discuss is known as GRID-LEAK BIAS. You will recall that grid-leak bias is used in the self-biased oscillator. Fig. 10-3 shows the r-f amplifier, V_2, employing grid-leak bias. R_1 is the bias resistor and C_1 is the bias condenser. Before the signal from the previous stage is applied to the grid of the amplifier tube, the bias on the grid is zero. However, when a signal is applied, a grid bias voltage develops across R_1. Let us review once again how this comes about: On the positive half of the incoming signal, the grid is driven positive with respect to the cathode. This causes a flow of grid current which charges up condenser C_1. On the negative half of the signal, the condenser discharges through R_1. The discharge current that flows through R_1 develops a d-c voltage across R_1. Condenser C_1 which is effectively in parallel with R_1 tends to keep this voltage constant. Since the current enters R_1 at the top (the grid side), the top part of the resistor is negative with respect to the bottom part. Therefore, the grid is negatively biased with respect to the cathode.

Among other factors, the amount of grid-leak bias that is developed depends upon the strength of the signal. This may sometimes be a serious disadvantage. If for some reason the signal or excitation is lost, the bias will disappear and the plate current may rise to excessively high values.

FIXED BIAS

Another method of obtaining bias for class C amplifiers is through the use of a battery. The negative terminal of the battery is connected to the grid, and the positive terminal is connected to the cathode. This, of course, makes the grid negative with respect to the cathode. An r-f by-pass condenser is usually shunted across the battery to complete the r-f path around the battery. The amount of battery voltage to be used for a particular tube can be found by consulting a transmitting tube manual.

COMBINATION GRID-LEAK, CATHODE BIAS

A third method of obtaining bias is shown in fig. 10-5 This method is a combination of grid-leak and cathode bias. R_1 provides most of the bias voltage. R_2 is placed in the circuit to act as a protective bias in case the input signal to

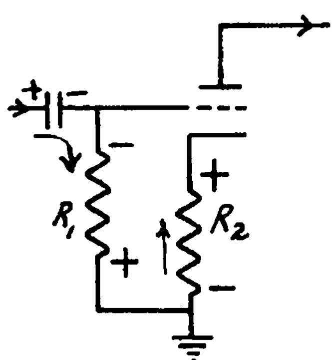


Fig. 10-5. Combination grid-leak, cathode bias.

the stage should fail. Upon loss of grid-leak bias, the increased plate current will flow through R_2 developing a heavy bias voltage which will in turn limit the plate current to a safe value. R2 will not cause any appreciable loss of plate voltage, since its value is small. It will simply serve to bias the tube should the grid-leak bias disappear.

NEUTRALIZATION

Examine the r-f amplifier of fig. 10-6. Note that the tank circuit L_2C_2 is not only the plate tank circuit of the oscillator, but can also be considered as the grid tank circuit of the r-f amplifier. The portion of the schematic of fig. 10-6 inside the dotted line is exactly the same as a type of oscillator called the tuned-plate, tuned-grid oscillator. This portion of the circuit will therefore oscillate unless certain precautions are taken. An oscillating r-f amplifier is very undesirable. An amplifier is supposed to amplify and not to oscillate.

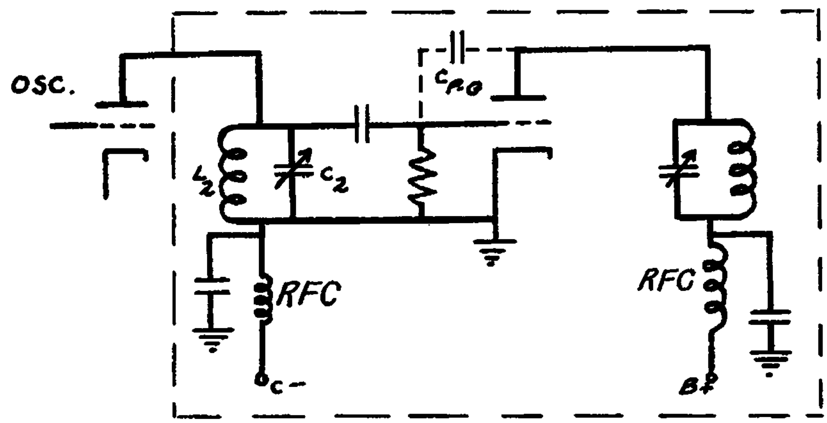


Fig. 10-6. Oscillatory circuit in an unneutralized RF amplifier.

There are two general methods of preventing an r-f amplifier from oscillating. One is to use a tetrode or pentode instead of a triode. As you have previously learned, the addition of a screen grid reduces the grid-plate capacitance. It would therefore be very difficult for a tetrode or pentode to oscillate since there would be no feedback through the grid-plate capacitance. Most high powered r-f amplifying tubes, however, are triodes, and therefore we have the problem of preventing oscillations from taking place. This problem can be solved by the addition of special neutralizing condensers. These neutralizing condensers are placed in the circuit in such a way that they cancel out the effect of the grid-plate capacity and thereby prevent oscillation.

THE MODULATED TRANSMITTER

Communication by means of C.W. (code) transmission is known as RADIOTELEGRAPHY. The disadvantage of radiotelegraphy is that the radio operator must know code. In order for operators who are not familiar with code to be able to send and receive messages directly, the transmission of speech is necessary. The transmission of audio (speech) by means of radio communication is known as RADIOTELEPHONY.

A radiotelephone transmitter consists of a C.W. transmitter (minus the telegraph key) plus an audio frequency amplifier system. The audio frequency system amplifies the audio signals and superimposes them on the r-f signal that is generated by the r-f oscillator. THE PROCESS OF SUPERIMPOSING THE AUDIO ON THE R-F IS KNOWN AS MODULATION. The r-f signal is called a CARRIER since it "carries" the audio through space to the receiving antenna.

AMPLITUDE MODULATION

There are several methods of modulating a carrier. The method which is used most is called AMPLITUDE MODULATION.

In amplitude modulation, the modulating frequency is the intelligency (voice or music) which is to be transmitted through space to receivers many miles away. This modulating frequency is audio and, by itself, cannot be transmitted. A radio-frequency wave, however, is capable of being transmitted through space. If we combine or mix an audio-frequency wave with a radio-frequency wave, we obtain an r-f output which contains the audio and can be transmitted. Fig. 10-7 illustrates a voice modulated radio-frequency wave whose amplitude varies according to the amplitude of the audio wave. (Thus the term "amplitude modulation", abbreviated a-m). An a-m wave, is therefore, a radio-frequency wave which contains, in its amplitude variations, the audio or intelligence which we desire to transmit.

THE A-M TRANSMITTER

A block diagram of a typical amplitude modulated radiotelephone transmitter is shown in fig. 10-8. Above each block is drawn the waveshape of the voltage output of that particular stage. With the aid of these waveshapes and the block diagram layout, we shall discuss the operation of the radiotelephone transmitter.

To begin with, the oscillator stage generates a radio-frequency voltage called the carrier. Following the oscillator, is the buffer-amplifier stage which amplifies the output of the oscillator and isolates the oscillator from the power amplifier. The final stage is the power amplifier

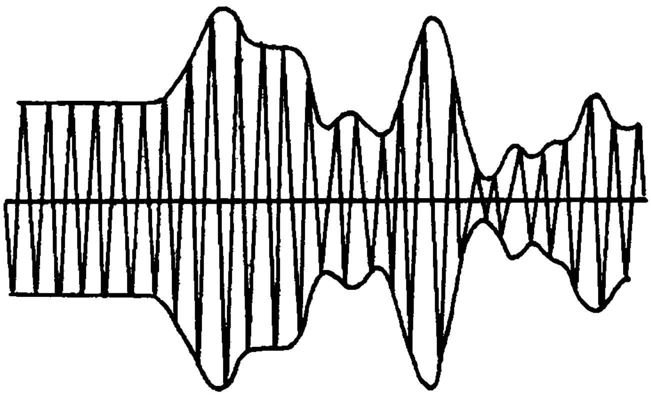


Fig. 10-7. Radio wave modulated with voice.

which delivers energy to the antenna. Notice that the output waveshape of the final r-f stage does not resemble the input waveshape from the buffer. The r-f waveshape has been altered by modulation. This brings us to the modulation or audio section. The microphone converts the sound

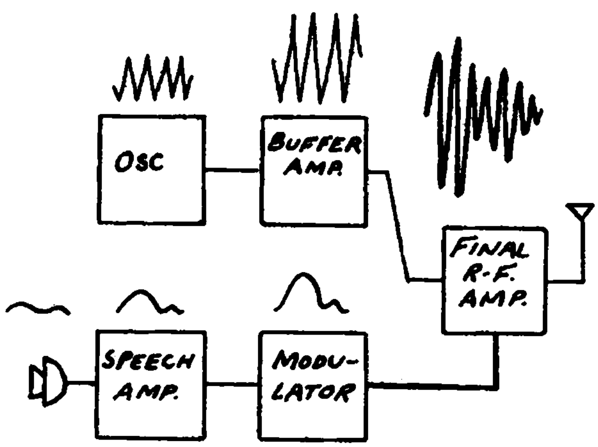


Fig. 10-8. Block diagram of amplitude-modulated transmitter.

that is to be transmitted into electrical variations. The weak output of the microphone is fed into an audio amplifier (speech amplifier). The output of the speech amplifier is fed into an audio power amplifier called a MODULATOR. The modulator injects the audio signals into the r-f power amplifier.

METHODS OF MODULATION

In the last paragraph we discussed the general principles of amplitude modulation. We are now ready to study exactly how the audio signal is superimposed onto the carrier.

There are many different methods of amplitude modulation. The most common method is to apply the audio-frequency modulating voltage to the plate of one of the r-f amplifiers. This popular method is known as PLATE MODULATION. If the audio-frequency modulating voltage is applied to the control grid of the r-f amplifier, we have what is called GRID MODULATION. If a pentode power amplifier is modulated by applying the audio-frequency modulating voltage to the suppressor grid, we have SUPPRESSOR MODULATION. SCREEN GRID MODULATION and CATHODE MODULATION can be similarly accomplished by applying the audio-frequency modulating voltage to the screen and cathode electrodes respectively. In other words, the method of modulation is determined by the electrode of the r-f amplifier tube to which the audio frequency modulating voltage is applied.

Since there are several r-f amplifier stages in a transmitter, a transmitter designer has his choice as to which stage should be modulated. Modulating the final r-f stage of a radiotelephone transmitter is known as HIGH-LEVEL MODULATION. The term is derived from the fact that the modulation takes place at the highest power level of the transmitter. If the modulation process takes place in a stage preceding the final stage, the system is known as LOW-LEVEL MODULATION. In low-level modulation, the r-f amplifiers which follow the modulated stage are operated as linear or class A amplifiers, rather than class C. A class C amplifier will distort the audio component of the modulated signal, whereas a class A amplifier will amplify all signal frequencies without distortion. If the audio component of the modulated wave is distorted, the receiver will in turn reproduce a distorted audio signal. In high-level modulation, the final r-f amplifier is always operated as a class C amplifier. High-level modulation is the most efficient modulating system, and is also much more popular than low-level modulation.

Most transmitters use high-level plate modulation. We will discuss this method in detail.

PLATE MODULATION

There are several variations of plate modulation. A simple one is illustrated in fig. 10-9. The audio-frequency output of the modulator stage is coupled through transformer T, to the plate circuit of the power amplifier. Transformer T is called the modulation transformer. The audio voltage induced from the primary into the secondary winding, S, is in series with the B+ voltage which is applied to the plate of the r-f power amplifier stage. Fig. 10-10A shows the audio voltage.

