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THE A B C OF VACUUM TUBES IN RADIO RECEPTION

AN ELEMENTARY AND PRACTICAL BOOK ON THE THEORY AND OPERATION OF VACUUM TUBES AS DETECTORS AND AMPLIFIERS. EXPLAINS NON-MATHEMATICALLY THE FUNDAMENTAL PRINCIPLES UPON WHICH ALL VACUUM TUBE CIRCUITS ARE BASED

INCLUDES

PRACTICAL CIRCUITS AND PRACTICAL QUESTIONS AND ANSWERS. IT IS WRITTEN ESPECIALLY FOR THE BEGINNER. ALL ELECTRICAL AND RADIO TERMS ARE FULLY EXPLAINED

BY

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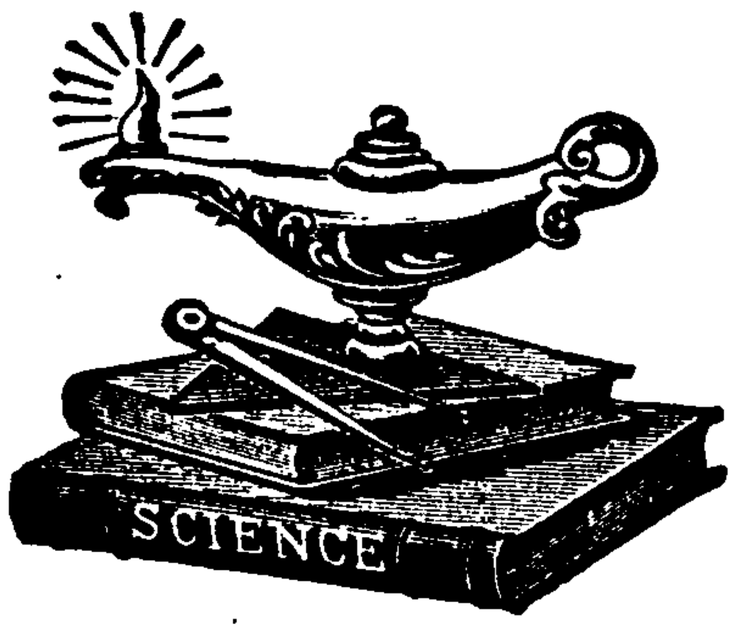
East Side Y. M. C. A., New York City.



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PREFACE

The inauguration of radio-telephone broadcasting has quickly aroused an enormous general interest in radio reception of speech and music. The possibilities of this new method of broadcasting information of general interest and entertainment can hardly be estimated. The method is revolutionary and has been aptly compared to the invention of the printing press in this respect.

Vacuum tubes make possible the reception of radio-telephone speech and music and radio-telegraph signals with a degree of satisfaction not approached by prior devices.

The vacuum tube appears to the layman as a complicated form of incandescent electric lamp which operates in a very mysterious manner. In writing this little book the author has endeavored to overcome this impression and to clearly set forth the elementary principles of theory and operation. It is assumed that the reader has no knowledge of radio and very little, if any, of electricity. Mathematics has been especially avoided in the treatment of the subject and no technical terms are used without their meaning being made clear.

The functioning of the "lamps" is fascinating to a great many people and the author hopes that the desire for elementary information regarding it will be fulfilled in the text. No attempt has been made to set forth all the possible circuit arrangements but those shown may serve as suggestions to experimenters who desire to evolve their own circuits. The practical questions and answers, it is hoped, may be of value to those who are contemplating the installation of receiving

492191

equipment or who are getting unsatisfactory results because of insufficient information.

Suggestions regarding improvement of the material presented and the manner of presentation will be gratefully received from readers.

April, 1922. THE AUTHOR.

CONTENTS

PAGE

CHAPTER I

Introductory

Electric current—Electrical pressure or Electromotive force—Resistance—Direct current—Alternating current—Frequency—Inductance—Capacitance—Resonance—Oscillations—The Reception of signals—Wave length—Tuning the receiving antenna—The Antenna as a complete circuit 15

CHAPTER II

The Vacuum Tube as a Rectifier and Relay Without Moving Parts

Tube construction—The Edison Effect—Electron emission from a heated filament—Dependence of plate current upon plate potential—Dependence of plate current upon filament current—Effect of grid potential upon plate current—Relay action—Rectification . . . 38

CHAPTER III

The Vacuum Tube Detector

The telephone receiver—Simple detection—Detection with grid condenser—Effect of gas in a detector tube—Heterodyne action or the production of beats 59

CHAPTER IV

The Vacuum Tube Amplifier

General characteristics—Audio frequency amplification—Radio frequency amplification—Radio frequency regenerative amplification—Autodyne production of beats 76

CHAPTER V

Practical Circuits and Their Operation

Methods of coupling—The variometer—Inter electrode tube capacitance—Wave length, Frequency and Resonance—Circuits and explanations of their arrangement and operation 90

CONTENTS

CHAPTER VI

Voice Distortion

PAGE

Amplifier transformers—Normal grid potential—Too great regeneration—Telephone receiver 111

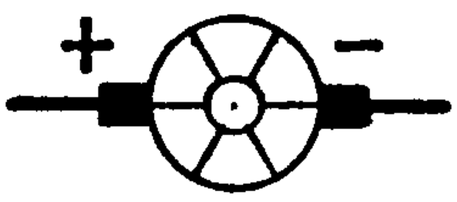
CHAPTER VII

Practical Questions and Answers

Practical Questions and Answers 116

~ List of Symbols ~

Battery ----------

Direct Current Dynamo ---  or

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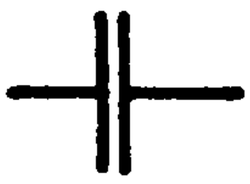
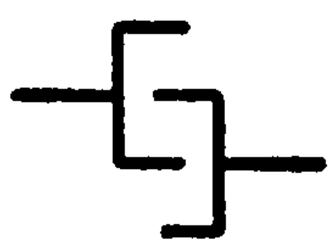
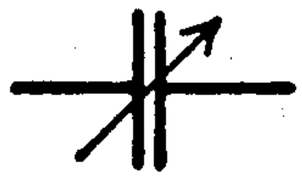
Fixed Capacitance (Condenser) ----------  or 

Variable Capacitance (Var. Condenser) ---------- 

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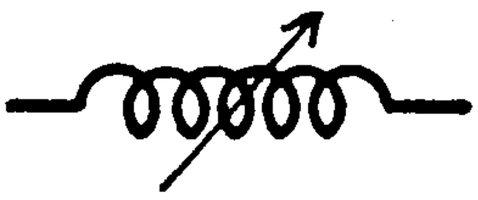
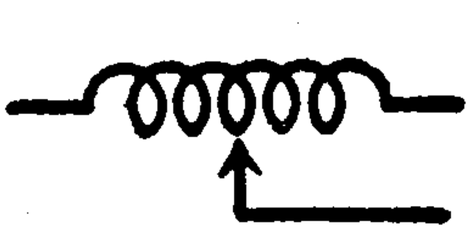
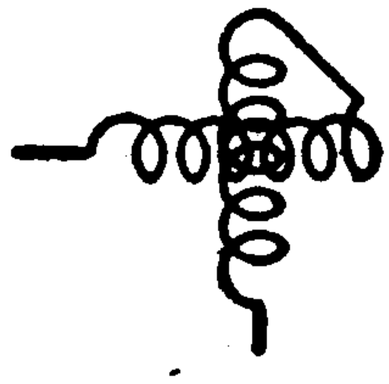
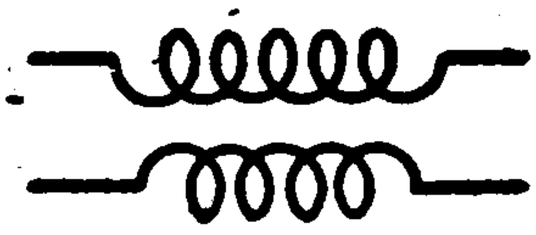
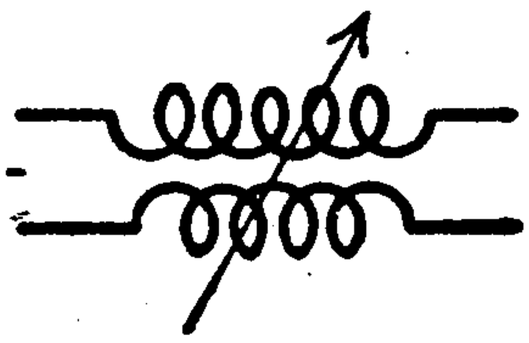
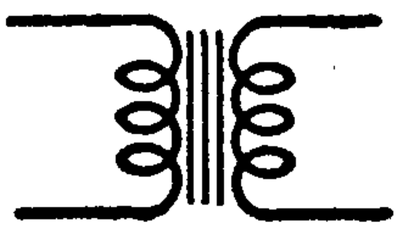
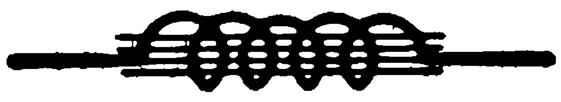
Variable Inductance (Air Core Coil) ----------  or 

Variometer (Variable Inductance) --- 

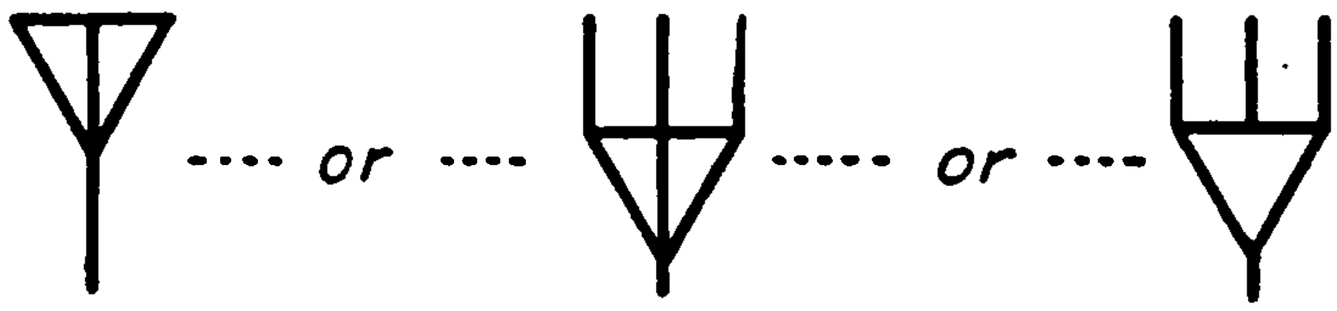
Fixed Coupling of Coils (Fixed Inductive Coupling) ---------- 

Variable Coupling of Coils --------- 

Transformer ---------- 

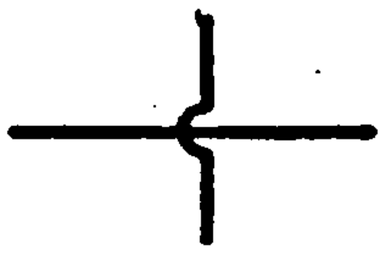
Iron Core Inductance (or Reactance Coil) ---------- 