When the audio voltage causes the top of the transformer secondary, S, to go positive with respect to the bottom, the audio voltage and the power supply voltage will aid each other. The plate voltage of the r-f amplifier stage will therefore be the sum of the power supply voltage and the audio voltage. Fig. 10-10B shows the rise in the r-f amplifier plate voltage above the B+ value during the positive alternation of the audio. Since the plate power input to the stage is directly dependent upon the plate voltage, the plate power input will increase during the positive audio alternation. An increase in plate power input will in turn cause

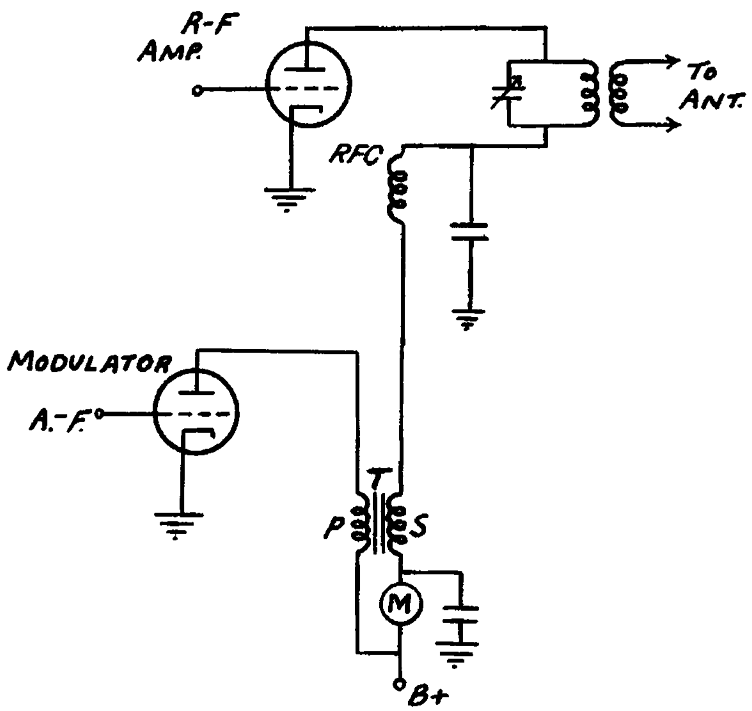


Fig. 10-9. Transformer-coupled modulator circuit.

the useful power output to increase. The r-f output therefore rises during the positive half of the audio cycle. Fig. 10-10C illustrates the r-f output voltage waveform before the modulating audio voltage is applied, and the resulting increase in amplitude of the r-f during the positive peaks of modulation.

During the negative half of the audio cycle, the top of the transformer secondary, S, is negative with respect to the bottom. Now the audio voltage and the power supply voltage are in "series opposing". The two voltages therefore buck each other, and the plate voltage of the r-f amplifier is the difference between the two voltages. Fig. 10-10B shows the drop in the r-f amplifier plate voltage below the B+ value during the negative alternation of the audio. The drop in plate voltage causes the plate power input to decrease. Fig. 10-10C shows the resulting decrease in amplitude of the r-f during the negative peaks of the audio. Fig. 10-7 illustrates the r-f output from a transmitter that has been modulated by speech or music.

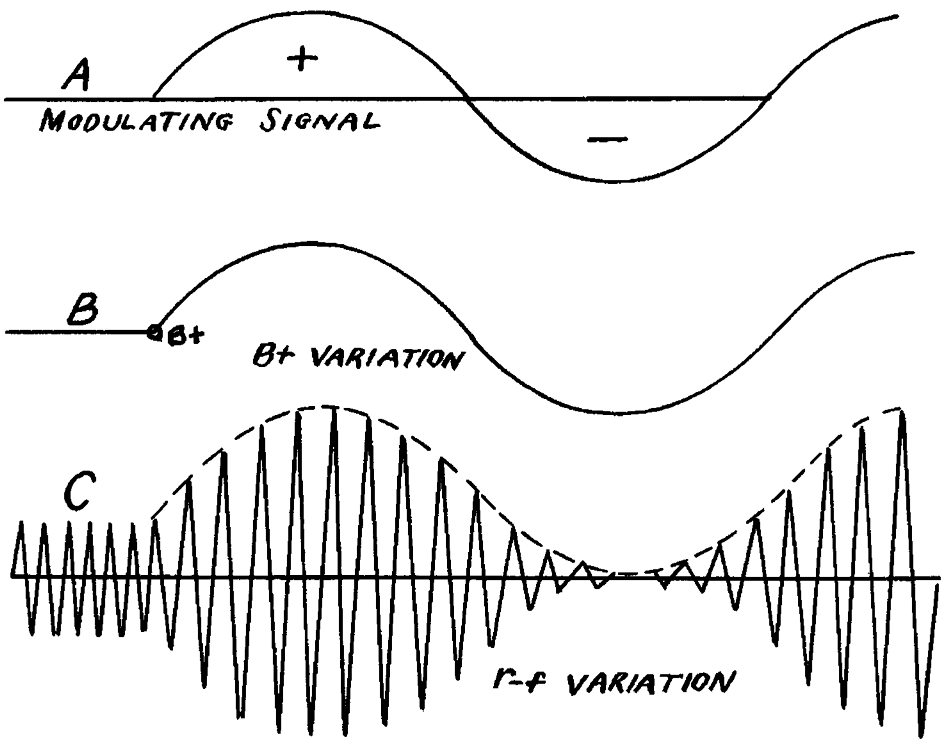


Fig. 10-10. Amplitude Modulation.

THE PUSH-PULL MODULATOR

The single ended (one tube) modulator stage of fig. 10-9 is operated class A so that there will be no distortion of the amplified modulating signal. The disadvantage of a one tube class A amplifier is that it operates at low efficiency. A low efficiency tube cannot always deliver the power that is required of a modulator stage. A push-pull amplifier which is capable of delivering more power than a single tube is therefore preferred. Fig. 10-11 illustrates a push-pull modulator circuit.

The push-pull modulator may be operated either class A or class B depending upon the power output requirements.

A class B push-pull amplifier requires a large driving power applied to its grid circuit. The positive peaks of the grid

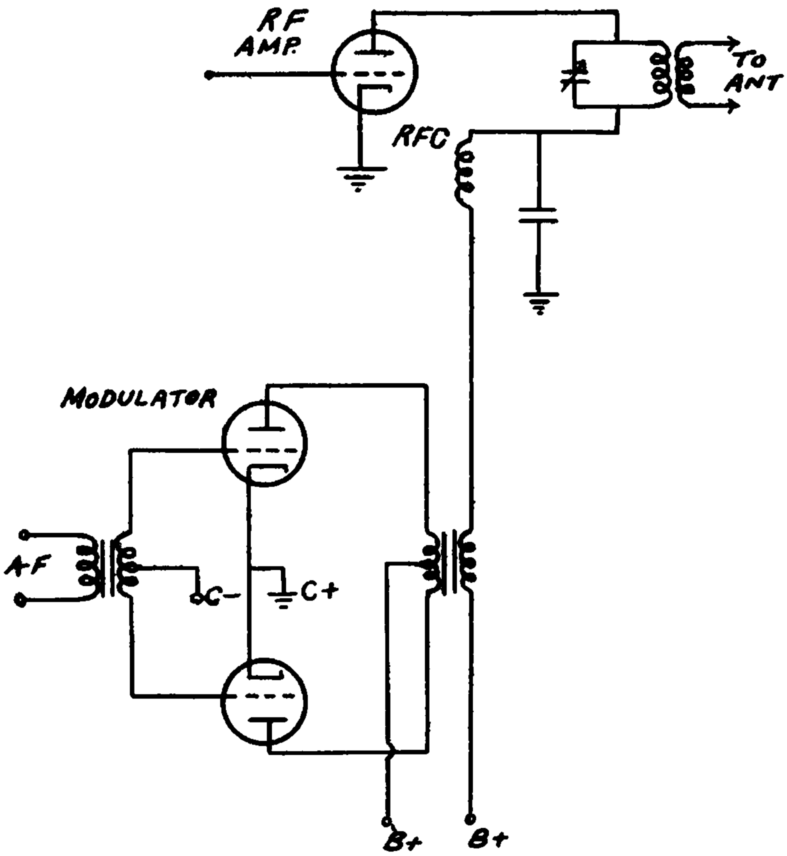


Fig. 10-11. A push-pull modulator circuit.

signal usually drive the grid into grid current. Flow of grid current causes power to be dissipated in the grid circuit. The driver stage must be able to supply the power dissipated in the grid circuit.

A push-pull amplifier operated class A does not operate in the grid current region, and therefore requires very little grid driving power from the driver stage. The class A push-pull amplifier amplifies the audio modulating voltage without distortion. The class B modulator introduces a certain amount of distortion into the modulating signal.

CHAPTER 11

DETECTION

It has been pointed out in a previous chapter that the detector is the heart of the receiver. It is the detector that extracts the audio intelligence from the signal that enters the receiver. Actually, a detector, by itself, can be considered as a simple type of receiver.

In this chapter, we shall study four different types of detection: diode detection, plate detection, grid-leak detection, and regenerative detection.

THE DIODE DETECTOR

Figure 11-1 illustrates a diode detector. With its antenna, ground, and headphones, it is a simple one-tube receiver. Let us see how this circuit operates.

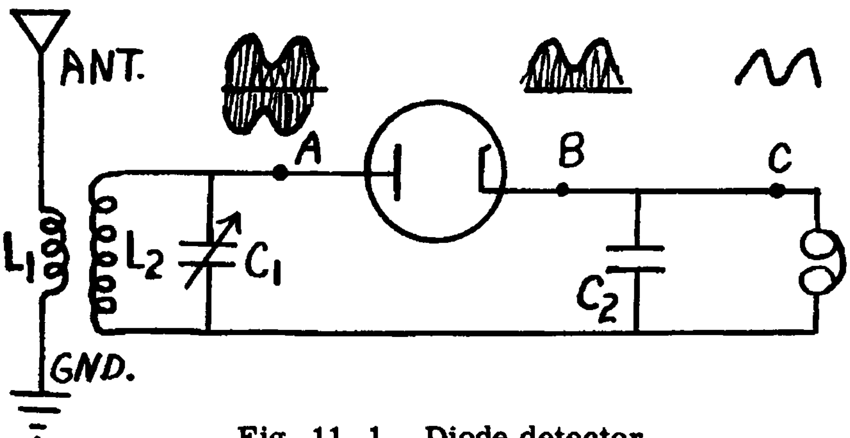


Fig. 11-1. Diode detector.

The radio frequency waves radiated by the transmitter cut across the receiver antenna and induce a signal voltage into it. This r.f. signal is brought down into coil L_1, by means of the transmission line that connects the antenna to the receiver. Because of the coupling between L_1 and L_2, the signal is induced into L_2. L_2 and C_1 form a resonant circuit. By varying C_1, we can make this circuit resonant to any one of a great many frequencies. Since each broadcast station transmits a signal on a different frequency, we can use C_1 to tune in the station that we wish to listen to.

Once we choose the desired signal, we can then proceed to "detect" the information in this signal. In figure 11-1, we show the waveshape of the signal as it appears at different points of the circuit. Notice the wave at point A, the output of the tuned circuit. The upper half is exactly the same as the lower half. Since the audio is represented by a line joining the peaks of the wave, we actually have the audio duplicated in the upper and lower halves of the signal. Either the upper or the lower part of the signal must be removed because the upper audio signal, which is positive, and the lower audio signal, which is negative, would cancel each other out when the r.f. component of the signal is removed. Removing the upper or lower half of the signal will in no way harm the audio intelligence since each half of the signal contains the complete audio information.

Cancelling one half of the signal is accomplished by means of the principle of rectification. The entire r.f. signal is simply a high frequency a-c signal and we use a diode vacuum tube to remove the lower half of the signal. (It doesn't make any difference which half of the signal is removed). Rectification of the r.f. signal is accomplished in the following manner: when the positive half of the signal drives the plate of the diode positive with respect to the cathode, the tube conducts and current flows through the circuit. When the negative half of the signal drives the plate of the diode negative with respect to the cathode, the tube will not conduct and current will not flow through the circuit during this half of the cycle. The lower half of the r.f. signal will therefore be cut off and does not appear at the output of the detector tube. (See figure 11-1)

We still haven't extracted the audio from the r.f. carrier. This is accomplished by C_2, a low value condenser in the order of .0001 mfd. The signal across C_2 consists of 2 components: the low frequency audio intelligence and the high frequency r.f. carrier. Because a low value condenser has a low reactance to the high frequency r.f., the r.f. component will be shorted out by the condenser and will not appear in the headphones. Because C_2 has a high reactance to the low audio frequencies, the audio will not be shorted out and will appear in the headphones. Thus we have succeeded in extracting the audio intelligence from the r.f. carrier by means of the diode detector.