~ List of Symbols ~

Antenna ----------  ---- or ---- ---- or ----

Ground ----------

Wire Connections ---- or

No Connections of Wires ---------- 

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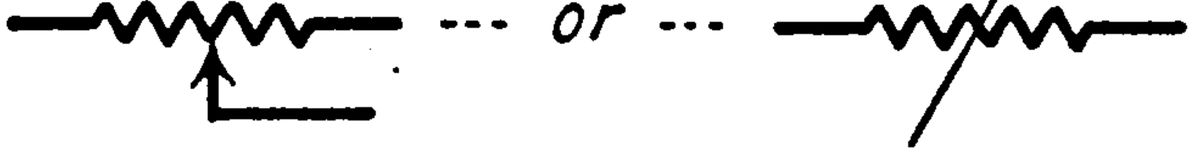
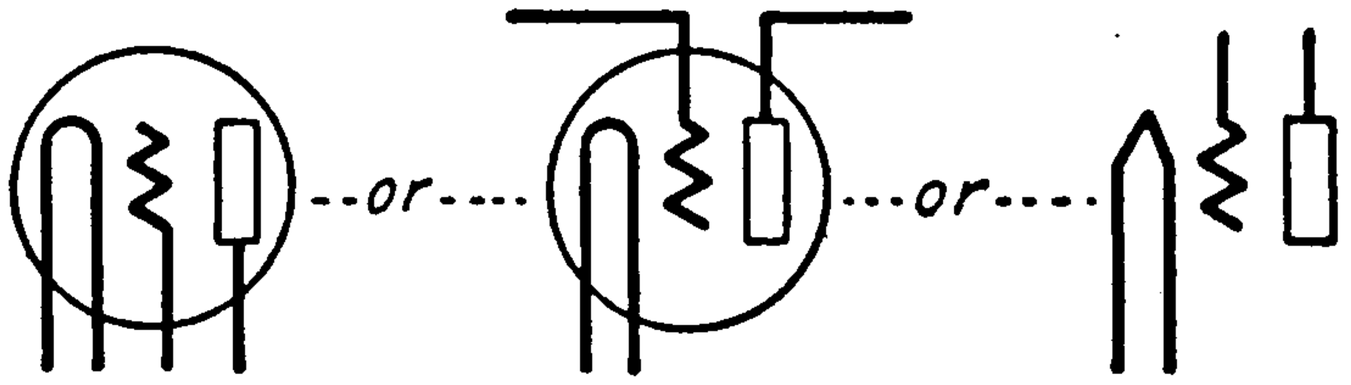
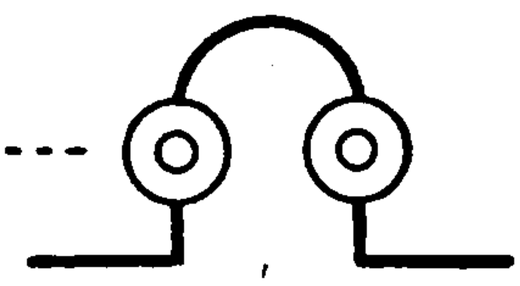
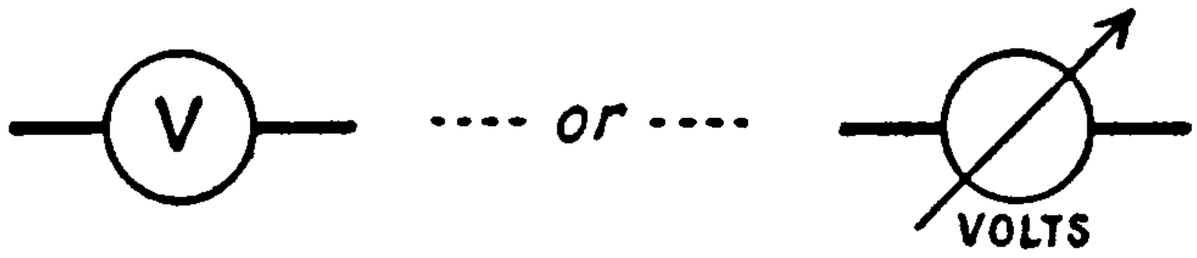
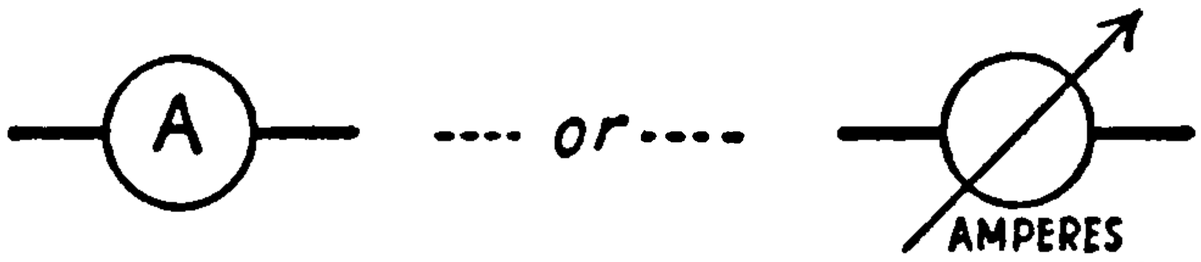
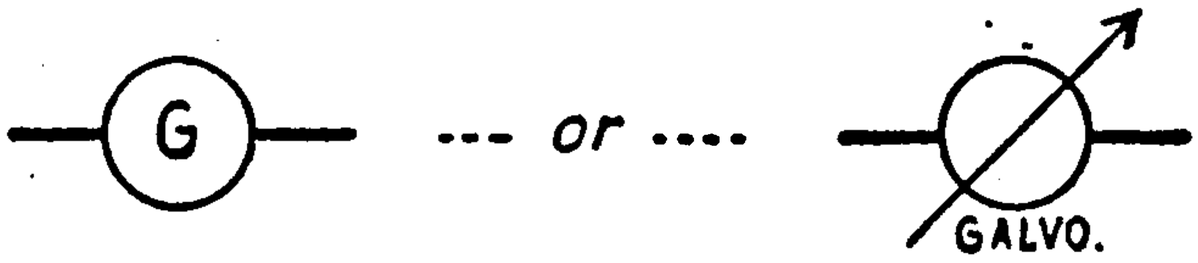
Variable Resistance ------  --- or ---

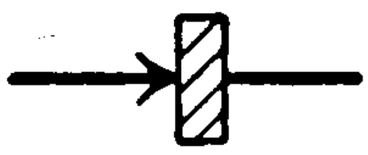
Vacuum Tube -------  --or---- ---or----

Telephone Receivers ---------- 

Voltmeter ----------  ---- or ----

Ammeter ----------  ---- or ----

Galvanometer --------  --- or ----

Crystal Detector ---------- 

CHAPTER I

INTRODUCTORY

Electric current—Electrical pressure or Electromotive force—Resistance—Direct current—Alternating current—Frequency—Inductance—Capacitance—Resonance—Oscillations—The reception of signals—Wave length—Tuning the receiving antenna—The antenna as a complete circuit.

Before taking up the subject of vacuum tubes a brief outline of the most common electrical and radio phenomena together with the explanation of common electrical terms will be given. It is understood that for some this may be a review of knowledge previously gained. For others it may, however, serve to fix some very vague understandings and some familiarity with these fundamental facts is necessary in order to comprehend that which follows.

Electrical Current

It is very commonly known that a battery and a dynamo furnish what is called a "current of electricity" and that the electrical current will not flow unless a path is provided for it. The path is called the "electrical circuit" or simply the "circuit." For example, if it is desired to ring a door-bell it is necessary to connect the bell to a battery by means of insulated wires and if the path, or circuit, is broken at any point the bell will not ring. A push button may be used to keep the circuit broken until the button is pressed, whereupon an electric current flows through the circuit and the bell rings.

Fig. 1 represents such a circuit which may be closed at will by pushing the button. Since no electricity flows when the circuit is open we may assume that it flows in all parts of the circuit when it is closed. Thus, if the current flows from the battery at "A" it must return to the battery at "B." The terminal of the battery from which the current flows is called

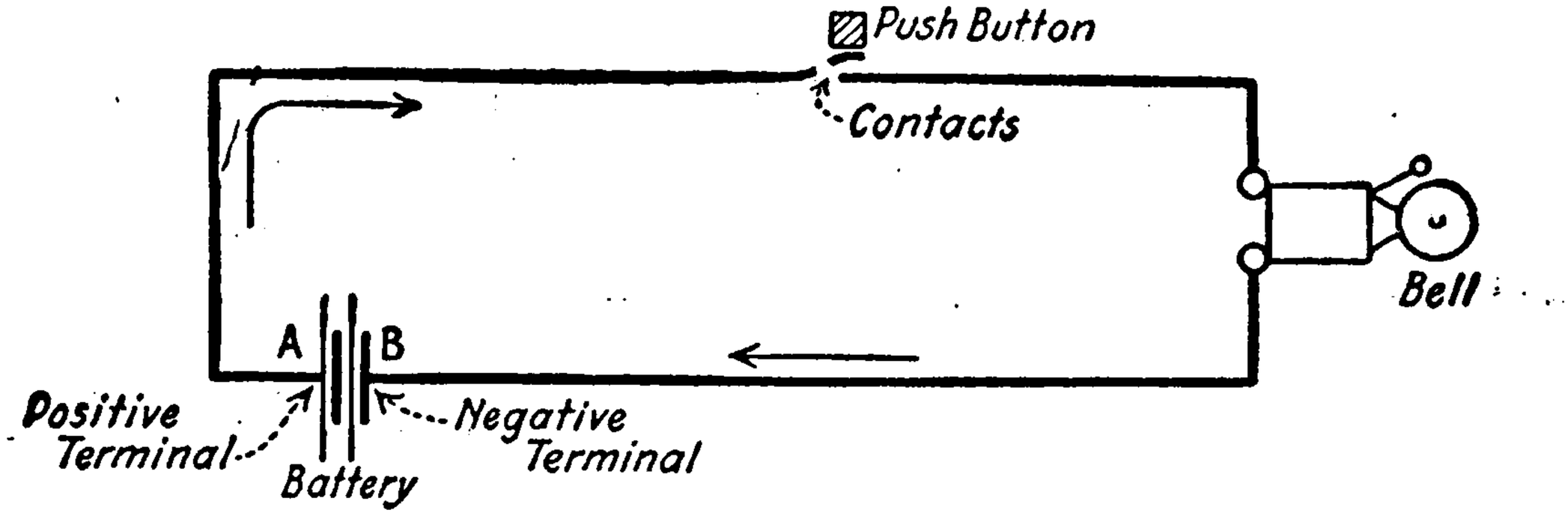


Fig. 1—Simple electrical path or circuit.

the "positive terminal and the other the "negative" terminal.

To illustrate the flow of current, a closed circuit of pipe may be used. A pump is located at "A" in Fig. 2 and the

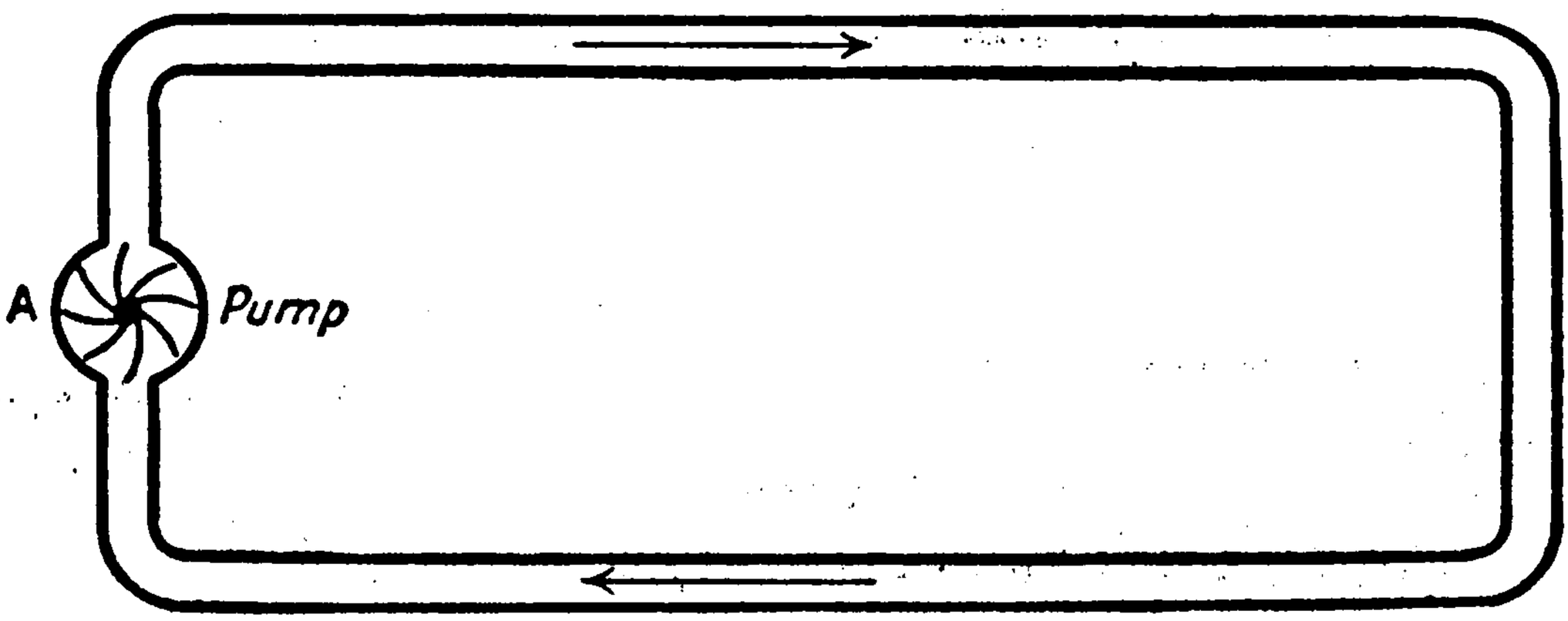


Fig. 2—Water analogy of simple electrical circuit.

pipe is considered to be full of water. When the pump is operated the water will be forced to flow, let us say, in the direction of the arrow. It flows from the pump through the pipe and returns to the pump and the same amount of water which leaves the pump in one second of time will return to

it in the same length of time. In other words, there is a continuous flow of water until the pump stops. This corresponds to the electrical circuit and it may very easily be proven that the current is no stronger in one part than it is in any other part of the circuit.