THE PLATE DETECTOR

The diode detector just described is commonly used. However, it has one disadvantage. It can only detect; it cannot amplify the signal that it has detected. Additional stages of amplification are necessary. The plate detector shown in figure 11-2 is both a detector and an amplifier.
Its operation is similar to the diode detector in that it rectifies the incoming r.f. signal and then filters out the r.f. from the signal. Rectification occurs in the following manner: The plate current flows through R_1 and creates a voltage drop or grid bias across it. The resistor value is chosen to provide a bias sufficiently negative to cut the tube off when no r.f. signal is applied to the circuit.

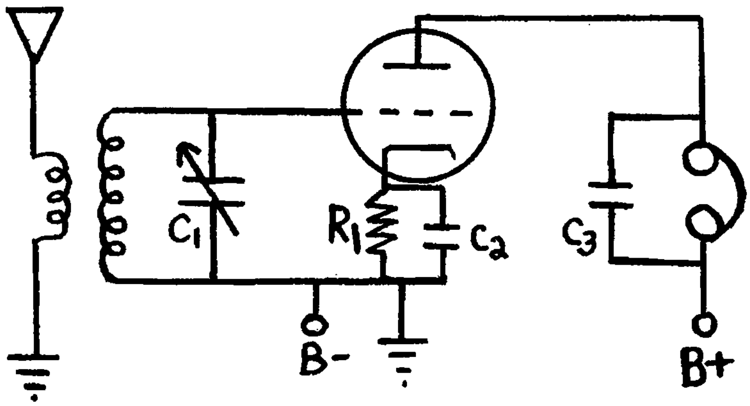


Fig. 11-2. Plate detector.

When the signal is applied to the circuit, the positive half of the signal overcomes part of the negative bias and causes plate current to flow. When the negative half of the incoming signal appears at the grid the plate current stops flowing since the negative signal voltage adds to the bias voltage, making the grid more negative. Since the positive half of the signal is reproduced and the negative half is eliminated, we have succeeded in rectifying the signal.

The r.f. is filtered out of the signal by C_2 in the same manner as in the diode detector. The audio component is then applied to the earphones.

THE GRID-LEAK DETECTOR

The grid-leak detector is actually a combination of a diode detector and an amplifier. This can easily be realized by looking at the grid-leak detector in figure 11 3. Consider the grid as the plate of the diode detector. The grid-leak resistor, R_1, acts as the load of the diode detector in the same manner as the earphones of figure 1.

When a modulated r.f. signal is applied to the grid-leak detector, current flows from cathode to grid and through the grid circuit only on the positive halves of the signal.

This is because a negative grid, just like a negative plate, will repel the electrons. The incoming signal is thus rectified.

C_1 filters out the r.f. component of the incoming signal and the audio intelligence appears across the grid-leak resistor, R_1. The audio signal across the grid-leak resistor acts as the bias of the triode tube and the plate current will vary in accordance with the voltage across R_1.

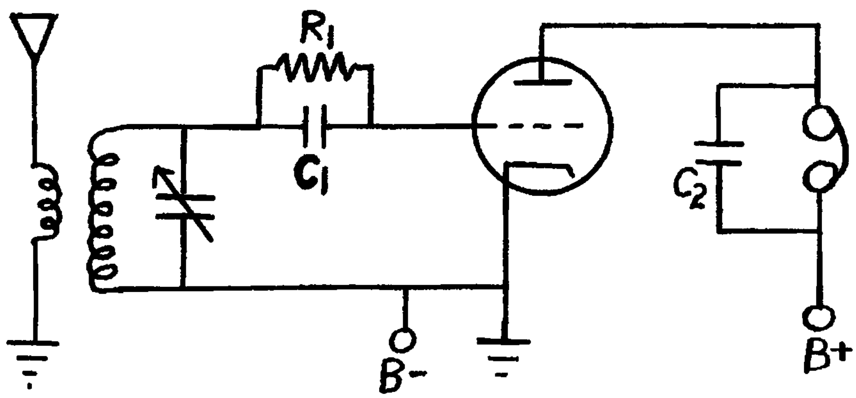


Fig. 11-3. Grid-leak detector.

Because of the amplification property of a triode we find that the audio developed in the plate circuit, across the headsets, is much larger than that across the grid-leak resistor. Condenser C_2 filters out any r.f. that might appear in the plate circuit.

While the grid-leak detector has more gain than the plate detector it has the disadvantage of being easily overloaded by strong r.f. signals and causing distortion of its output.

THE REGENERATIVE DETECTOR

Figure 11-4 illustrates a regenerative detector. You will notice that it is similar to the grid-leak detector. The only difference is that a coil has been added in the plate

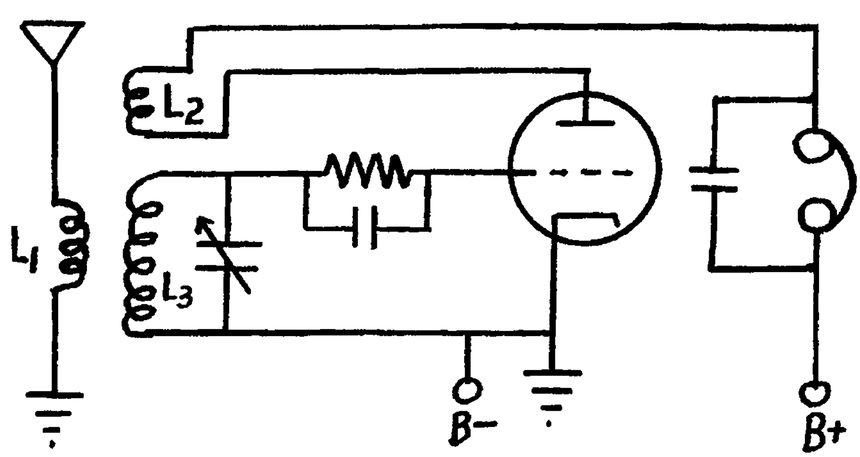


Fig. 11-4. Regenerative detector.

circuit. This coil, L_2 is called the TICKLER coil. It is magnetically coupled to the grid coil L_3.

When the incoming modulated r.f. signal enters the circuit, it is detected in the grid circuit the same as it is in a grid-leak detector. However, because L_2 is coupled to L_3, some of the amplified signal in the plate circuit is fed back to the grid circuit to be reamplified. This increases the amplification of the circuit considerably.

It is important that the tickler coil be placed in such a position with respect to the grid coil that the signal fed back to the grid coil is in phase with the incoming signal. In this way, the feedback voltage will add to the incoming signal voltage. If the feedback voltage is out of phase with the incoming signal, it will cancel out some of the incoming signal and reduce the amplification.

The regenerative detector is the most sensitive triode detector and is capable of receiving signals over long distances.

CHAPTER 12
THE TRF RECEIVER

INTRODUCTION

A radio frequency signal diminishes in strength at a very rapid rate after it leaves the transmitting antenna. When it reaches the receiving antenna it is very weak, so weak that it is seldom possible for a detector circuit (unaided) to produce a useful output from it. To remedy this, it is desirable to amplify the signal before and after it is detected. This is accomplished by the use of an r.f. amplifier before the detector and an audio frequency (a.f.) amplifier after the detector.

The r.f. amplifier, like the detector, is provided with one or more tuned circuits. This enables it to select and amplify the desired signal only. Thus, the addition of an r.f. amplifier to the detector not only increases sensitivity (ability to receive weak signals), but also gives greater selectivity (ability to separate signals.

The output of the detector stage is followed by one or more stages of a.f. amplification. If a headset is to be used, only one stage of audio amplification is necessary. If a loudspeaker is to be used, two or more stages of audio amplification will be necessary.

The complete receiver, consisting of one or more radio frequency amplifiers, detector and one or more audio frequency amplifiers is called a TUNED RADIO FREQUENCY receiver, or simply a TRF receiver. A block diagram of a TRF receiver, together with the waveform of the signal at each stage, is shown in figure 12-1.

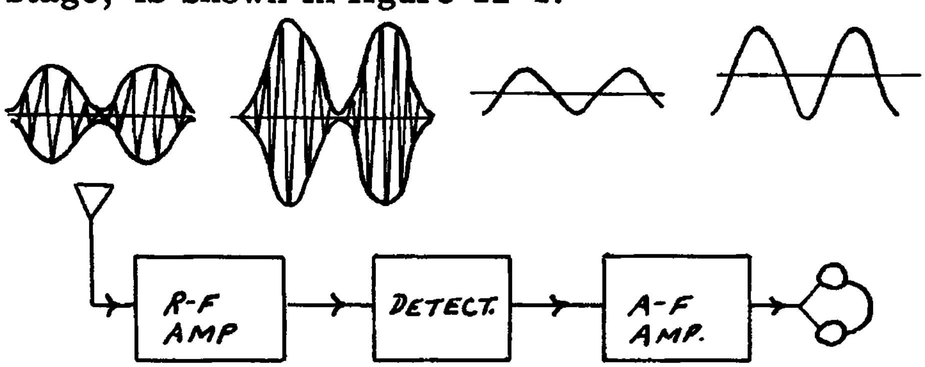


Fig. 12-1. Block diagram of a TRF receiver.

THE R. F. AMPLIFIER

The r.f. amplifier, as previously stated, gives the receiver the desired selectivity and sensitivity required for satisfactory reception. Figure 12-2 illustrates an r.f. stage of amplification. You will note that essentially it consists of a tuned circuit (L_1C_1) that selects the desired signal and a

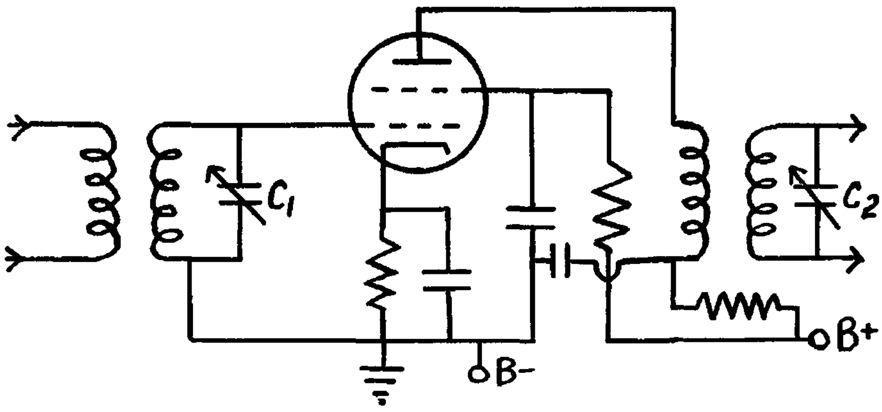


Fig. 12-2. R. F. stage of amplification.

tube that amplifies the signal. The important operating characteristics of the amplifier are as follows:

1. The r.f. amplifier tube is biased to operate as a class A voltage amplifier. We do this because a class A amplifier will amplify the signal without distorting it. It is important not to distort the signal at this point since it contains the audio intelligence.

2. The tube used in the r.f. amplifier is generally a pentode because of its low interelectrode capacitances. If a triode, with its high interelectrode capacitances, were used, there would be sufficient feedback from plate to grid at radio frequencies to cause the r.f. amplifier to oscillate. An oscillating amplifier would cause serious distortion making satisfactory reception almost impossible.

3. Self-bias is almost always used in an r.f. amplifier. A cathode biasing resistor and a cathode by-pass condenser provide the bias for the tube.

4. The r.f. transformer consists of a primary coil and a secondary coil. The secondary coil is designed to cover the desired frequency range when tuned by condenser C_1.

Most TRF receivers use two or three r-f amplifier stages ahead of the detector. Each stage is tuned to the same frequency. Since it would be impractical to tune each of the stages individually, we mount all the tuning capacitors on a common shaft so that all the r.f. stages can be tuned simultaneously. Condensers mounted on a common shaft in this manner are said to be "ganged".

In order that each stage be tuned to the exact same frequency at any setting of the ganged condensers, the condensers and coils in each stage should be identical. However, because of manufacturing tolerances and stray capacitances and inductances, this is not possible. In order to compensate for the small differences in value of the tuned circuit components, small variable condensers, called trimmers, are placed across the tuning condensers. These trimmers are mounted at the side of the tuning condensers and their capacities can be varied with a screwdriver. Figure 12-3 illustrates a 3 gang tuning condenser with its trimmers. We adjust the trimmers so that each one of the r.f.