We may measure the current or rate of flow of the water in gallons per second. That is, if there is one gallon flowing in one second past any given point in the pipe the rate of flow is one gallon per second. The current or rate of flow of electricity also may be measured and the unit is called the "ampere." The rate of flow of electric current is sometimes referred to as its "strength" and if the current strength is one ampere its rate of flow is one ampere, a certain fixed quantity of electricity per second.

It must not be assumed that electricity is actually a fluid like water. It is not. No one knows just what electricity is but its effects may be noted and its "flow" may be compared in many respects to that of water.

Electrical Pressure or Electro-Motive Force

Electrical pressure is referred to as "electro-motive force" since in order to create a current of electricity it is necessary to provide some force to make it flow. In the case of the pipe full of water the pump must exert a force or pressure upon the water to push it through the pipe. In the case of the electrical circuit in Fig. 1 the battery furnishes the electrical pressure. Neither water nor electricity can flow unless a pressure is provided. If we wish either the water or the electric current to flow faster (at an increased rate) the pressure applied to it must be increased.

Water pressure may be measured in pounds per square inch

but electrical pressure or electro-motive force is measured in volts. Sometimes electrical pressure is referred to as "voltage." E. M. F. is a convenient abbreviation to use for the long expression "electro-motive force" and it will be used hereafter in this text.

Resistance

When water flows through a pipe there is always a certain amount of friction between the water and the pipe. This hinders the flow of the water, that is, reduces the rate at which the water current flows. And the reduction in rate of flow depends directly upon the increase of the friction. Likewise there is friction present in the path of the electric current which acts as a "resistance" to the current flow. If the pressure or E. M. F. is kept constant the rate of current flow (current strength) increases as the resistance is decreased and vice versa. If, however, the resistance is kept constant it is natural to expect the current (rate of flow) of the electricity to increase with an increase of E. M. F. and vice versa. The current thus depends upon both the resistance and the E. M. F.

The unit of electrical resistance is called the "ohm" and if the resistance of a circuit is one ohm, one ampere of current will flow if the E. M. F. is one volt. This relation between current, E. M. F. and resistance is called "Ohm's Law" and is the first fundamental law of electrical circuits.

Direct Current

If the E. M. F. applied in a circuit is steady and only acts to force the current to flow in one direction through a circuit the resulting current is steady and is called a "direct current."

If the E. M. F. rises and falls but only acts in one direction the resulting current rises and falls and is called a "pulsating direct current" or a "pulsating current." Batteries produce a steady direct current in one direction through a circuit. Many dynamos, however, produce a pulsating E. M. F. which causes a pulsating current to flow (in one direction only) through a circuit. The periodical increases and decreases of E. M. F. and current may be made very small, however, so that they are hardly perceptible.

Alternating Current

Imagine that instead of a battery we have a dynamic generator of electrical pressure in a circuit and that the E. M. F. produced acts in first one direction, then the other, and that

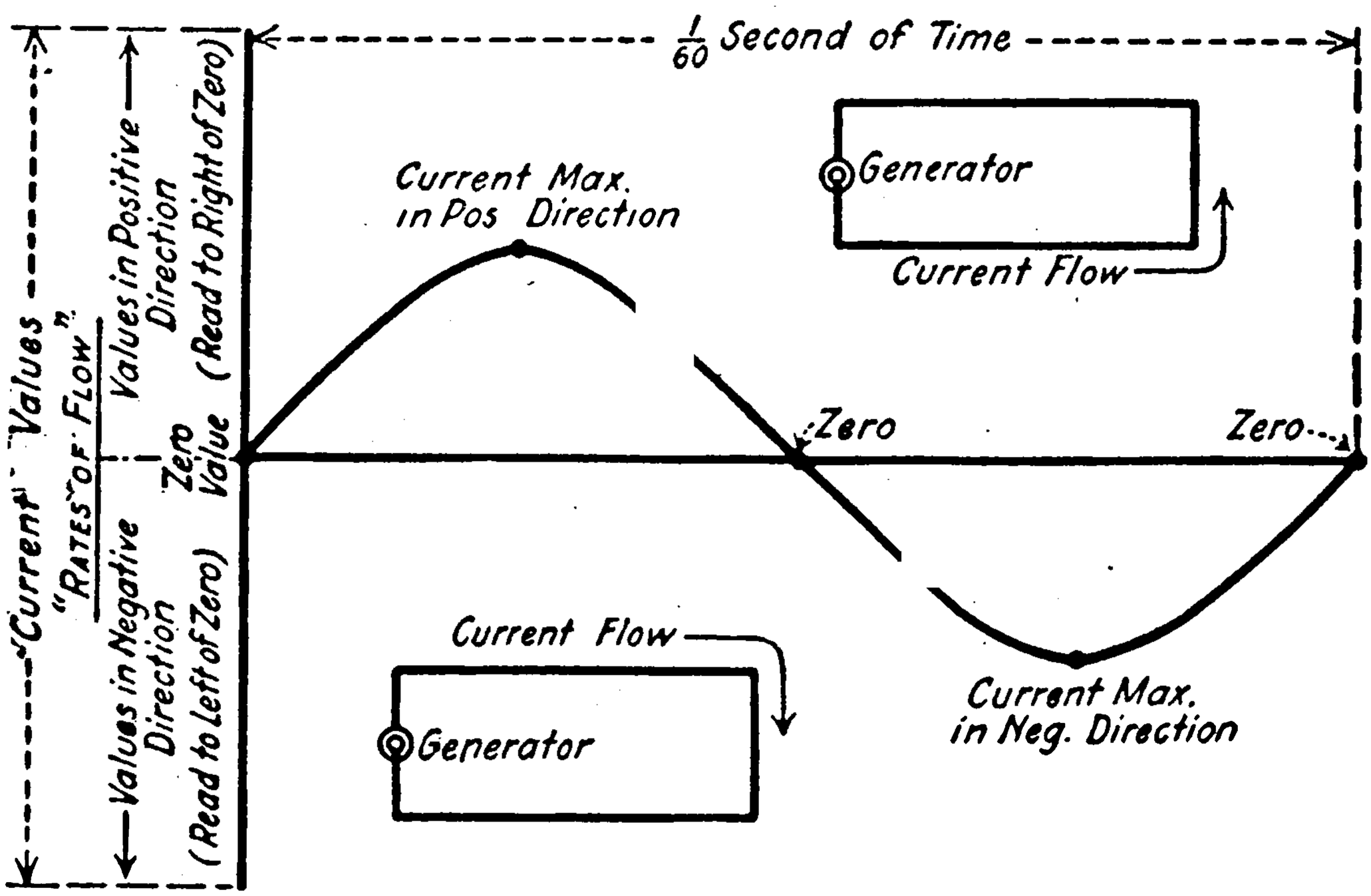


Fig. 3—One cycle of current changes and reversals. Frequency 60 cycles per second.

while acting in each direction it increases to a maximum value and decreases to zero. The current created will also change its direction of flow and increase and decrease in strength periodically, as shown in Fig. 3. Such a current could be

said to "alternate" in its direction of flow and is aptly called an "alternating current." These alternations or reversals of current flow, with their accompanying increases and decreases in rate of flow, take place very rapidly and at perfectly regular intervals. In this figure the current values or "rates of flow" are shown as increasing and decreasing in one direction above the horizontal line and increasing and decreasing in the opposite direction below that line. In order to distinguish the directions of flow from each other we may call one the "positive" direction and the other the "negative" direction, so that all current values along the vertical line and above the horizontal line are in the positive direction and all those along the vertical but below the horizontal are in the negative direction. During the period of time represented by the horizontal line the current has increased to a maximum value and decreased to zero in the positive direction then has reversed its direction and increased to a maximum and decreased to zero again. In increasing and decreasing, the current has passed through all values from zero to maximum in each direction. It has thus gone through one "cycle" of current changes and directions of flow. As long as the E. M. F. acts, the current will continue to go through these changes in a perfectly regular manner periodically.

Frequency

In the ordinary house lighting circuit, if it has alternating current, the periodical reversals of current flow usually take place at the rate of 60 cycles per second. It may be said then that the "frequency" of the alternating current is 60 cycles per second.

In radio work extremely high frequencies, varying approxi-

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In an alternating current circuit, if we for the moment disregard the actual resistance, the average value of current decreases as the reactance increases providing that the E. M. F. has a constant average value. That is, the reactance has the *effect* of a resistance although it is not true "ohmic' 'or actual resistance. If the circuit contains reactance *and* ohmic resistance, the average current value will decrease with an increase in either or both providing again that the average E. M. F. is constant.

A straight wire possesses inductance to some extent and the inductance of a wire increases with its length. Given a certain length of wire, its inductance and therefore its reactance may be very greatly increased by coiling it. Also, if more turns are added to the coil or if an iron core is placed inside of it, its inductance is increased and its reactance as well.

To distinguish this type of reactance from a type considered below we may call it "inductive reactance." To sum up, then, inductive reactance depends directly upon the inductance and frequency of current. The average value of alternating current in a circuit varies inversely with the reactance.

Capacitance

Capacitance, or, as it is sometimes called, "capacity," has exactly the opposite effect of inductance upon an alternating current. Capacitance has the effect of causing the current to rise to its maximum value before the E. M. F. The current in this case is said to "lead" the E. M. F., as is graphically shown in Fig. 5.

* The reciprocal of the product of capacitance and fre-

* If the product were 2, the reciprocal would be ½. The reciprocal of 3 is 1-3, of 2 x 100 it is $\frac{1}{2 \times 100}$ and so forth.

quency determines the value of a reactance which in this case may be called a "capacitive reactance." The capacitive reactance, however, does not have the effect of a resistance to the alternating current but exactly the opposite. The average