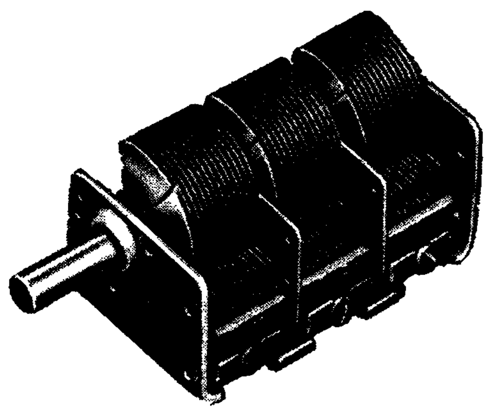


Fig. 12-3. A 3 gang tuning condenser with trimmers.

amplifier stages tunes to the same frequency at any particular setting of the station selector knob. The process of adjusting the trimmers is called "alignment" and when the receiver is properly aligned, it has maximum gain and selectivity.

VOLUME CONTROL

Some method of controlling the volume of a radio receiver is necessary since the signals arriving at the receiving antenna vary in their intensity. There are many methods of controlling the volume. Some control the gain of the r.f. stages and are referred to as r.f. gain controls; others vary the output of the detector.

Figure 12-4 illustrates a method of controlling the volume by varying the grid bias of an r.f. amplifier stage. The tube that is used is so constructed that its amplification varies as the bias is varied. We call this type of tube a variable-mu tube. Thus, as we change the value of Rc, the grid bias of the tube varies, causing the amplification of the stage to vary. This raises or lowers the volume of the receiver's audio output.

Figure 12-5 illustrates another method of controlling the volume of a receiver. The variable resistor R1 is both

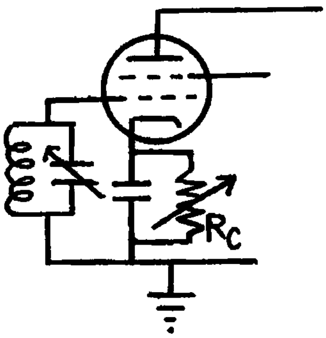


Fig. 12-4. Volume control in r.f stage.

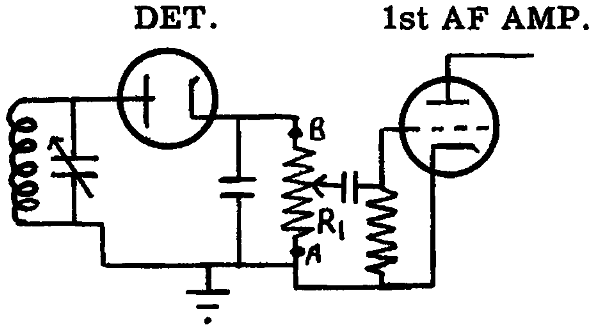


Fig. 12-5. Volume control in detector stage.

the load of the diode detector and the volume control. The entire audio output of the detector is across R_1. By sliding the arm of the potentiometer from A to B we tap off varying amounts of audio and apply it to the grid of the first audio amplifier stage. In this way, we control the volume of the receiver.

CIRCUIT OF A TRF RECEIVER

Figure 12-6 shows the schematic diagram of a 4 tube TRF receiver. The receiver consists of two r.f.stages, a diode detector stage and an audio amplifier stage. The power supply is not shown. You will note that while transformer coupling is used between the r.f. stages, resistance coupling is used between the detector stage and the audio amplifier stage. Resistance coupling is used in the audio section because of its simplicity and because it gives better fidelity than transformer coupling. The dotted lines connecting the three tuning condensers indicate that these condensers are ganged.

The following table indicates the function of each component shown in figure 12-6.

V1, V2	R. F Amplifier Tubes
V3	Diode Detector tube
V4	Audio Amplifier Tube
T1, T2, T3	R. F. Transformers
T4	Audio Output Transformer
R1, R3, R7	Cathode Bias Resistors
R2, R4	Screen Voltage Dropping Resistors
R5	Volume Control and Diode Detector Load Resistor
R6	Grid Load Resistor

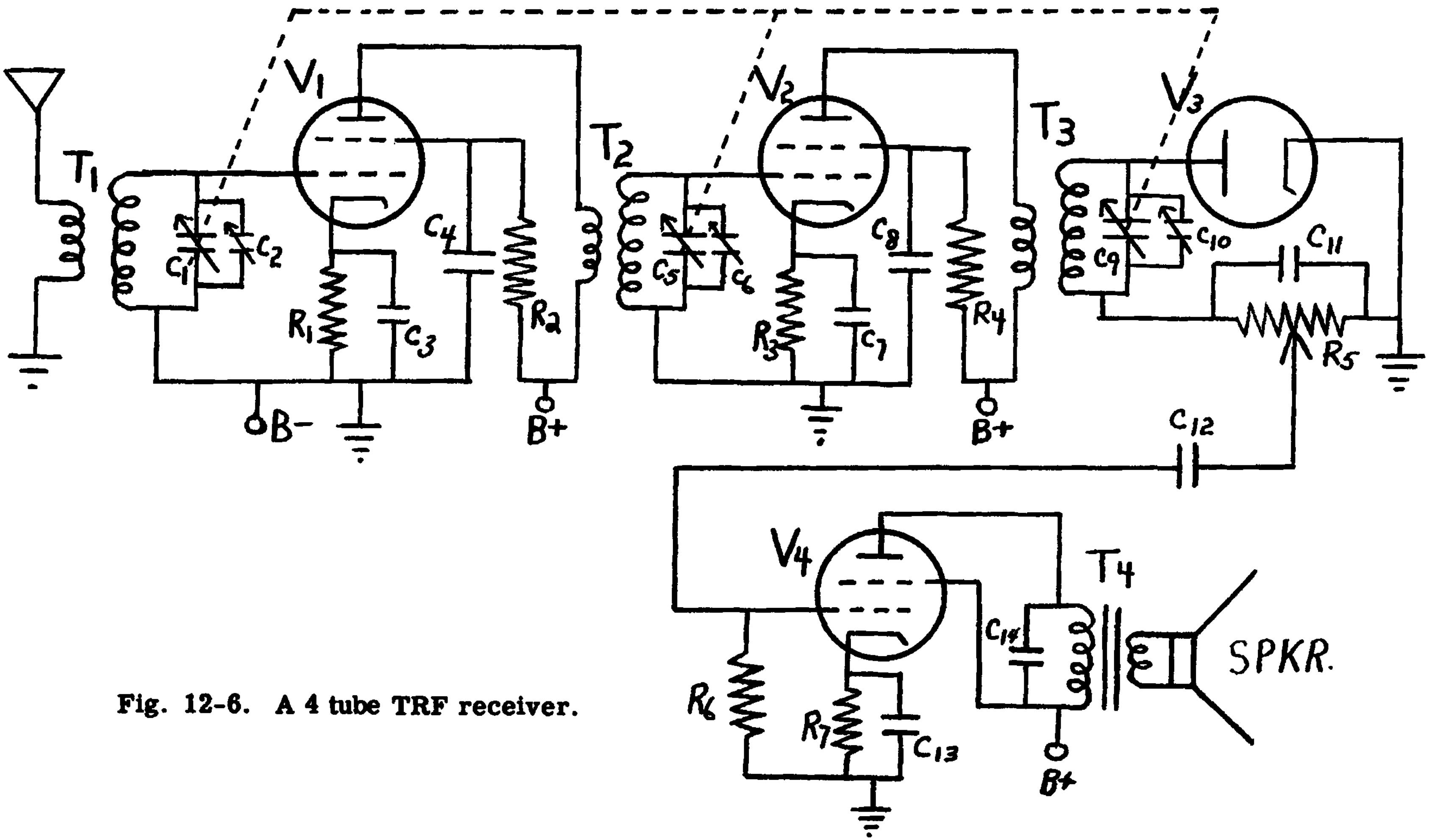


Fig. 12-6. A 4 tube TRF receiver.

C1, C5, C9	Tuning Condensers
C2, C6, C10	Trimmer Condensers
C3, C7, C13	Cathode By-Pass Condensers
C4, C8	Screen By-Pass Condensers
C11	Detector R. F. Filter Condenser
C12	Audio Coupling Condenser
C14	Condenser to by-pass high audio frequencies.

CAPABILITIES OF A TRF RECEIVER

A TRF receiver will operate in a satisfactory manner when it is used for a single low frequency r.f. band. However, it is not satisfactory when used for high frequencies or over a wide range of frequencies. At the higher frequencies, a TRF receiver has difficulty picking one signal apart from another. In other words, its selectivity is poor.

Also, the amplification of the r.f. amplifier is low at the higher frequencies. This limits the reception of the TRF receiver. Not only are the gain and selectivity of the TRF poor, but they vary considerably from one frequency to another. It is impossible to design an r.f. amplifier whose gain and selectivity are constant over its tuning range.

These disadvantages of the TRF receiver led to the development of the superheterodyne type of receiver. The principles of the superheterodyne type of receiver and how it overcomes the disadvantages of the TRF receiver are fully discussed in the next chapter.

CHAPTER 13

THE SUPERHETERODYNE RECEIVER

GENERAL THEORY OF THE SUPERHETERODYNE RECEIVER

The detector stage in a superheterodyne receiver is similar to the detector stage in a TRF receiver. The audio section is also the same. The differences between the two receivers lie in the stages preceeding the detector.

In the TRF receiver all the r. f. stages are tuned to the frequency of the incoming signal and the signal is thus amplified. This is not true in the superheterodyne receiver. Here, the incoming signal is first changed to a LOW FIXED frequency and is then amplified and detected. The new low fixed frequency is called the intermediate frequency (i. f.). In changing the incoming signal to the Intermediate Frequency, we do not in any way disturb the audio intelligence in the signal.

By amplifying the lower, fixed signal, it is possible to use circuits that have greater selectivity and sensitivity than those used in TRF receivers.

THE HETRODYNE PRINCIPLE OF GENERATING A FIXED I. F. SIGNAL

In our study of modulation, we learned that two different frequencies, when mixed together, will generate two new frequencies. The new frequencies are the sum and difference of the original frequencies. This principle is made use of in the superheterodyne.

The superheterodyne contains a variable oscillator stage that generates an r.f. signal. This r. f. signal is mixed together with the incoming r. f. signal to give the new intermediate frequency signal. Let us see how this works with actual examples: We will assume that we are listening to a station whose frequency is 1000 kc. The oscillator stage is then set to generate a signal whose frequency is 1456 kc. These 2 signals are mixed together and 2 new frequencies are produced: 456 kc. (the difference of the original two frequencies) and 2456 kc. (the sum of the original two frequencies). We disregard the 2456 kc. signal and amplify and detect the 456 kc. signal, which is the intermediate frequency signal. Let us assume that we desire to change to a new station whose frequency is 1300 kc. We then change the oscillator frequency to 1756 kc. The difference between the two frequencies is still 456 kc. and this signal is then fed to the i.f. amplifiers. The i.f. amplifiers are tuned to the i.f. frequency (456 kc.) and amplify only this one frequency. No matter what station we tune to, the difference between the incoming signal frequency and the oscillator frequency is always the same. In the above example the i.f. was 456 kc. Most receivers use this frequency for the i.f. A few receivers use other frequencies.

THE SUPERHETERODYNE RECEIVER

Figure 13-1 shows the block diagram of a typical superheterodyne receiver. The graphical form of the signal passing through the receiver is also shown. We will now study the operation of the superheterodyne receiver by following the signal through its stages.