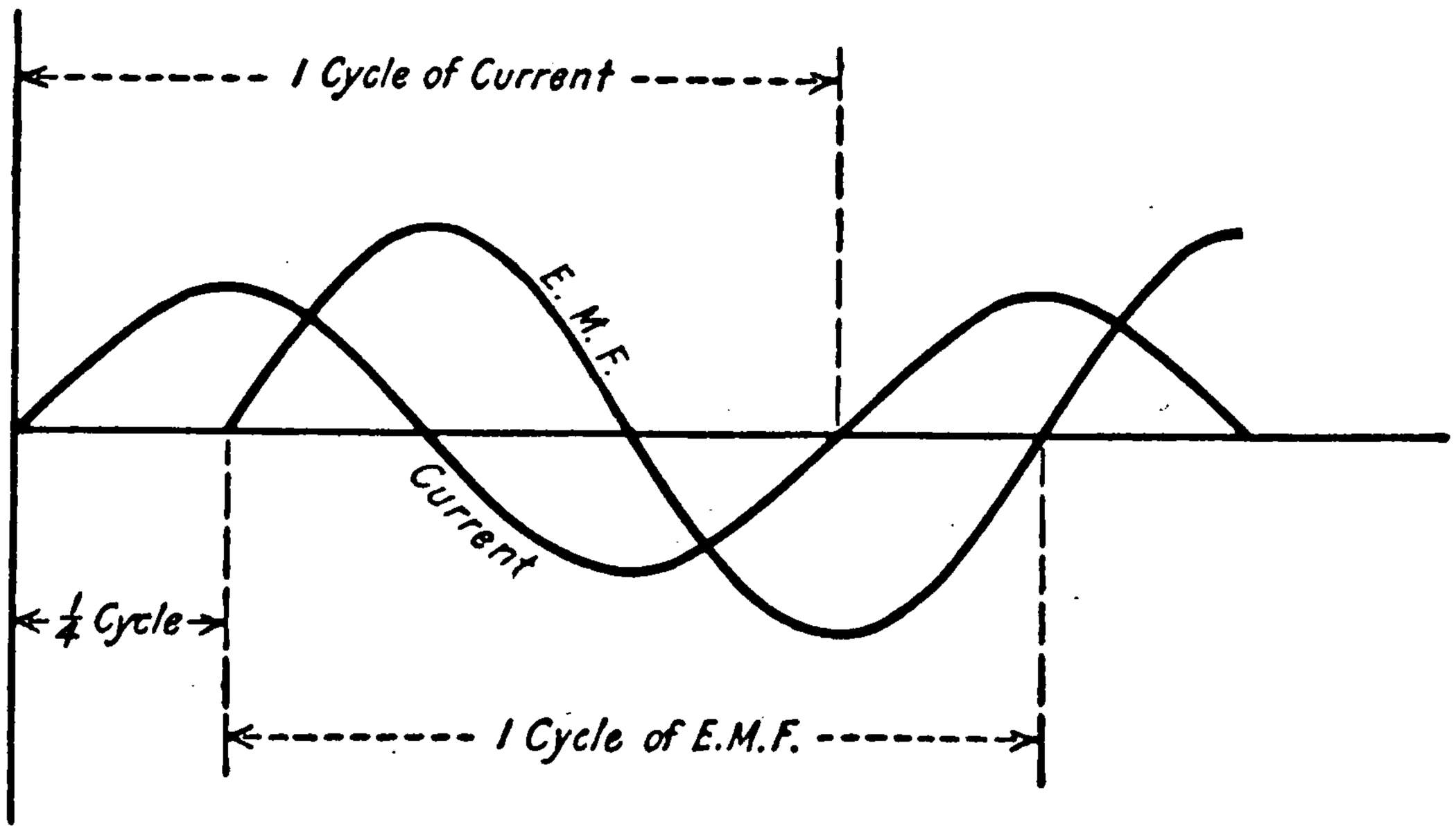

Fig. 5—Effect of capacitance in an alternating current circuit.

current value depends directly upon the capacitive reactance in a circuit, providing the average value of E. M. F. is kept constant. The average value of the alternating current then increases with an increase in either the average E. M. F. or the capacitive reactance and decreases with an increase of actual resistance. Capacitive reactance decreases with an increase of either capacitance or frequency, and vice versa.

A straight wire has some capacitance which increases with the length of the wire. Coiling the wire will also increase its capacitance. But since inductance is the predominant property the capacitance of a wire or coil is very small in comparison.

If two metallic plates are assembled with a sheet of glass between them there is produced what is known as a "condenser." This arrangement would have a very appreciable capacitance. To increase the capacitance of this con-

denser we could (1) increase the area of the glass and the metallic plates; (2) decrease the thickness of the glass (the distance separating the metallic plates); (3) use a substance between the plates which has a higher "dielectric constant." The material between the plates, whatever it may be, is called the "dielectric" and although it may not be an absolute insulator it does have a very high resistance, usually, to the passage of a current. Air is assumed to have a "dielectric constant" of unity (or one) and if a condenser with the same dimensions has a dielectric which gives five times the capacity of the air condenser, the "dielectric constant" of the other material is five. Some dielectric constants in the order of their increase are: Air—1, paraffine—2; hard rubber—2.5; glass—6 to 8; mica—8.

It would be very convenient at times to have a variable capacitance whose value could be adjusted at will. If the maximum value is not necessarily very large, an air dielectric may be used. A number of movable plates could be arranged so that they interleave with a number of stationary plates without touching them. All the stationary plates are connected together and to a terminal and the movable plates are connected together and to a second terminal. There will be an increase in the

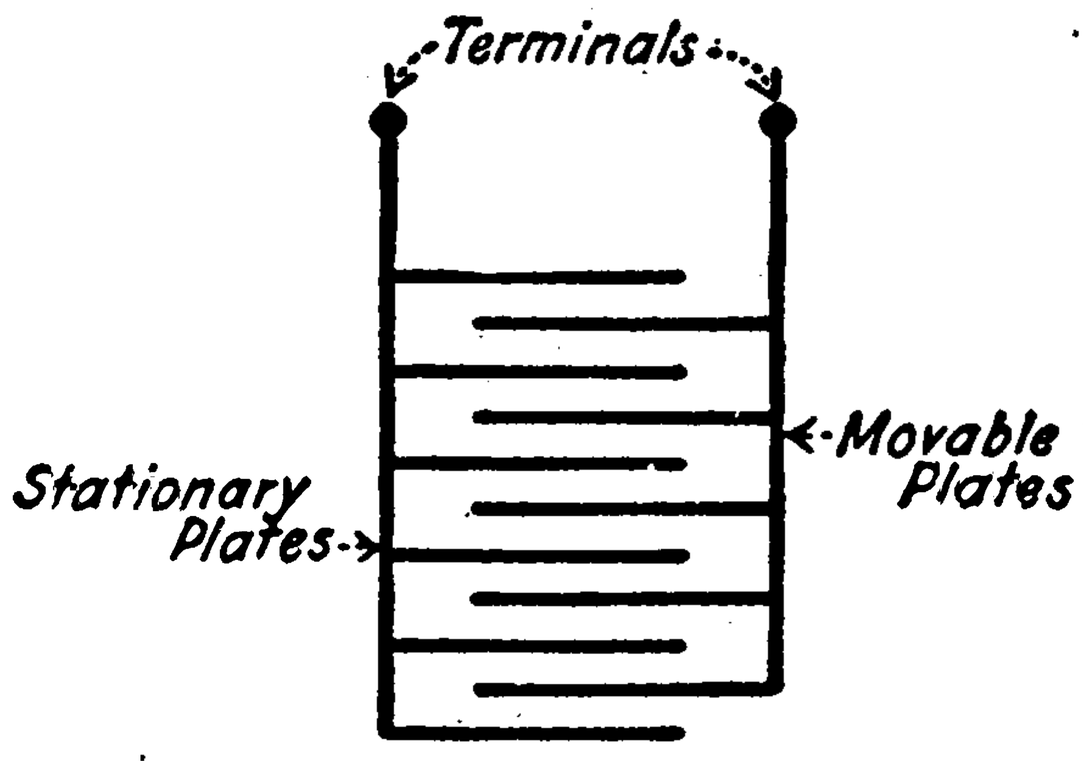

Fig. 6—Scheme of a variable condenser. (If the movable plates are made stationary it is a "fixed" condenser.)

maximum capacitance obtainable if more plates are used because this will increase the total plate area, the dielectric being the air between the stationary and movable plates. Fig. 6 shows how the plates are interleaved and Fig. 7 illustrates a variable air condenser with and without its case.

The question may be asked, "How does an electric current flow through a condenser if the dielectric is a good insulator

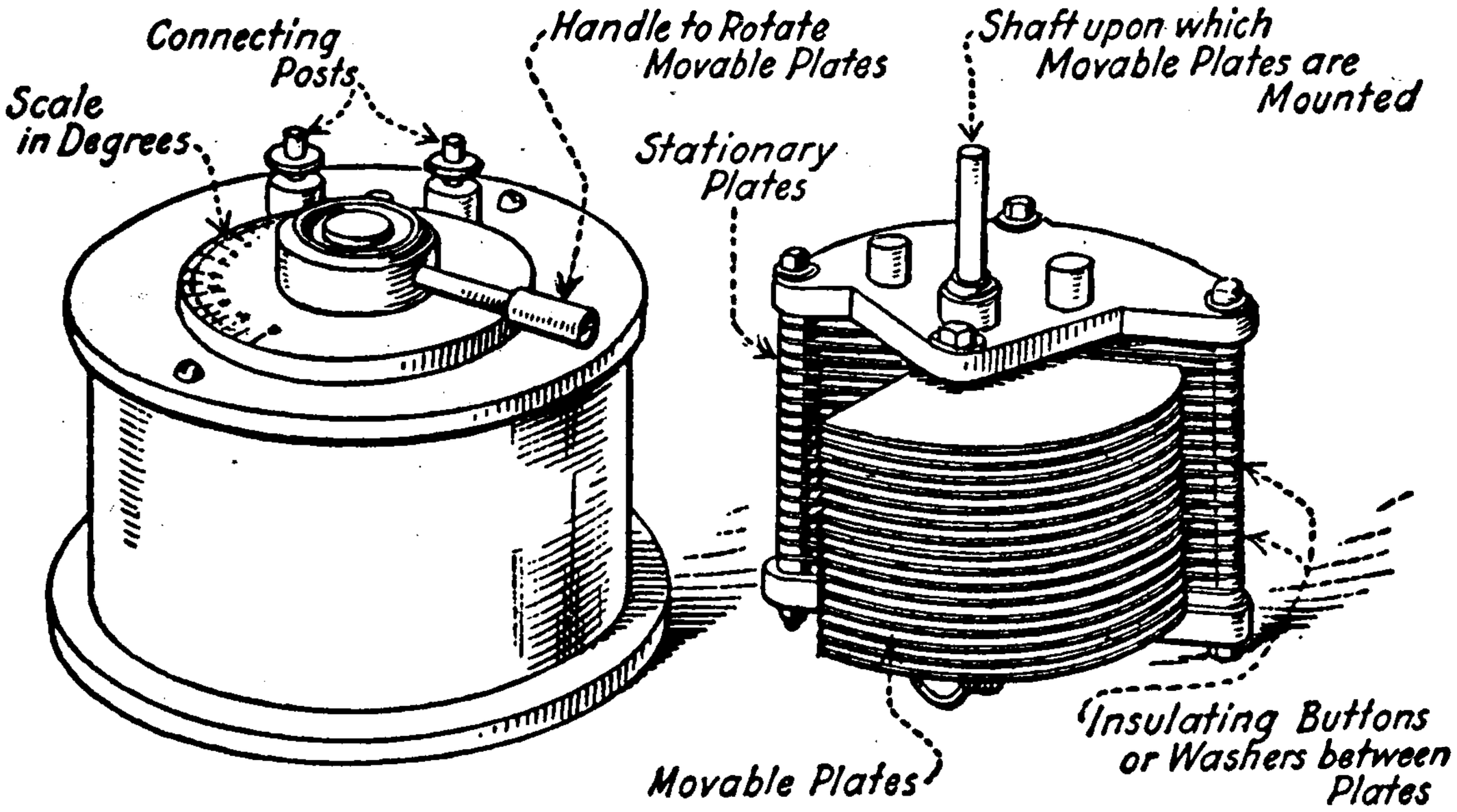

Fig. 7—Typical variable condenser with air dielectric.

and prevents the passage of current?" A direct current will not flow through a condenser and neither will an alternating current. But the alternating current will appear to flow through because in all parts of the circuit on either side of the dielectric it rises and falls in rate of flow back and forth between the dielectric and the source of E. M. F. To make the matter more clear, suppose an analogy is considered. In Fig. 8 a pipe full of water is represented with an elastic partition at "A" and a pump at "B." The pump is so arranged that the to-and-fro motion of the piston exerts a pressure periodically in one direction then the other and causes the

water, therefore, to flow in each direction periodically. The water does not flow past the elastic partition at any time. But, the elasticity of the partition allows it to stretch and during the time the current is forced in the direction of the full line arrow, it stretches and exerts a back pressure upon the water exactly equal to the pressure of the pump at every instant. When the pump pushes the water in the opposite direction the partition stretches in the opposite direction and again exerts a back pressure equal at every instant to the pump pressure. There is thus a surge of water back and forth through the pipe, causing the partition to stretch in first one direction then the other, within the limit of its elasticity. And, then, as far as the pipe is concerned, there is an alternating current of water in it in spite of the partition. The dielectric of a condenser is the "partition" and it must have electrical elas-