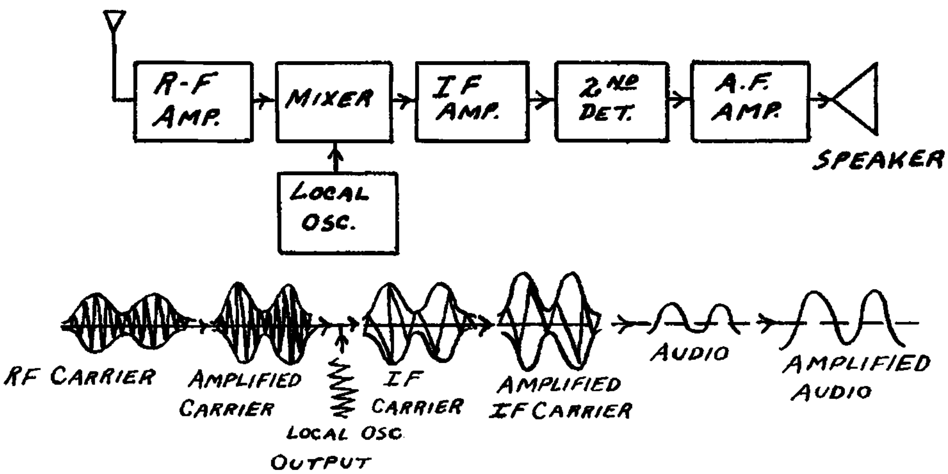


Fig. 13-1. Block diagram of a typical superheterodyne receiver.

From the antenna the incoming signal goes to the r.f. amplifier. Here it is selected and amplified in the same manner as in a TRF receiver. It is then passed on to the MIXER stage. The mixer stage "MIXES" the r.f. signal with signal generated by the local oscillator. The mixer is called a CONVERTER and sometimes a FIRST DETECTOR.

The mixing action of the mixer stage produces two new modulated r.f. signals in addition to the original two signals. They are the sum and the difference of the signal frequency and the oscillator frequency. It is the difference or intermediate frequency in which we are interested. Therefore in the output of the mixer stage there is a circuit, fixed-tuned to the intermediate frequency which rejects all other frequencies. The new i.f. signal contains all the modulation characteristics of the original signal.

The i.f. signal is then fed to the i.f. amplifier stage where it is amplified. From here the signal goes to the detector which is similar in operation to the detector of the TRF receiver. We sometimes refer to this stage as the second detector since we can consider the mixer stage as the first detector. After the audio is extracted from the modulated carrier, it is amplified by an audio amplifier stage.

Thus, we have briefly traced a signal through a superheterodyne receiver. We shall now discus in more detail the operation of the various stages and circuits of the superheterodyne receiver.

FREQUENCY CONVERSION

The combined circuits of the mixer stage and oscillator stage form the frequency converter. As we previously pointed out, the purpose of the frequency converter is to convert the incoming signal to a low fixed frequency (the intermediate frequency) which is then passed on to the i.f. amplifiers. There are a large number of possible combinations of tubes and circuits which may be used for frequency conversion. These various combinations may be broken down into two different types: 1. Circuits using a separate mixer tube and oscillator tube, and 2. Circuits using one tube for both the oscillator and mixer stages. We shall now study each type in detail.

Figure 13-2 illustrates a frequency conversion circuit using a triode mixer stage and a separate triode oscillator stage. An Armstrong oscillator circuit is used. Practically any type of oscillator could be used.

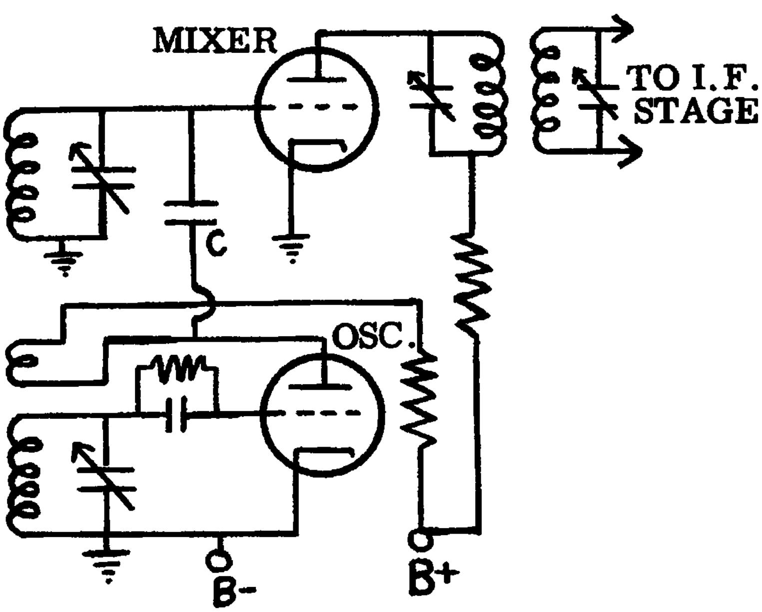


Fig. 13-2. Frequency conversion using two tubes.

The output of the oscillator is fed or injected into the grid of the mixer through a coupling capacitor, C. This is called grid injection. The oscillator output can also be injected into the cathode of the mixer. The coil and tuning condenser in the mixer grid circuit are tuned to the frequency of the incoming signal. The coil and condenser in the oscillator grid circuit are tuned to a frequency higher or lower than the signal frequency by an amount equal to the intermediate frequency. The plate circuit of the mixer stage is fixed tuned to the intermediate frequency. An example will clarify this point: Let us assume that the incoming signal has a frequency of 1000 kc. and the intermediate frequency of the receiver is 456 kc. The oscillator would then be tuned to 1456 kc. (The oscillator could also be tuned to 544 kc. but practically all receivers tune the oscillator frequency above that of the incoming signal). The oscillator signal and the incoming signal mix together in the mixer tube and produce the intermediate frequency of 456 kc. Now let us assume that we wish to receive an incoming signal at 1200 kc. We must tune the mixer grid circuit to 1200 kc. and at the same time, we must tune the oscillator to 1656 kc. These two frequencies will mix together in the mixer tube to produce the 456 kc. i.f. In order to tune the oscillator tank circuit and the mixer tank circuit at the same time, both tuning condensers are on the same shaft and are both rotated when we change stations on the receiver. The two condensers are said to be ganged. Figure 13-3 shows a typical superheterodyne tuning condenser. The smaller section is the oscillator condenser and the larger section is the mixer condenser.

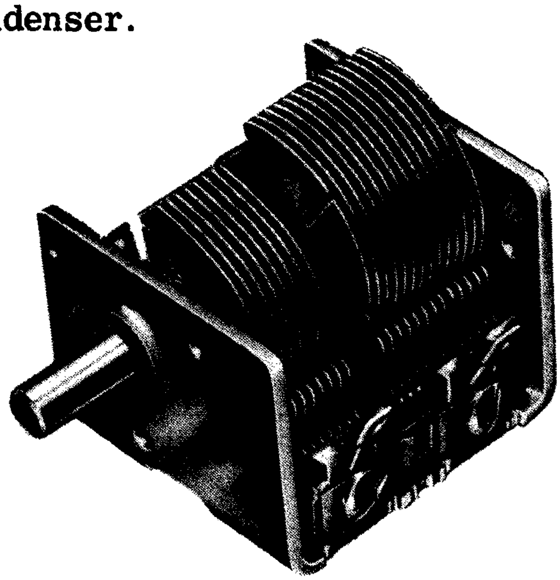


Fig. 13-3. Typical superheterodyne tuning condenser.

Figure 13-4 illustrates our second type of frequency conversion. You will notice that only one tube is used for both the mixer and the oscillator. The tube has five grids and is called a pentagrid converter. The cathode, grid 1 and grid 2 act as the cathode, control grid and plate of the oscillator section respectively. The oscillator is a Hartley type of oscillator. L2 is the oscillator coil and C2 is the oscillator tuning condenser. R1 and C3 are the oscillator grid leak resistor and condenser. Grid 4 acts as the mixer grid. It receives the incoming signal from the mixer tuned circuit, L1-C1. Grids 3 and 5 are connected together within the tube. They serve as the screen of the mixer and also as an electrostatic shield between the oscillator and mixer sections of the pentagrid converter.

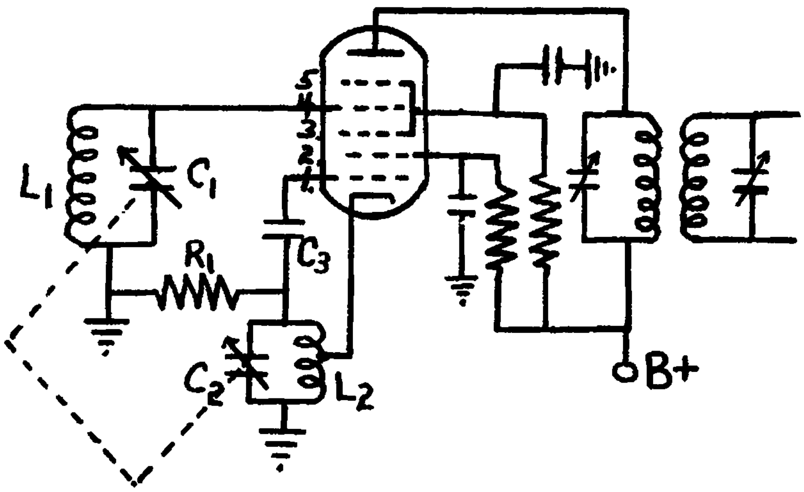


Fig. 13-4. The pentagrid converter.

The oscillator output is actually coupled to the mixer section by means of the tube's electron stream. We can consider the cathode and the first two grids as a composite cathode which supplies to the rest of the tube an electron stream that varies at the oscillator frequency. The incoming signal voltage, that is applied to grid 4, further controls the electron stream so that the plate current variations are a combination of the oscillator and the incoming signal frequencies. The plate circuit of the pentagrid converter is tuned to the difference of the two frequencies, the intermediate frequency.

I. F. AMPLIFIERS

The i.f. amplifier is a high gain stage that is permanently tuned to the frequency difference between the incoming signal and the local oscillator. Pentode tubes are generally used as i.f. amplifiers because of their high gain and low interelectrode capacities. We desire low interelectrode capacities to prevent the i.f. amplifiers from breaking into oscillation. The i.f. section of the superheterodyne receiver consists of one or more stages, with each stage adjusted to tune to the i.f. frequency. Since all incoming signals are converted to the same frequency by the mixer, the i.f. amplifier operates at only one frequency. The tuned circuits, therefore, are designed for maximum gain and for the desired selectivity. It is in the i.f. section that practically all the voltage gain and selectivity of the superheterodyne are developed.

The diagram of an i.f. amplifier stage is shown in figure 13-5. Note T_1 and T_2. They are called i.f. transformers. The dotted lines around them indicate that the i.f transformers are in metal cans. The cans act as shields and prevent oscillation. Double-tuned i.f. transformers are used in practically all radio receivers. The tuned circuits of figure 13-5 are adjusted to the exact i.f. frequency by means of the variable condensers, C_1, C_2, C_3 and C_4. These condensers are actually small trimmers located inside the transformer can. There are 2 holes in the transformer can that allow a small screwdriver to reach through the can and adjust the trimmers. In recent years radio manufacturers have been using i.f. transformers that have fixed condensers and variable inductors. The inductors use a powdered iron core and we tune the transformers by moving the core in and out of the coil. This is called PERMEABILITY TUNING.

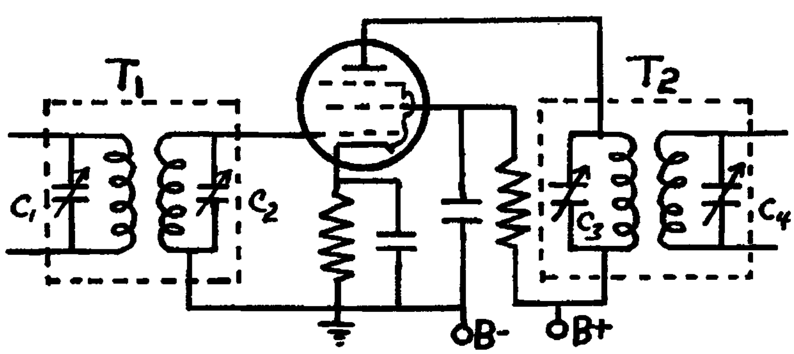


Fig. 13-5. I.f. stage.

Most radio receivers use an intermediate frequency of 456 kc. This has been selected as a compromise between a lower and a higher value. The lower the i.f., the greater is the gain and selectivity. However, a low intermediate frequency allows the receiver to pick up some stations at 2 points on the dial. This results in interference. If we use a high i.f., we overcome this defect, but we lose gain and selectivity. An i.f. of 456 kc. has been chosen by most receiver manufacturers, though some receivers have their i.f. as low as 100 kc. and as high as 15,000 kc.

SECOND DETECTORS

The "second detector" of the superheterodyne receiver is the actual detector of the set. It is here that we extract the audio intelligence from the r.f. carrier. We call it a "second detector" because we sometimes refer to the frequency converter as the "first detector".

Figure 13-6 illustrates the diagram of a second detector used in a superheterodyne.

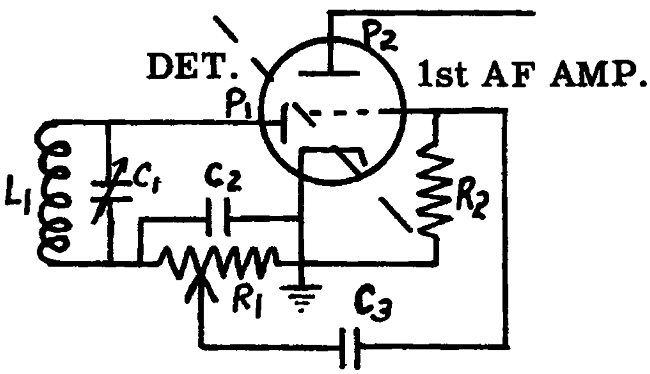


Fig. 13-6. Second detector and first a.f. stage.

The second detector and first audio frequency amplifier are combined in one envelope. This is done in most receivers to save tubes and space. The plate, P_1 and the cathode are the diode detector portion of the receiver. The plate, P_2, the grid and the cathode represent the first audio frequency amplifier stage.

The detector of figure 13-6 operates in the same manner as all diode detectors. The explanation in chapter 11 applies here. L_1-C_1 is the secondary tuned circuit of the last i.f. transformer. It is also the tuned circuit of the detector. R_1 is the detector load resistor across which the audio appears. By using it as a voltage divider to tap off various amounts of audio, we control the volume of the receiver. C_2 is the condenser that filters out the r.f.. C_3 is an audio coupling condenser that couples the audio from the detector to the grid of the first a.f. amplifier. R_2 is the grid load resistor.

In spite of the diode detector's lack of amplification, it is used in practically all modern superheterodyne receivers because of its excellent fidelity. Sufficient amplification is provided by the other stages.

AUTOMATIC VOLUME CONTROL

Controlling the volume by varying the load resistor of the diode detector is a simple satisfactory method. However, by itself, this method leaves a certain amount to be desired. For instance, every time we change from one station to another of different signal strength, we must reset the volume control. It would be far better to set the volume control at a desired level and have the audio output remain constant regardless of the strength of the incoming signal. This can be accomplished by means of a system known as AUTOMATIC VOLUME CONTROL. Figure 13-7 shows a circuit using this system.

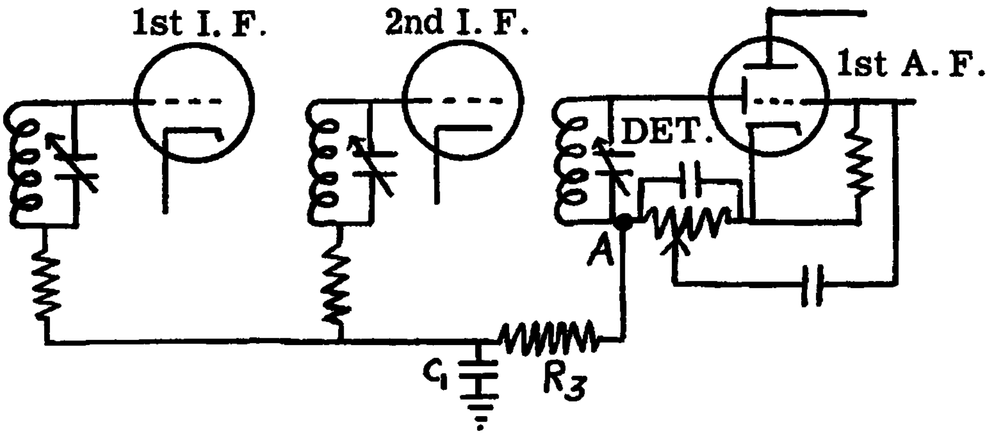


Fig. 13-7. Automatic volume control circuit.

In the system of automatic volume control (abbreviated a.v.c.) we automatically reduce the strength of the strong signals and build up the strength of the weak signals. This is accomplished in the following manner:

The audio output voltage of the diode detector is developed at point A of figure 13-7. This voltage varies directly with the strength of the incoming signal. As the strength of the incoming signal increases, the audio voltage at point A increases; as the strength of the incoming signal decreases, the audio voltage at point A decreases. The voltage at point A is fed back through a filter (C_1, R_3) to the grids of the i.f. amplifiers. (This voltage can also be fed to the grid of the r.f. amplifier if the superheterodyne has one). In other words, this voltage is applied as bias to the grids of the i.f. and r.f. stages.

The tubes used in the i.f. and r.f. stages are variable-mu tubes. A variable-mu tube is so constructed that its amplification varies inversely with its bias. As the bias on the grid of a variable-mu tube is made more negative, the amplification of the tube is decreased; and as the bias is made less negative the amplification is increased.

We shall now see how all these factors operate to keep the output level of the receiver constant. Let us assume that we are listening to a certain station and have set the volume control to the desired audio output. We then change to a station whose incoming signal is stronger than the first station. This station will produce a larger audio voltage at point A of figure 13-7 than the previous station. This larger negative voltage will be fed back to the grids of the variable-mu amplifier tubes. The increased negative bias will reduce the amplification of the tubes and therefore the gain of their stages will be reduced. This reduction in the gain of the receiver will compensate for the increased signal strength and will keep the audio output level constant.

Now, let us assume that we tune to a station whose signal strength is weak. There will be a low voltage at point A of figure 13-7. The negative grid bias of the variable-mu tubes will decrease and the amplification of the tubes will automatically increase. This will increase the overall gain of the receiver and bring the audio output of this weak signal up to the output level of the other signals.

The function of R_3, C_1 is to filter out the audio variations and keep them from being fed back to the i.f. and r.f. stages. All that we want to feed back are the slower variations resulting from changes in the incoming signal strengths and not the audio variations.

R. F. AMPLIFIERS AND IMAGES

The more expensive superheterodyne receivers contain one or two r.f. amplifiers ahead of the mixer. An r.f. amplifier will increase the gain and selectivity of the receiver. It will also reduce the reception of IMAGES. An image is an UNWANTED signal that differs in frequency from the local oscillator frequency by an amount equal to the intermediate frequency. For instance, if we are tuned to 1000 kc. and the i.f. is 456 kc., then the oscillator frequency would be 1456 kc.. Assume there was a station at 1912 kc.. The signal of this station would appear at the grid of the converter and beat with the oscillator to produce the i.f. of 456 kc.. This signal would be heard in addition to the 1000 kc. signal that we are tuned to. We call 1912 kc. the image frequency. By adding a tuned r.f. amplifier ahead of the mixer, we reduce the reception of images. This is because the r.f. amplifier is tuned to the frequency of the station that we wish to listen to and it is difficult for the image frequency to get through the additional tuned circuits. Without the r.f. amplifier, the image frequency has only to get through the mixer tuned circuits.

The circuit of an r.f. amplifier used in a superheterodyne receiver is the same as those discussed in chapter 12. The variable condenser in the grid circuit of the r.f. amplifier is ganged together with the mixer condenser and the oscillator condenser.

ALIGNMENT

In addition to the ganged variable condenser, there are also a number of small variable condensers (trimmers or padders) and variable inductors found in a superheterodyne. Their function is to correct for any variations that may exist in the tuned circuits. When the station selector knob is turned, the various r.f. stages must all tune to the same frequency and the local oscillator frequency must vary in such a manner that the frequency difference between the local oscillator and the r.f. stages is always equal to the intermediate frequency. When the circuits are adjusted in this manner, they are said to be TRACKING. It is also necessary to adjust the i.f. stages so that they all tune to the intermediate frequency. When all circuits are correctly tuned, we say that the receiver is properly aligned. Misalignment in any stage of a superheterodyne will cause a decrease of sensitivity or selectivity or both.

In order to align a superheterodyne receiver, a calibrated oscillator or signal generator and some form of output indicator are needed.

A signal from the signal generator is injected into the receiver at various points and we tune the trimmers or variable inductors of the various circuits for maximum reading on the output indicator.

A TYPICAL SUPERHETERODYNE RECEIVER

The circuit diagram of a typical ac/dc superheterodyne is shown in figure 13-8. Each component part of the circuit is labelled. The table below, showing the function of each part will serve as an excellent review of the theory of the superheterodyne receiver.

Part	Value	Function
V1	12BE6	Pentagrid converter tube
V2	12BA6	I. F Amplifier tube
V3	12AV6	2nd Detector, A.V.C. and 1st Audio Frequency amplifier tube
V4	50C5	A.F. power amplifier tube
V5	35W4	Rectifier Tube

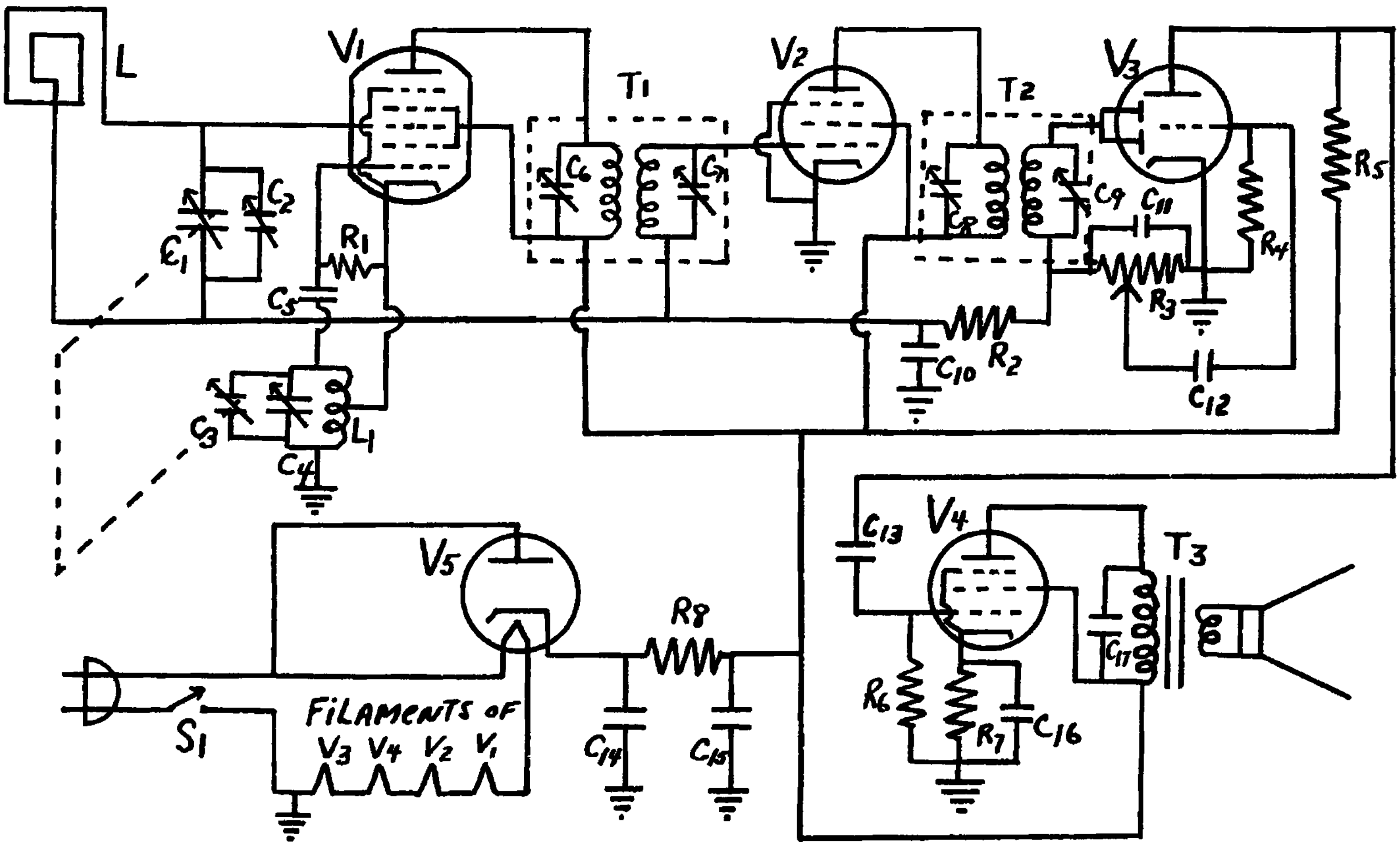


Fig. 13-8. A typical a-c/d-c superheterodyne receiver.