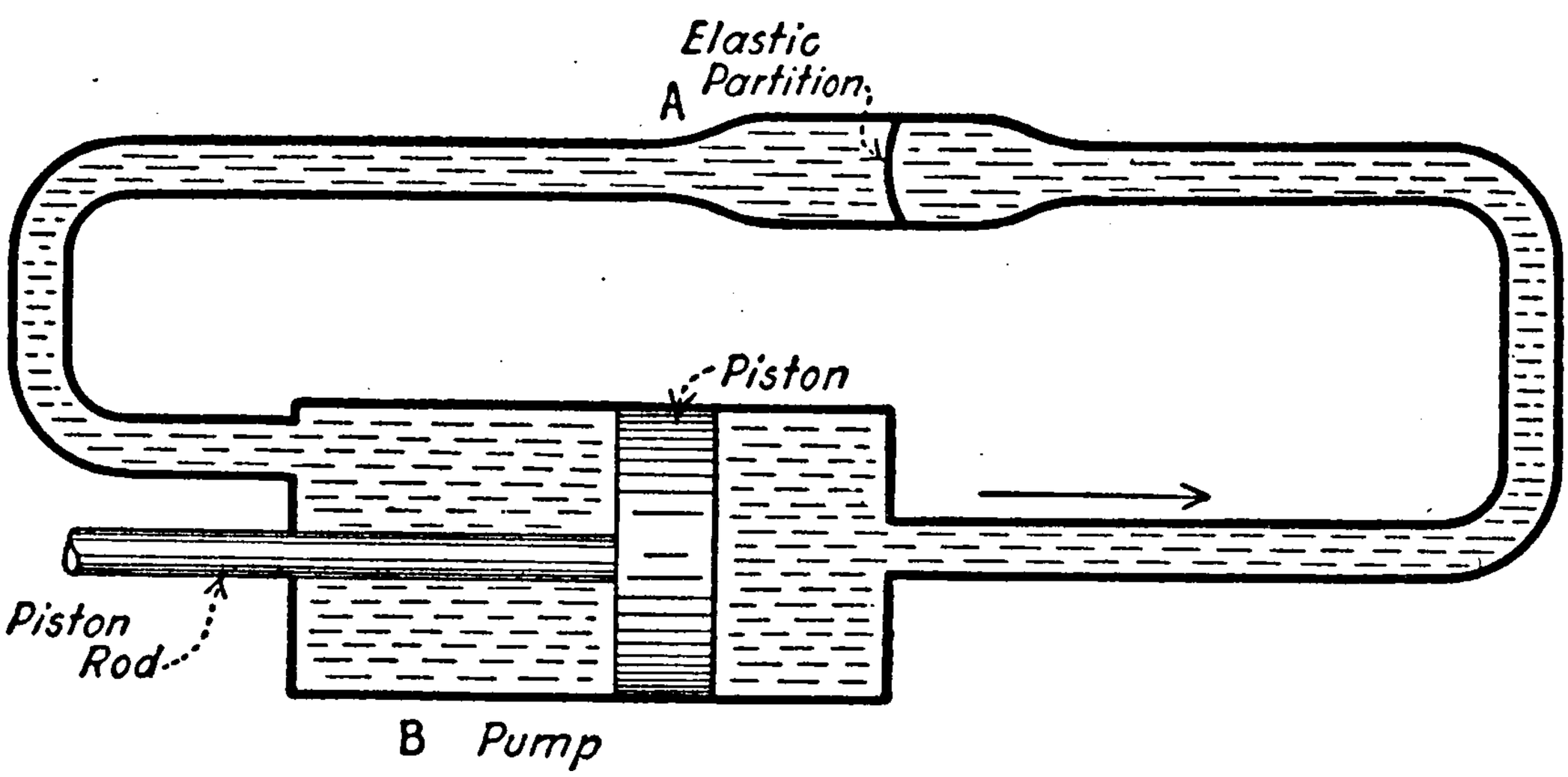

Fig. 8—Water analogy of alternating current in a circuit containing a condenser.

ticity, otherwise it might be ruptured in the same manner that the partition in the pipe would be, if the pump pressure became too great. It is thus readily seen that while an alternating current does not actually flow through the dielectric, the current does alternate in the circuit in spite of the dielectric.

Resonance

Suppose two tuning forks are tuned to the same musical pitch and placed a foot or so apart. If one is struck a light blow it vibrates and a sound is heard which is the musical pitch dependant upon the rate of vibration of the fork. The fork is setting up waves in the air which reach the ear and are translated by the brain into a musical tone which is recognized. What is perhaps more interesting, however, is that the second tuning fork also vibrates in sympathy with the first. If the first fork is grasped in the hand to stop its vibration, the second will still vibrate for a short time and emit a musical tone exactly of the same pitch as the first one. It is evident that the second fork is vibrating at the same rate as the first before it was grasped. It is said to be "in tune" or "in resonance" with the first.

Suppose, however, that the first tuning fork is adjusted so that, when struck, it vibrates at a different rate. This time the second one will not vibrate in sympathy as it would if it also had been adjusted to vibrate at the same rate. The two forks are then not in tune with each other and the second is "out of resonance" with the first.

In the first case the second fork was forced to vibrate at the same mechanical frequency (of vibration) as the first fork, because it was in resonance. In the second case there was no resonance, so the second fork was unaffected.

An electrical circuit in which an alternating current flows does not vibrate mechanically, but it may be thought of as vibrating electrically. Also, one electrical circuit may be adjusted so that it is "in resonance" with another and so that an alternating current flowing in one will produce an alternating current in the other of the same frequency. In this

case of "electrical resonance," the second circuit is caused to "vibrate electrically" in sympathy with the first.

Oscillations

Alternating electrical currents of extremely high frequency are said to be alternating at "radio frequencies," as has been noted. And such high frequency alternating currents are

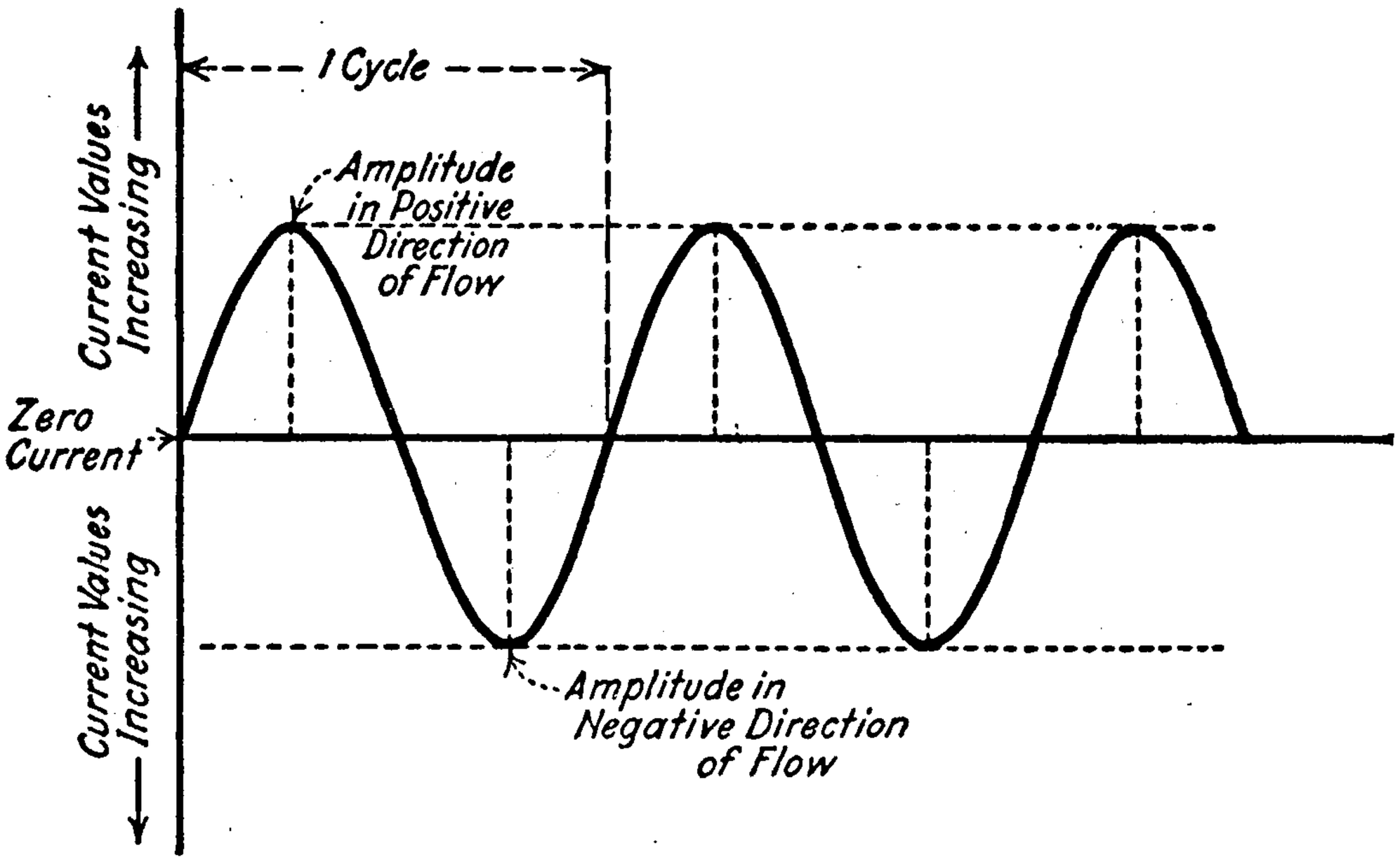

Fig. 9—Continuous oscillations.

called "Radio frequency alternating currents." Instead of using this long name a shorter one has been selected for practical use, and it is said that such alternating currents are "oscillations." A definition of oscillations may then be, "radio frequency alternating current."

The maximum value of current strength attained in each direction of current flow during each cycle is called the "amplitude." If successive amplitudes are of equal values as long as the current flows, the oscillations are said to be "continuous oscillations." An alternating E. M. F. of constant amplitude is, of course, necessary to the production of continuous oscil-

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were suddenly applied and immediately withdrawn, the circuit would vibrate electrically in the same manner as the struck tuning fork vibrated mechanically. An alternating current would be produced in the circuit, providing its resistance were not too great, but the successive amplitudes would decrease and the oscillations would die out just as the vibrations of the tuning fork die out a short while after the fork is struck. In the second circuit, just as with the second fork, even though there is resonance the vibrations die out after a short time.

If, however, the first tuning fork were tapped very lightly at the end of each swing it would continue to vibrate as long as the tapping took place at the proper times and in the proper amounts to maintain these vibrations (or swings). The regular periodical tapping may be compared to a regular periodical E. M. F. applied in an electrical circuit. If the E. M. F. is applied at the proper times and always in the same amounts, the oscillations will not decrease in amplitude but will be "continuous." Now, in the case of the tuning forks, if the vibrations of the first one are continuous (due to continuously applied taps), the vibrations of the second one will continue and be of constant amplitude. Likewise, in a second electrical circuit, if the oscillations in the first are continuous those in the second will also be continuous. Continuous oscillations in a second circuit are then the result of a continuously applied E. M. F. in that circuit due, in turn, to a continuously applied E. M. F. (and therefore oscillations of continuous amplitude) in the first circuit.

The action of producing oscillations in a second circuit by creating oscillations in a primary circuit is called "induction," and we may say that when oscillations are produced in a secondary circuit they are "induced" therein.

The Reception of Signals

It should now be quite clear that if oscillations are produced in a suitable circuit at a transmitting station oscillations will be produced by induction in a suitable circuit at a receiving station, when the two circuits are in resonance with each other. Each of the circuits is called an "antenna," or sometimes, an "aerial," since each is frequently erected so that it extends some distance from the earth up into the air.

When vibrations are induced in a tuning fork by another, the air between them is set in motion and it is this air which transmits the motion from one fork to the other. That is, the first fork sets the air into vibration and the vibrating air sets the second fork into vibration. Another illustration would be the dropping of a stone into a quiet pond of water. Water waves radiate from the point where the stone strikes the water until they reach a cork located a distance away. The cork is set into motion and bobs up and down, or oscillates. But the cork does not move further away from or closer to the point where the oscillations were created in the water. This proves that the water itself does not travel from one place to another but that the oscillating motion is transmitted or radiated from the point where the disturbance occurs. In the case of either the air or the water it is the oscillatory or vibratory motion which is transmitted.

This throws some light upon electrical induction. But in the case of oscillations produced in a secondary electrical circuit neither air nor water is necessary to transmit the motion. In fact, electrical oscillations in a circuit have no effect upon either air or water. There must be some medium, however, which is capable of being set into vibration by the electrical oscillations and will, in turn, create electrical oscillations

in a distant circuit. This medium is called the "ether," and is one which pervades all space. It is present in the entire universe where water and air may be entirely absent. It is, in fact, the ether which is set into vibration by the oscillations in a transmitting antenna. These vibrations spread out in circles just like the ripples in the water after a stone is dropped and when they reach a receiving antenna, create electrical oscillations in that circuit. The whole purpose of "radio" is to create ether vibrations and to translate them at a distant point.