Part	Value	Function
T1		Input I. F. Transformer
T2		Output I. F. Transformer
T3		Audio output transformer
C1	15-350 mmfd	Mixer tuning condenser
C2	3-30 mmfd	Mixer trimmer condenser
C3	10-200 mmfd	oscillator tuning condenser
C4	3-30 mmfd	oscillator trimmer condenser
C5	100 mmfd	oscillator grid leak condenser
C6, C7, C8, C9	3-30 mmfd	I. F. transformer trimmer condensers - used in alignment of I. F. stages
C10	0.5 mfd.	A. V. C. Filter condenser
C11	100 mmfd	Detector r. f. filter condenser
C12, C13	.01 mmfd	Audio coupling condensers
C14, C15	16 mfd. 150V.	Power supply filter condensers
C16	20 mfd. 25V.	Cathode by-pass condenser
C17	1000 mfd.	tone condenser - to filter out high audio frequencies.
L		Serves as both loop antenna and coil of mixer tuned circuit.
L1		Local oscillator coil (Hartley type oscillator)
R1	25K	Oscillator grid-leak resistor
R2	2 Meg.	A. V. C. Filter resistor
R3	1/2 Meg.	Diode detector load resistor and volume control
R4	1/2 Meg.	Grid load resistor
R5	250K	Plate load resistor
R6	5 Meg.	grid load resistor
R7	200 ohms	Cathode bias resistor
R8	1,000 ohms	Power supply filter resistor
S1		On-off switch

CHAPTER 14

ANTENNAS

ANTENNA RADIATION

Once an r.f. signal has been generated in a transmitter, some means must be provided for radiating this r.f. energy into space. This is accomplished by the transmitting antenna. The transmitting antenna provides the link or impedance matching device between the output stage of the transmitter and space. The r.f. output, in the form of an electromagnetic field, travels through space and cuts across a receiving antenna, inducing a voltage in it. If the receiver is tuned to the same frequency as the transmitter, the signal will be received and heard.

PRINCIPLES OF RADIATION

The currents flowing in the antenna, due to the excitation from the transmitter, set up magnetic and electrostatic fields which are pushed out from the antenna and fly off into space in all directions. The two fields moving through space as an electromagnetic wave have the following characteristics:

1. The wave has a very definite frequency which is equal to the carrier frequency of the transmitter.
2. The wave travels through space at a constant velocity regardless of the frequency at which it is being transmitted. This velocity is 186,000 miles per second or 3×10^8 meters per second. ($3 \times 10^8 = 300,000,000$)
3. The wave has a certain wave length which is defined as the distance the wave travels through space during one cycle of the antenna voltage or current. The wave length is measured in meters and is given the symbol "λ". λ=wavelength in meters. λ is the Greek letter "Lambda".
4. An equation which ties together wavelength, frequency, and velocity of an electromagnetic wave is given below:

$$V = F\lambda$$

where: V is the velocity of the electromagnetic wave in free space
$V = 3 \times 10^8$ meters per second.
F is the frequency of the wave in cycles per second
λ is the wavelength in meters.

If the frequency is in kilocycles per second, the formula becomes:

2. $F\ (\text{kc}) \times \lambda\ (\text{meters}) = 300,000$

If we wish to solve for the wavelength, the formula becomes:

$$3.\quad \lambda\ (\text{meters}) = \frac{300,000}{F\ (\text{kc.})}$$

If we wish to solve for the frequency, the formula becomes:

$$4.\quad F\ (\text{in kc. per second}) = \frac{300,000}{\lambda\ (\text{meters})}$$

For Example

a) Find the wavelength of the distress frequency, 500 kc.

Solution

Use formula no. 3

$$\lambda\ (\text{meters}) = \frac{300,000}{F\ (\text{kc.})} = \frac{300,000}{500} = \underline{\underline{600\ \text{meters}}}$$

b) Find the wavelength of the frequency 1500 kc.

Solution:

Use formula no. 4

$$\lambda\ (\text{meters}) = \frac{300,000}{F\ (\text{kc.})} = \frac{300,000}{1500} = \underline{\underline{200\ \text{meters}}}$$

Radio waves today are designated in frequency rather than in wavelength; for example, you talk about a 30 megacycle carrier frequency, rather than a 10 meter carrier wavelength. However, wavelength figures are very convenient in the discussion of antenna systems because the wavelength gives some indication of the actual physical dimension of the antenna. For example, a half wave antenna for 10 meter transmission is 5 meters long, or converting to yard units; approximately 5 1/2 yards.

FUNDAMENTAL ANTENNA CONSIDERATIONS

Fig. 14-1 shows an antenna connected to an r.f. source. The alternating current starts from point A and travels out along the wire until it reaches point B. The wave cannot continue farther and bounces back, or is reflected, from point B (figure 14-2). The distance an r.f. wave travels during the period of one cycle is known as

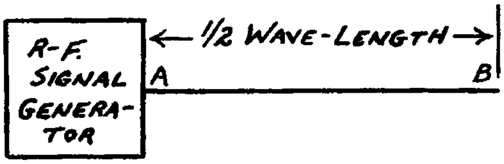


Fig. 14-1. Half-wave antenna.

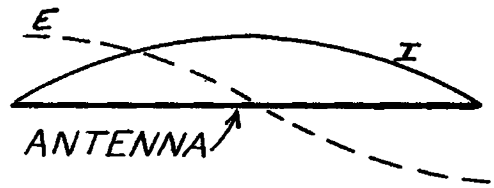


Fig. 14-2. Distribution of voltage and current on half-wave antenna.

the wavelength. If the wave is to travel exactly the length of the wire and back, during the period of one cycle, it is evident that the wire must be equal in length to one half the wavelength of the voltage being applied. The wire is then said to be resonant to the frequency of the applied voltage. During the negative alternation of the r.f. generator, electrons will move along the wire away from point A toward point B. The electrons are stopped and accumulate at point B, which represents a high voltage point. During the positive alternation of the r.f. power source, electrons move away from point B and crowd together at point A, which also represents a high voltage point. In the center of the antenna there is at all times a maximum movement of electrons causing a high current or a low voltage point. Very little voltage will appear, therefore, at the center of the antenna. On the other hand there will be a low current at the ends. Fig. 14-2 illustrates the voltage and current distribution on a fundamental half wave antenna. This representation of a voltage and current distribution is known as a standing wave pattern. The points of minimum current and minimum voltage are known as current and voltage nodes respectively. An antenna is said to be resonant when there exist standing waves of voltage and current along its length. Since the waves traveling back and forth in the antenna reinforce each other, a maximum radiation of electro-magnetic waves into space results. When there is no resonance (no standing waves), the waves tend to cancel each other, thus dissipating their energies in the form of heat loss, rather than being radiated into space. Therefore, a resonant antenna connected to an r.f. generator can dissipate power because most of the energy leaves the antenna in the form of radiation.

ANTENNA IMPEDANCE

Since voltage and current vary along the length of the antenna, a definite impedance value must be associated with each point along the antenna. The impedance varies according to the relative crowding of the electrons as the ends are approached. The impedance existing at any point is simply the voltage at that point divided by the current at that point. Thus, the lowest impedance occurs where the current is highest (at the center), and the highest impedance occurs where the current is lowest (at the ends).

THE HERTZ ANTENNA

A Hertz antenna is any length of wire far enough from ground so that it will not be influenced by grounded objects. Therefore, its physical length will directly determine the wavelength to which it will tune. A short length antenna will be resonant to a short wavelength or a high frequency; a long length antenna will be resonant to a long wavelength or low frequency. Therefore, the resonant frequency of a Hertz antenna can be changed by varying its physical length. This is true because an antenna acts like a resonant circuit. Fig. 14-3 illustrates a center fed Hertz half-wave antenna. Since the center of a half-wave antenna is a high current point, we say that the antenna is current fed by the transmitter. The impedance at the center of this Hertz antenna is about 73 ohms. The impedance rises uniformly towards each end of the antenna where it is about 2400 ohms.

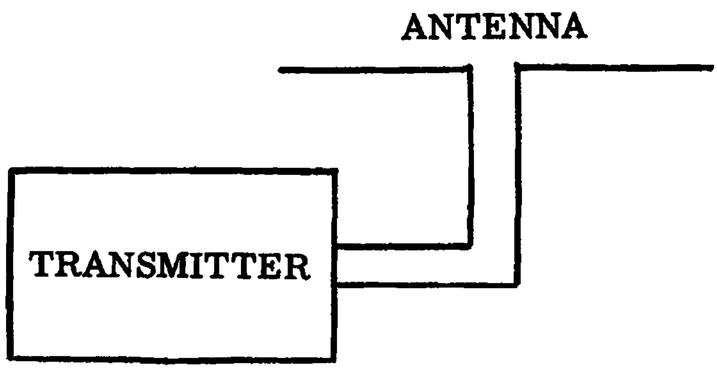


Fig. 14-3. Center-fed Hertz antenna.

PROPAGATION OF RADIO WAVES

The radio wave that leaves a transmitter takes two general paths. One path is along the surface of the earth and is called the GROUND WAVE. The other path is towards the sky and the radiated wave that travels along this path is called the SKY WAVE.

In traveling along the surface of the earth, the GROUND WAVE gradually loses its strength until it is completely diminished. On the other hand, the sky way can travel for thousands of miles.

Some distance above the earth, the sky wave strikes a gaseous mass called the IONOSPHERE. Here, the wave is reflected back to the earth. (See figure 14-4). If a receiver is located between the end of the ground wave and the point where the sky wave returns to the earth, it will not pick up the transmitted signal. The area between the ground wave zone and the point where the sky wave hits the earth

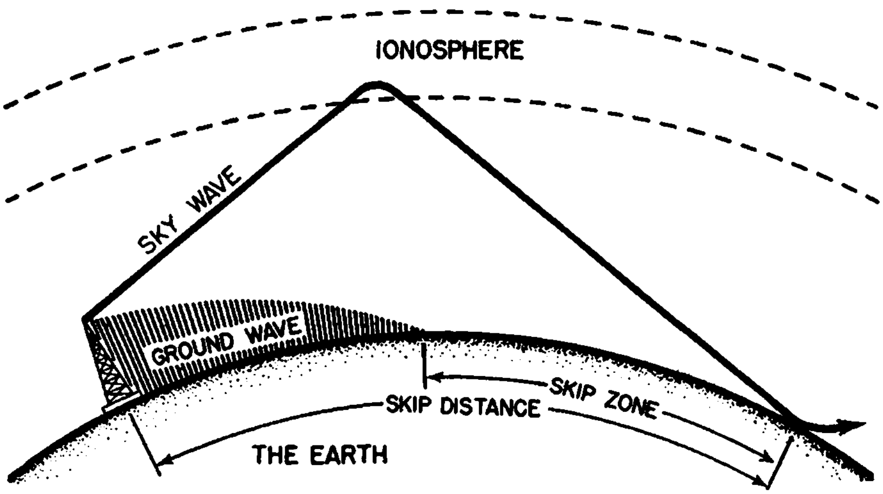


Fig. 14-4. Propogation of radio waves.

is called the SKIP ZONE. After the wave strikes the earth it may again be reflected up to the inosphere and back to the earth. In this way, a signal can travel all around the world.

Frequencies above 50 Mc. generally don't relect from the ionosphere. They penetrate the ionosphere and never return to earth. Thus, for frequencies above 50 Mc. (FM and TV. stations), we depend only upon the ground wave.

RECEIVING ANTENNAS

The antenna theory that has been discussed in this chapter applies to receiving antennas as will as to transmitting antennas. In many cases, good reception can be obtained with a makeshift antenna because of strong transmitted signals. However, if the receiving antenna is accurately designed, reception will definitely be better.

In locatities where the receivers are located close to the transmitting station an indoor antenna will operate in a satisfactory manner. Those receivers located far from the transmitting station should have a high outdoor antenna for satisfactory reception.

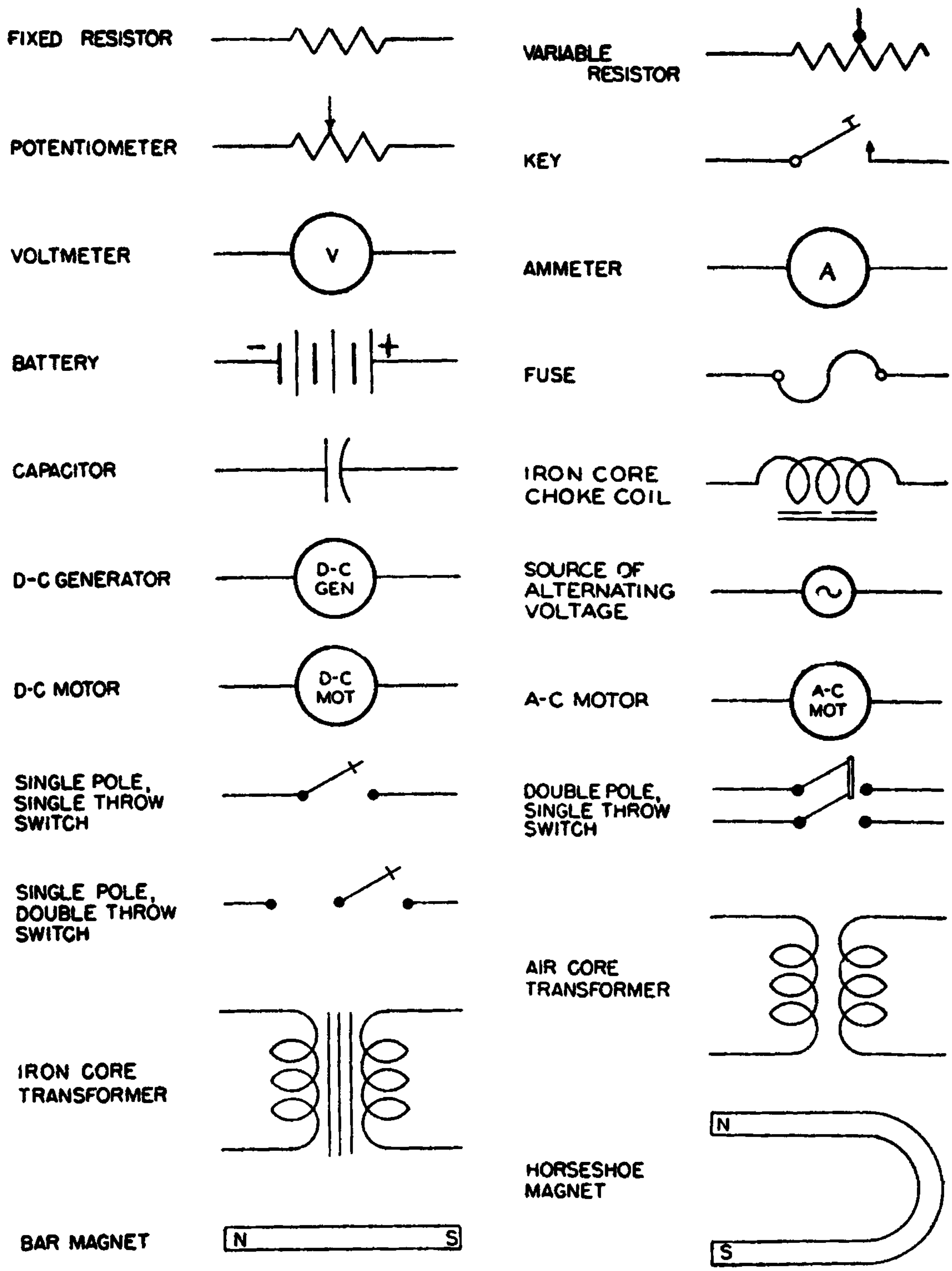
APPENDIX 1

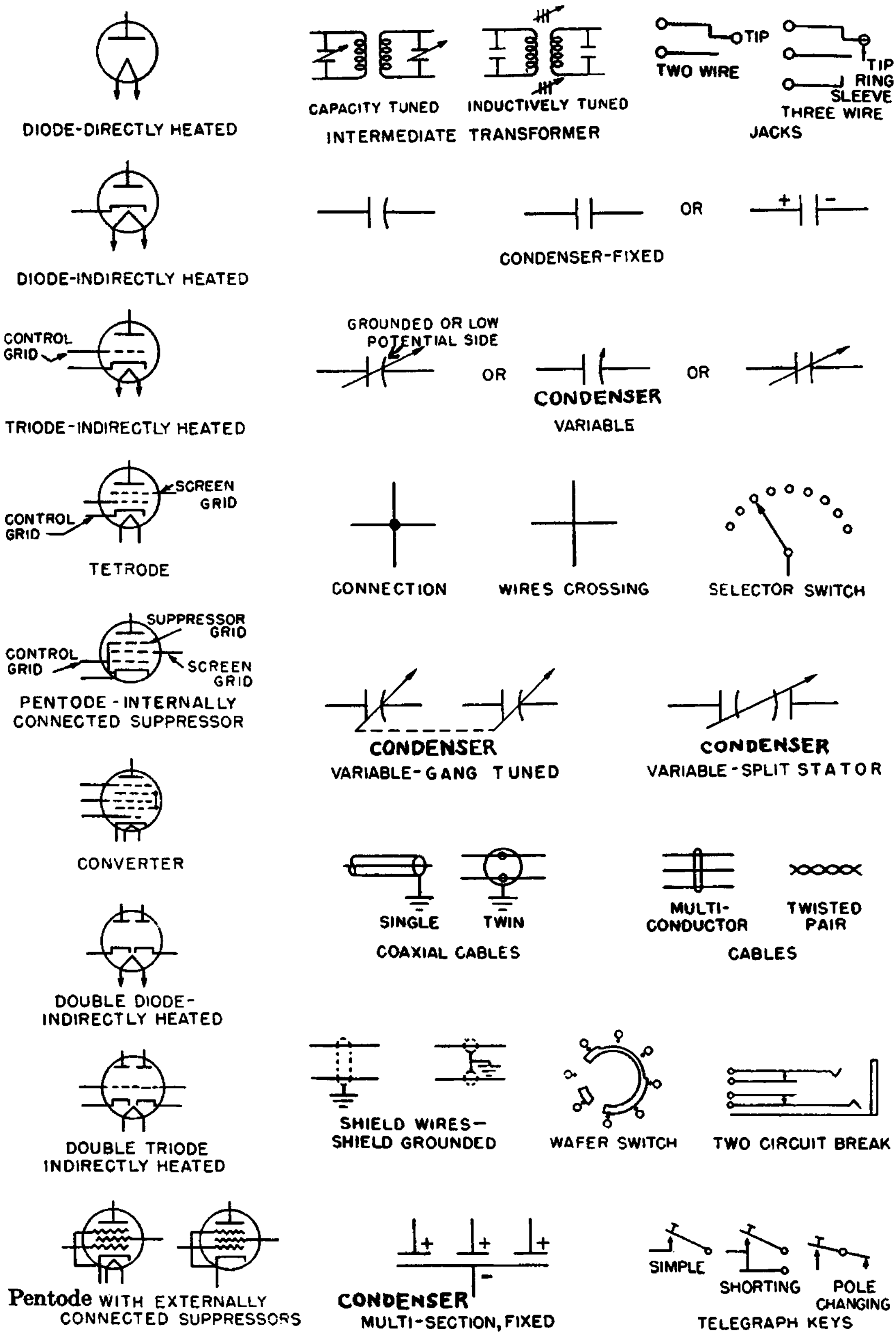
RADIO ABBREVIATIONS

ABBREVIATION	MEANING
A or Amp.	ampere
ma.	milliampere
μa.	microampere
a-c	alternating current
a-f or a.f.	audio frequency
a-m	amplitude modulation
Ant.	antenna
AVC	automatic volume control
C	capacitance
c	cycles
cps	cycles per second
kc.	kilocycles per second
Mc.	megacycles per second
c-w	continuous wave
d-c	direct current
E	voltage
e-m-f or e.m.f.	electro-motive force
f	frequency
fd	farad
μfd	microfarad
$\mu\mu$fd	micromicrofarad
f-m	frequency modulation
G	conductance
Gnd.	ground
H or h	henry
mh.	millihenry
μh.	microhenry
I	current
i-f or i.f.	intermediate frequency
L	inductance
m-o-p-a	master-oscillator, power amplifier
Ω (Omega)	ohm
M or Meg.	megohm (1 million ohms)
P	power
R	resistance
r-f or r.f.	radio frequency
TRF.	tuned radio frequency
UHF.	ultra high frequency
v	volt
kv.	kilovolt
VHF.	very high frequency
w	watts
Kw.	kilowatts
X_C	capacitive reactance
X_L	inductive reactance
Z	impedance

APPENDIX 2

COMMON RADIO SYMBOLS




DIODE-DIRECTLY HEATED
CAPACITY TUNED
INDUCTIVELY TUNED
INTERMEDIATE TRANSFORMER
TIP
TWO WIRE
TIP
RING
SLEEVE
THREE WIRE
JACKS
DIODE-INDIRECTLY HEATED
OR
+
-
CONDENSER-FIXED
CONTROL GRID
TRIODE-INDIRECTLY HEATED
GROUNDED OR LOW POTENTIAL SIDE
OR
OR
CONDENSER
VARIABLE
SCREEN GRID
CONTROL GRID
TETRODE
CONNECTION
WIRES CROSSING
SELECTOR SWITCH
SUPPRESSOR GRID
CONTROL GRID
SCREEN GRID
PENTODE - INTERNALLY CONNECTED SUPPRESSOR
CONDENSER
VARIABLE-GANG TUNED
CONDENSER
VARIABLE-SPLIT STATOR
CONVERTER
SINGLE
TWIN
COAXIAL CABLES
MULTI-CONDUCTOR
TWISTED PAIR
CABLES
DOUBLE DIODE-INDIRECTLY HEATED
DOUBLE TRIODE INDIRECTLY HEATED
SHIELD WIRES—SHIELD GROUNDED
WAFER SWITCH
TWO CIRCUIT BREAK
Pentode WITH EXTERNALLY CONNECTED SUPPRESSORS
+
+
+
-
CONDENSER
MULTI-SECTION, FIXED
SIMPLE
SHORTING
POLE CHANGING
TELEGRAPH KEYS

APPENDIX 3

RADIO FORMULAS*

Ohm's Law: $I = \frac{E}{R}$ $\quad E = IR \quad$ $R = \frac{E}{I}$

Power: $P = EI \quad P = I^2R \quad P = \frac{E^2}{R}$

Resistors in Series: $R_T = R_1 + R_2 + R_3 \ldots.$

TWO Resistors in Parallel: $R_T = \frac{R1 \times R2}{R_1 + R_2}$

Resistors in Parallel: $R_T = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} \ldots.}$

Inductors in Series: $L_T = L_1 + L_2 + L_3 \ldots.$

Inducators in Parallel: $L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \ldots.}$

Inductive Reactance: $X_L = 2\pi fL$

Condensers in Parallel: $C_T = C_1 + C_2 + C_3 \ldots.$

Condensers in Series: $C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C2} + \frac{1}{C3} \ldots.}$

Capacitive Reactance: $X_c = \frac{1}{2\pi fC}$

Resonant Frequency of a Tuned Circuit: $f_r = \frac{1}{2\pi\sqrt{LC}}$

Wavelength of Radio Waves: $= \frac{300,000,000}{f}$

*In the above formula, I is current in Amperes, E is voltage in volts, R is resistance in ohms, P is power in watts, L is inductance in Henries, T stands for total, X_L is inductive reactance in ohms, f is frequency in cycles, C is capacity in farads, and X_C is capacitive reactance in ohms.

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