Now, assume that continuous oscillations or recurrent trains of damped oscillations are produced in a transmitting antenna and either continuous or recurrent trains of damped oscillations are induced in the receiving antenna. We still lack a device to make the received oscillations perceptible to one of our senses. But in a following chapter means for accomplishing this necessary result are considered.

Wave Length

The ether vibrations or oscillations have the same frequency as the electrical oscillations which create them. Moreover, this oscillatory motion of the ether is projected through it with the speed of light, light being only ether vibration at considerably different frequencies. This rate of speed is 300,000,000 meters (approximately 186,000 miles) per second of time. Almost too rapid a rate to conceive—in fact, ether oscillations caused by electrical oscillations travel over seven times around the earth in one second.

The ripples created in a pond of water by the dropping of a stone travel about 10 to 100 centimeters per second, a centimeter being roughly equivalent to one-hundredth of a yard.

The ripples are, of course, small water waves, and if we know their rate of travel and their frequency of production, we can easily calculate the length of one wave. For example, one wave is produced each second and travels a distance of one yard in that length of time. What is the length of the wave? It is, of course, the rate of travel (one yard in one second) divided by the frequency of wave production (one cycle per second or one wave per second), and equals, in this case, one yard. Likewise, if an ether wave travels 300,000,000 meters per second and the frequency of its oscillation is 300,000, its length must be 1,000 meters. That is, the wave length (length of one wave) is the result of dividing the velocity (distance traveled per second) by the frequency (number of waves per second). There are, of course, the same number of waves per second as cycles of oscillation. In speaking of these ether vibrations it is customary to think of their wave length rather than their frequency. If a transmitting station is said to "radiate" a "wave length" of 200 meters, what is meant is that the ether in the neighborhood of the transmitting antenna is set into vibration at the rate of 1,500,000 times per second (frequency equals 1,500,000) and that the length of each ether wave created is 200 meters.

Tuning the Receiving Antenna

Under "Inductance" and "Capacitance" it was brought out that inductive reactance has the effect of a resistance upon an alternating current and that capacititive reactance has just the the opposite effect. It was also brought out that inductive reactance increases and capacitive reactance diminishes with increased frequency and vice versa. If, then, a circuit has an inductance and a capacitance selected at random there will be a certain frequency at which the two reactances are equal and,

since they are exactly opposite, the total reactance is zero. This frequency is called the "resonance frequency." On the other hand, if a certain frequency is selected at random then the two reactances must be adjusted so that they are equal for this frequency and, since they are opposite, they will then neutralize each other and the total reactance will be zero.

Now, when a receiving antenna is acted upon by ether vibrations of a certain definite frequency (the frequency of the oscillations in the transmitting antenna) an alternating (oscillating) E.M.F. is produced and an oscillating current will *tend* to flow in the antenna. Whether or not the current will actually flow and whether it will be of maximum value for the E.M.F. applied, will depend upon both the actual resistance and the total reactance (effective resistance) in the antenna circuit. The actual resistance may be assumed to be and in practice is, fairly low, and with an antenna already erected it is, on the whole, a fixed value. The current then depends upon the total reactance which, as has been stated, may be made zero by the proper adjustment of inductive and capacitive reactance. If the reactances are made equal for this definite applied frequency then the antenna may be said to be "tuned" or "in resonance" with the frequency and therefore with the frequency of oscillations in the transmitting antenna. Since inductive reactance may be increased and decreased by varying the number of turns of wire on a coil and since capacitive reactance may be increased and decreased by allowing the movable plates of a variable air condenser to interleave to a greater or lesser extent, tuning may be accomplished by either a variable coil or a variable condenser.

Increasing the inductance of the coil or the capacitance of the condenser means that the resonant frequency is decreased, providing the coil and condenser are in series with each other in the

circuit. That is, if the circuit is in resonance with a certain frequency and either the inductance of the coil or the capacitance of the condenser is increased, the circuit is no longer in resonance with this frequency but would be in resonance with a lower frequency of ether oscillations produced by, perhaps, some other transmitting antenna. The counter condition is of course true, that if the coil inductance or the condenser capacitance were decreased, the circuit would then be in resonance with a higher frequency of ether oscillations produced, possibly, by still another transmitting station. Either one of these stations or any one of possibly a large number of stations might then, of course, be picked up at will by simply tuning the receiving antenna circuit in this manner.

Wave-length of ether oscillations is perhaps thought of more popularly than frequency, and under "Wave Length" it was pointed out that as the frequency of oscillations increases their wave length diminishes and vice versa. If, then, we wish to speak in terms of wave-length, we may say that an increase of inductance or capacitance in a receiving circuit increases the wave length at which that circuit is in resonance and that a decrease of either of them decreases this wave length. Speaking still in terms of wave length rather than frequency, it may now be said that tuning is simply the process of adjusting inductive reactances (coils) and capacitive reactances (condensers) in a circuit so that, for the wave length of the ether oscillations acting upon the (antenna) circuit, the two reactances are equal and, being opposite, neutralize each other to reduce the total reactance to zero.

The Antenna as a Complete Circuit

As a general rule, the antenna appears not to be a complete circuit. If Fig. 11 is considered it is seen that there is a capaci-

tance effect (or a condenser effect) between the free end of the antenna and the end connected to earth or to a "counterpoise" consisting of a number of wires stretched beneath the antenna. That is, every inch of the antenna has a capacitance to earth (or to the counterpoise) so that considering the antenna as a

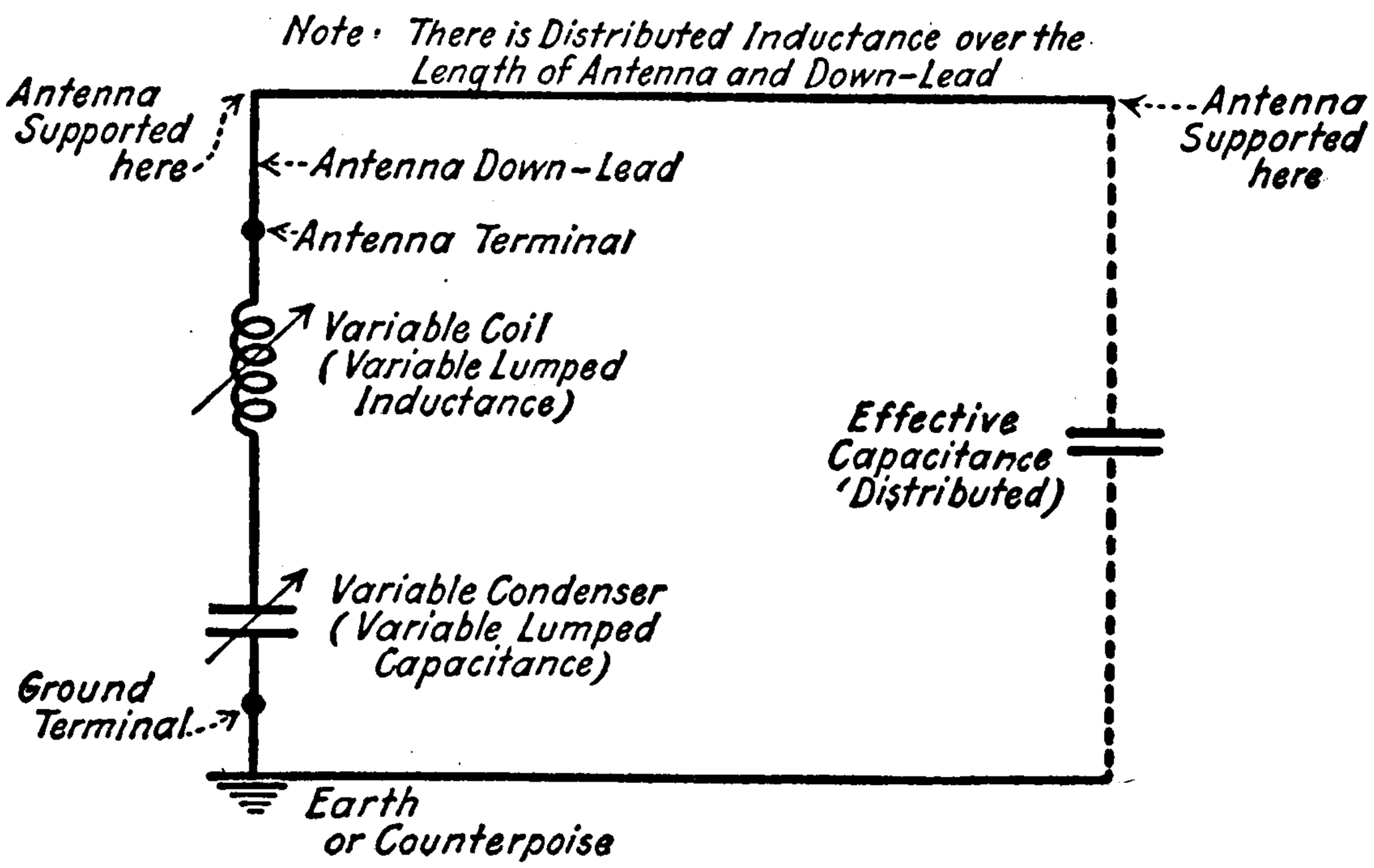

Fig. 11—Scheme of antenna as a complete circuit.

whole, it may be regarded as one plate of a condenser, with the earth or counterpoise acting as the other plate. There is then a circuit which is closed so far as alternating current (especially radio-frequency alternating current) is concerned and current readily flows in the circuit under the proper conditions mentioned above.

The reason that an antenna, particularly a transmitting antenna, has to be elevated a considerable distance above the earth is in order to allow a large amount of ether to be acted upon and set in motion by the antenna oscillations. It is readily seen that the higher the antenna the larger the amount of ether there is between its top and the surface of the earth. In the case of a receiving antenna this also applies to a considerable extent, since in this case it is desirable to have as large an amount of

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CHAPTER II

THE VACUUM TUBE AS A RECTIFIER AND RELAY WITHOUT MOVING PARTS

Tube construction—The Edison Effect—Electron emission from a heated filament—Dependence of plate current upon plate potential—Dependence of plate current upon filament current—Effect of grid potential upon plate current—Relay action—Rectification.

Tube Construction

A vacuum tube is somewhat similar in construction to an ordinary incandescent electric lamp which has a filament supported inside a glass tube or bulb from which the air has been exhausted. When an electric current flows through the lamp filament it is heated to incandescence and produces light. A vacuum tube also has a filament which may be made incandescent by allowing electric current to flow through it, but the production of light in this case is merely an accompaniment of more essential phenomena as will be explained.

When air is exhausted from any kind of a vessel a vacuum remains and the degree of vacuum depends upon the degree of air exhaustion. The vacuum within a so-called "vacuum tube" is very much higher than that within an incandescent electric lamp. What are known as "hard" tubes have an extremely high vacuum, often indeed the highest possible vacuum attainable. Others known as "soft" tubes contain a small amount of gas and, therefore, a somewhat lower vacuum. Each class of tube has its particular uses, although the "hard" tubes may be used for all purposes.

Regardless of the degree of vacuum, a tube contains, in

addition to a filament, a "grid" and a "plate" arranged, for example, as in Fig. 12. The grid is always placed between the filament and the plate.

The filament is usually of very fine tungsten wire and may be straight, "V" shaped or shaped like a "W." The apexes

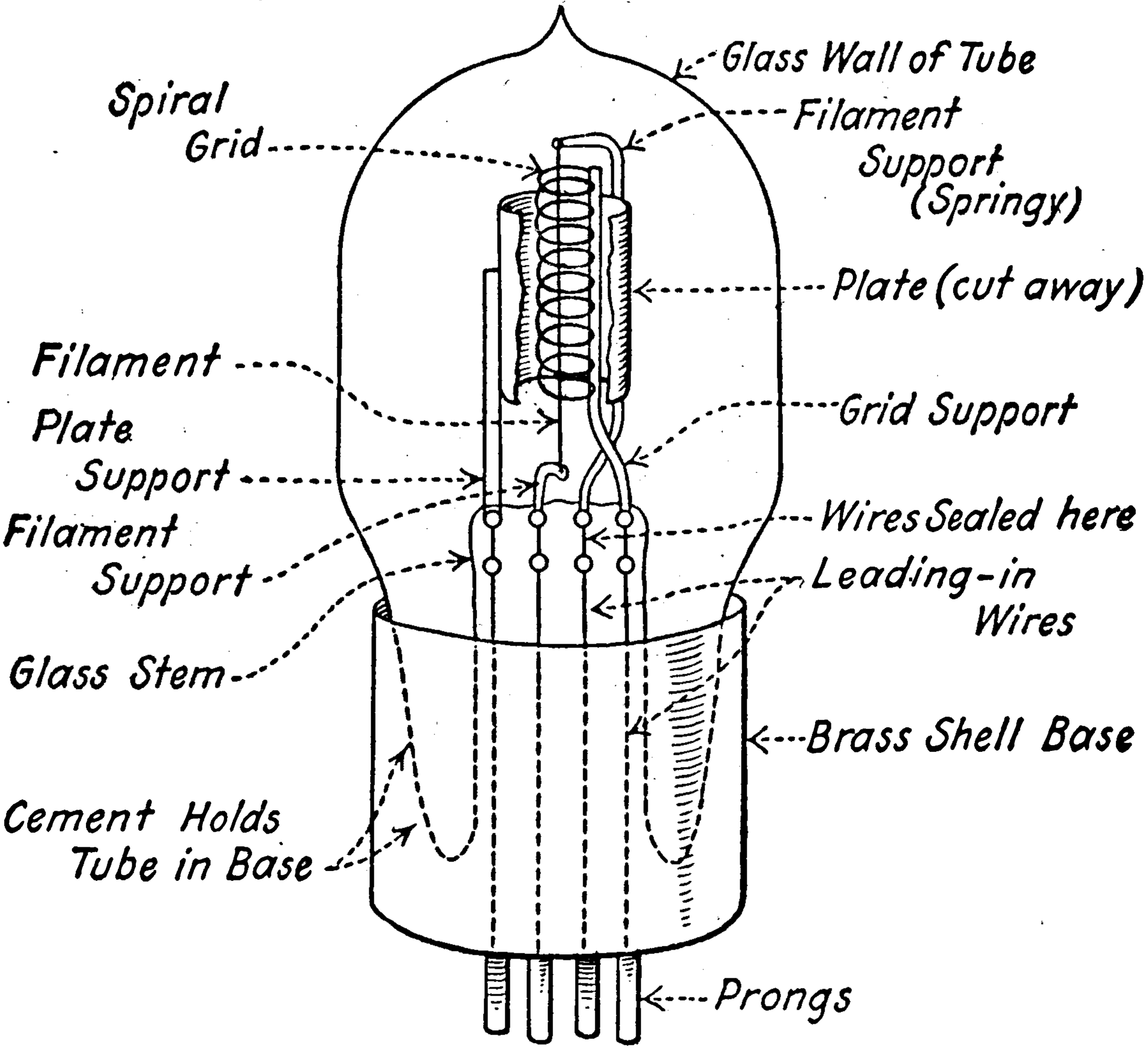

Fig. 12—Construction of a typical vacuum tube.

of the "V" and "W" shaped filaments are upwards. No matter what the filament shape, it is supported in such a manner as to prevent its displacement when jarred. The tube of Fig. 12 has a straight tungsten filament supported at its upper end by a nickle rod, to which it is carefully welded. The lower end of the filament wire is welded to a shorter nickle rod and both rods are anchored into a glass stem. The longer rod is springy, so that it will hold the filament taught.

The grid may be a mesh of nickle wire wound about two supports. In the figure it is shown as a spiral or helix, so supported by a nickle rod that the filament becomes the axis of the spiral. Each turn of the spiral grid is welded to a nickle supporting rod, the lower end of which is anchored into

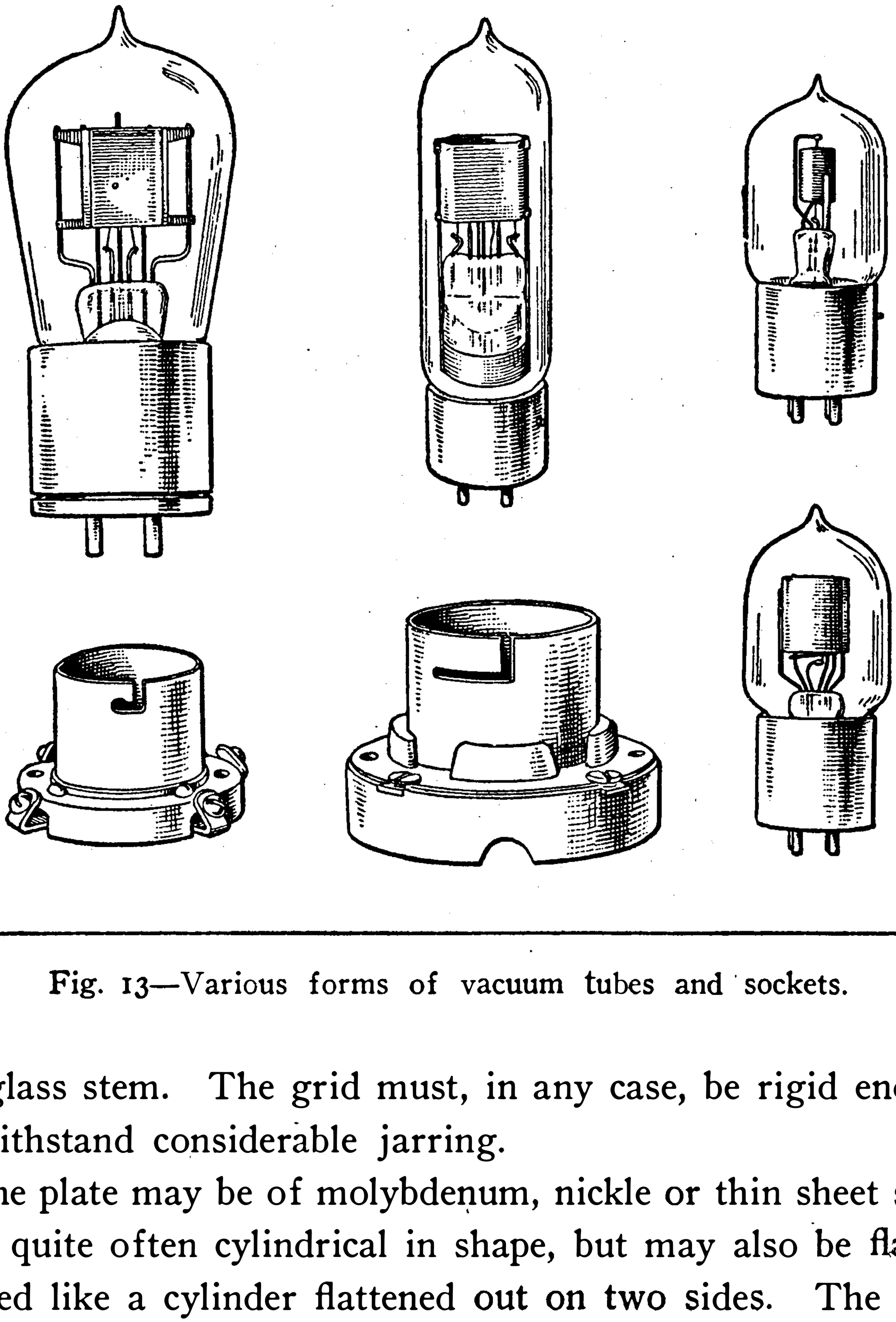

Fig. 13—Various forms of vacuum tubes and sockets.

the glass stem. The grid must, in any case, be rigid enough to withstand considerable jarring.

The plate may be of molybdenum, nickle or thin sheet steel. It is quite often cylindrical in shape, but may also be flat or shaped like a cylinder flattened out on two sides. The plate

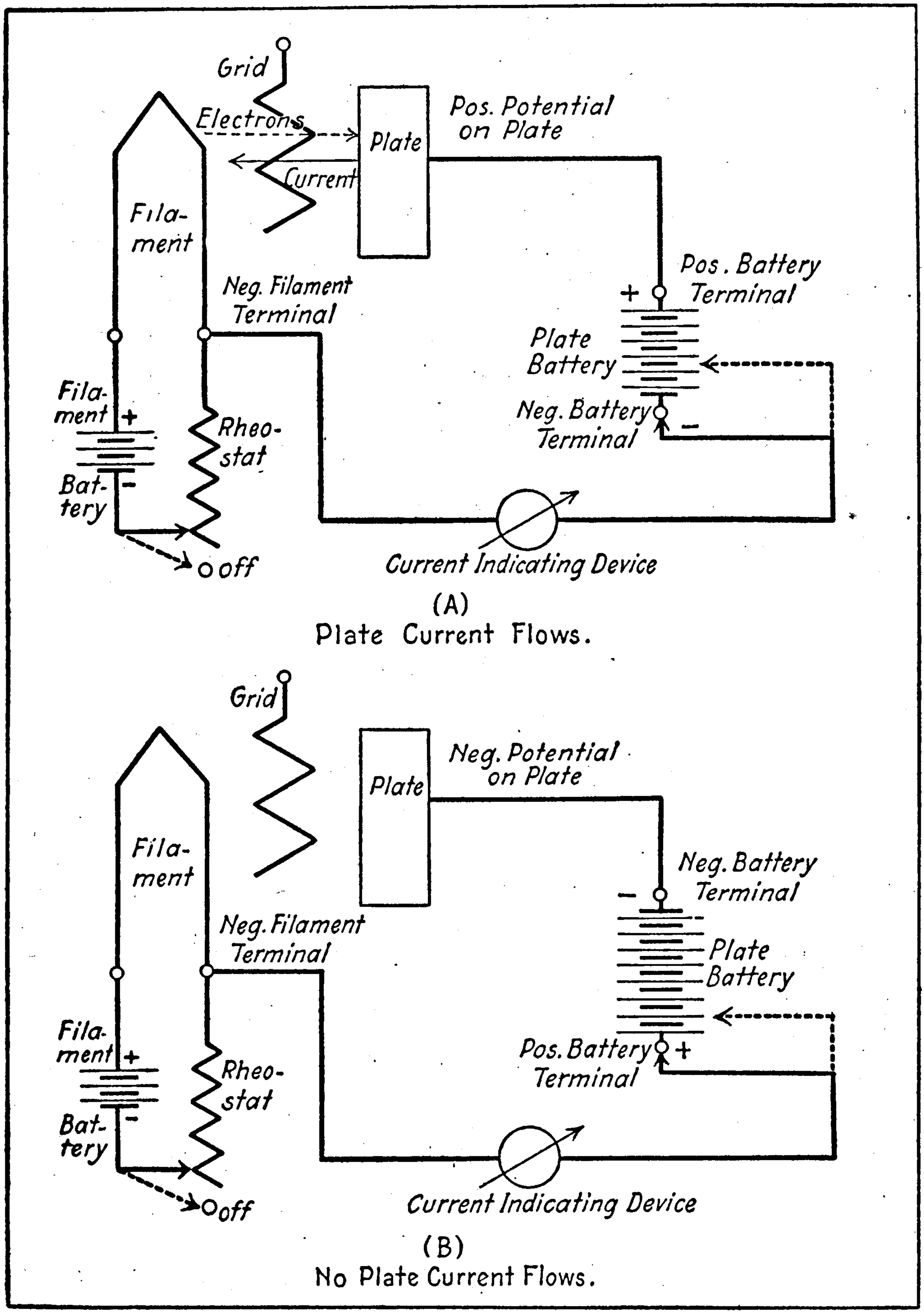

Fig. 14—The Edison Effect or one way conduction of electric current within a vacuum tube.

must also be rigidly supported. In the figure there is a cylindrical plate of nickle so supported by a nickle rod that it encloses the grid and, therefore, the filament. The filament is then the axis of both the spiral grid and the cylindrical plate. The plate support is welded to the plate and the lower end of the support is securely anchored into the glass stem.

There are, then, three members called "electrodes," the filament, the grid and the plate. A vacuum tube is seen to be a somewhat more complicated device than the incandescent electric lamp.

The four prongs which extend below the base of the tube are for connection into a circuit. Each of these is welded to a leading-in wire which connects it to a support. In this manner the two filament ends, the grid and the plate are each connected to a prong. The leading-in wires are very carefully welded to the supports and sealed into the glass stem, so that at no future time may there be any leakage of air into the tube. Air leakage would render the tube unfit for use.

Fig. 13 illustrates a few of the various forms of tubes and some tube sockets or receptacles. When a tube is inserted into a socket, each tube prong makes contact with a spring contact piece which is connected to a terminal binding post. Two binding posts are for the filament connections and one each is for the grid and the plate. This provides a convenient way of holding a tube and connecting it into a circuit.

The Edison Effect

In both Fig. 14-A and 14-B there is a battery called the "plate" or "B" battery connected between the plate and one of the filament leads. In each figure, also, a very sensitive current indicating device is connected into the plate circuit. Current may be allowed to flow through the filament from a

smaller battery called the "filament" or "A" battery. The current flowing through the filament may be controlled by a variable resistance in the filament circuit. This variable resistance is called a "rheostat." Increasing this resistance causes decreased filament current and vice versa. Also, of course, if the filament rheostat is turned off, no current flows in the filament. When there is no current flowing in the filament it is cold, but when current is allowed to flow, the filament is thereby heated to a temperature depending upon the current strength. The filament rheostat may, therefore, be used to control the filament temperature by controlling the filament current.

Suppose that the filament current is turned off (filament cold) and the positive terminal of the plate battery is connected to the plate, as in Fig. 14-A. Observation of the current indicating device shows that no current flows in the plate circuit.

With the filament still cold (rheostat turned off) the plate battery connections are reversed so that the negative terminal of the battery is connected to the plate, Fig. 14-B. Observation again shows that there is no current flowing through the indicating device.

The negative terminal of the plate battery is still connected to the plate and the rheostat is now turned on, allowing enough current to flow through the filament to heat it to incandescence. Observation once again shows no current in the plate circuit through the indicating device.

Now, with the filament still glowing, the plate battery connections are changed back again so that the positive battery terminal is connected to the plate, as in Fig. 14-A. This time there is an appreciable current indicated as flowing in the plate circuit from the positive terminal of the battery to

the plate, across the space within the tube to the filament and back to the battery. This is an interesting state of affairs. A direct current of electricity is flowing from the plate to the filament through the vacuum of the tube. There is electrical conduction between these two points, but only when the filament is glowing and the plate is connected to the positive terminal of the plate battery.

This phenomenon of one way conduction of electric current through a vacuum was noted by Thomas A. Edison and is termed "the Edison effect." Like numerous other discoveries, however, it was not fully investigated and used until some time later.

Electric current always flows or tends to flow from a point of high to a point of low potential. This may be compared to the flow of water down a hill. A point in the stream at the top of the hill is at a higher "potential" than a point in the same stream at the bottom of the bill. In the case of electricity, the high potential point is said to be the point of "positive" potential and the lower potential point that of "negative" potential. An electric current, therefore, flows or tends to flow always from a point of positive to a point of negative potential. When the positive terminal of the plate battery is connected to the plate, the potential of the plate is positive with respect to that of the filament, because current will flow from the plate to the filament, inside the tube, providing the filament is lighted. The glowing filament, in this case, causes the path or circuit from plate to filament to be closed.

Electron Emission from a Heated Filament

The smallest possible particle of negative electricity is called an "electron." The word means "carrier of electricity." An

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with respect to the filament) no plate current can flow because the plate repels the electrons. (Like charges repel). That is, if there are no electrons bridging the space between filament and plate no conduction can take place.

This, then, explains why there is electrical conduction through a vacuum when the filament is glowing and the plate is positively charged and, also, why there is no conduction when the plate is negatively charged or the filament is cold.

Dependence of Plate Current upon Plate Potential

The positive potential of the plate determines the number of electrons which may be attracted to it per unit of time and, therefore, the strength of the plate current. But suppose that the plate potential has been increased up to the point where electrons are attracted just as rapidly as they are shot from the filament into the tube space. A higher plate potential will not be able to attract them in any greater numbers, per unit of time, because it is already attracting them just as fast as they are being emitted from the filament. There is a limit, then, to the increase of plate current with an increase of plate potential. If larger plate current is desired, electrons must be projected from the filament in greater numbers.

The value of the positive potential on the plate depends upon the voltage of the plate battery. Therefore, in view of the foregoing, the plate current increases with the battery voltage only up to a certain point, providing no change is made in the filament current. If the filament current is increased by a certain amount, the plate current increases, with increase in battery voltage, up to a new point, after which no further current increase may be had unless the

filament current is again increased. There is, of course, a limit to the current which may be made to flow through the filament if it is not to be burned out. There is then a final limit to the current which can flow in the plate circuit no matter how high the plate battery voltage may be made. In practice, it is desirable to burn the filament at a moderate temperature and to secure the desired plate current by selecting the proper plate battery voltage. This will lengthen the life of the tube filament.

Dependence of Plate Current upon Filament Current

The rate of electron emission increases, as has been said, with the increase of filament current (increase of filament temperature). If the plate potential is held at a constant value and the filament current is increased, there will be an increase of plate current up to a certain point. The point where no further increase of plate current is had with increasing filament current is that at which the filament is emitting electrons as fast as the plate can attract them. Then, no matter how much faster the electrons are shot from the filament into the tube space, the plate will only attract a certain number of them per unit of time.

If the electrons are emitted at still increasing rates there will be no increase of plate current unless the potential of the plate is raised (plate battery voltage increased) in order that the plate may attract them in greater numbers per unit of time.

If there are more electrons emitted by the filament per unit of time than the plate can attract, some of the electrons in the tube space are continually reaching the plate while others are falling back upon the filament.

Another way of viewing this matter is to consider the

lumped effect of all the electrons in the tube space between filament and plate. Since each electron is a negative charge, the total electric charge in the space is negative. There are, then, two electric charges acting upon the electrons just leaving the filament. One is the positive charge of the plate and the other is the negative charge of the space (negative space charge). If the positive charge of the plate is greater than the negative charge of the space, electrons will be drawn to the plate from the space and others will be pulled into the space (from the filament) to take their places. But if the positive plate charge is exactly neutralized by the negative space charge, this space charge will repel one electron back to the filament for every extra electron projected from the filament into the space. Only a certain number of electrons per unit of time are, therefore, attracted to the plate and the plate current is at maximum value. This is called the "space charge effect."

Suppose that some concrete hypothetical examples are considered. The plate potential is assumed to be at such a positive value (due to plate battery voltage) that it can attract 1000 electrons per second. The filament temperature is low, at the start, and only 100 electrons are emitted from it per second. The 100 electrons are shot into the tube space each second to make the negative space charge at all times equal to that of 100 electrons. The plate charge is greater, however, and pulls electrons out of the tube space at the rate of 100 per second. This corresponds to a certain value of plate current. Now, the filament temperature is increased and 500 electrons are emitted per second. The plate will attract 500 electrons per second and the plate current is increased. The effect of the plate charge is still greater than that of the space charge. The filament temperature is again increased and

to such an extent, this time, that 1000 electrons are emitted per second. The plate now attracts 1000 electrons per second from the space. The effect of the plate charge is now equal to that of the space charge, so that for every electron shot into the space, one is attracted to the plate. But now suppose that the filament temperature is again increased until 1500 electrons are emitted per second. There are now 1500 electrons present in the space each second. The plate can only attract 1000 of them from the space so the negative space charge repels the extra 500 back to the filament. The plate current does not increase, because no matter how many electrons over 1000 per second are emitted, only that number per second are actually drawn to the plate from the space. If the potential of the plate is raised until it is able to attract 1500 electrons per second, the plate current increases until the plate is actually attracting 1500 electrons to it each second. Then the space charge again equals the plate charge and if electrons are emitted at a still greater rate, say 2000 per second, there are still only 1500 reaching the plate per second and the plate current remains constant at the higher value.

Effect of Grid Potential upon Plate Current

It has been pointed out that the grid electrode is located between the filament and the plate of a tube. The grid must then, of course, be situated in the region of the space charge.

If a positive potential is applied to the grid by a grid battery, as in Fig. 15, its potential is positive with respect to the filament and the positive charge thus placed upon the grid neutralizes some of the effect of the space charge. The result is an increase in plate current and the grid may be said to be adding the effect of its positive charge to that of the plate in order to cause more electrons per second to be attracted to the latter. If the positive

charge on the grid is sufficiently increased, however, the plate current ceases to increase because electrons are then being attracted to the plate just as rapidly as possible. A saturation point is then reached. When the grid is positively charged it will also attract some electrons to itself and cause a current to

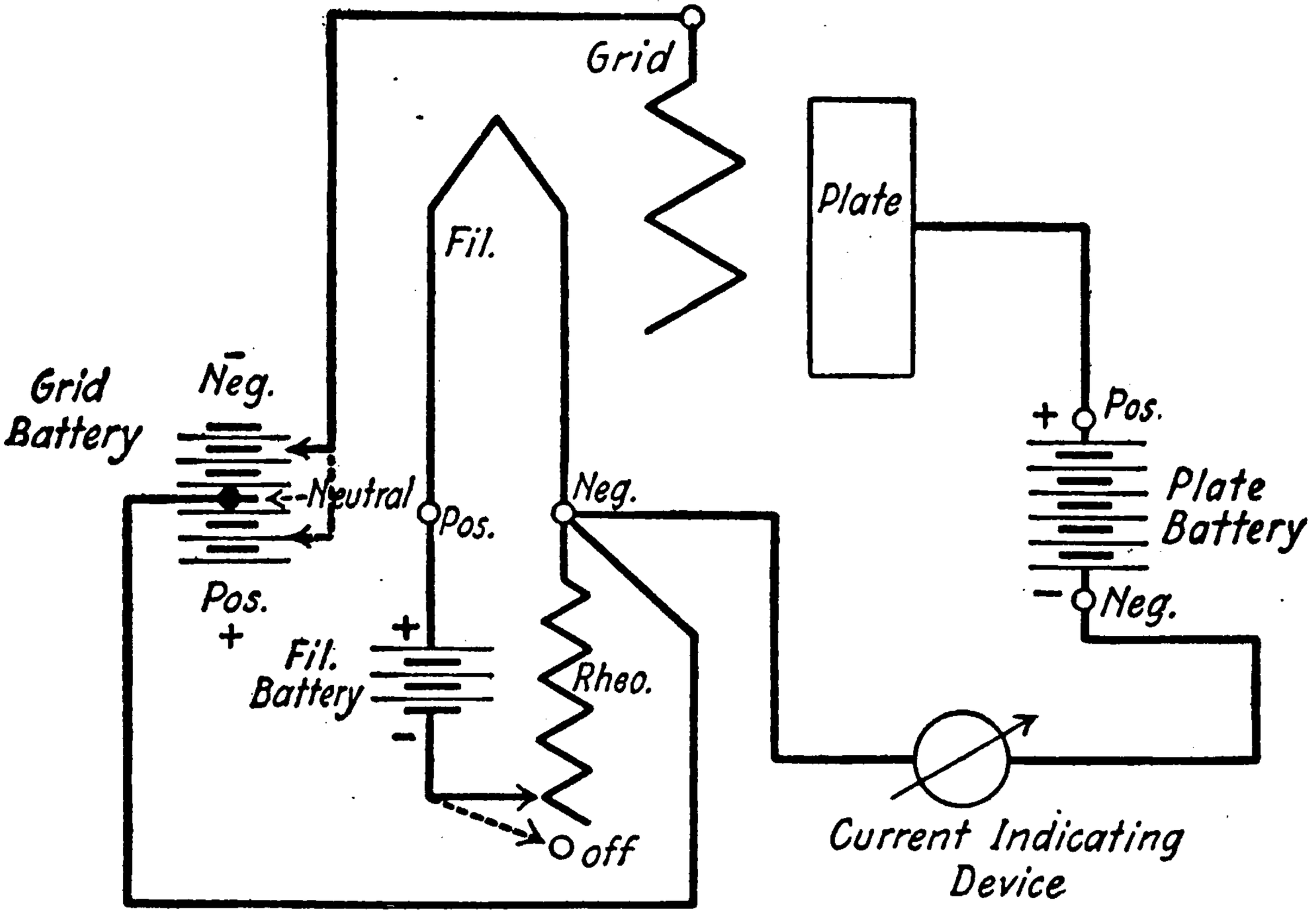

Fig. 15—One method of varying the grid potential.

flow in the grid circuit, from grid to filament inside the tube. This grid current also increases, up to a certain point, with the increase in positive grid potential.

If a negative potential is applied to the grid from the grid battery, its effect will be added to that of the space charge. The result is a decrease of plate current and the grid may be said to be opposing the effect of the plate. When the grid is negatively charged, it repels electrons back to the filament and therefore no grid current flows. Electrons in large numbers may, however, pass through the spaces between the grid wires because of

their high velocity and be attracted by the plate. If the grid potential is too negative it will completely neutralize the effect of the positive plate charge and cause the plate current to be

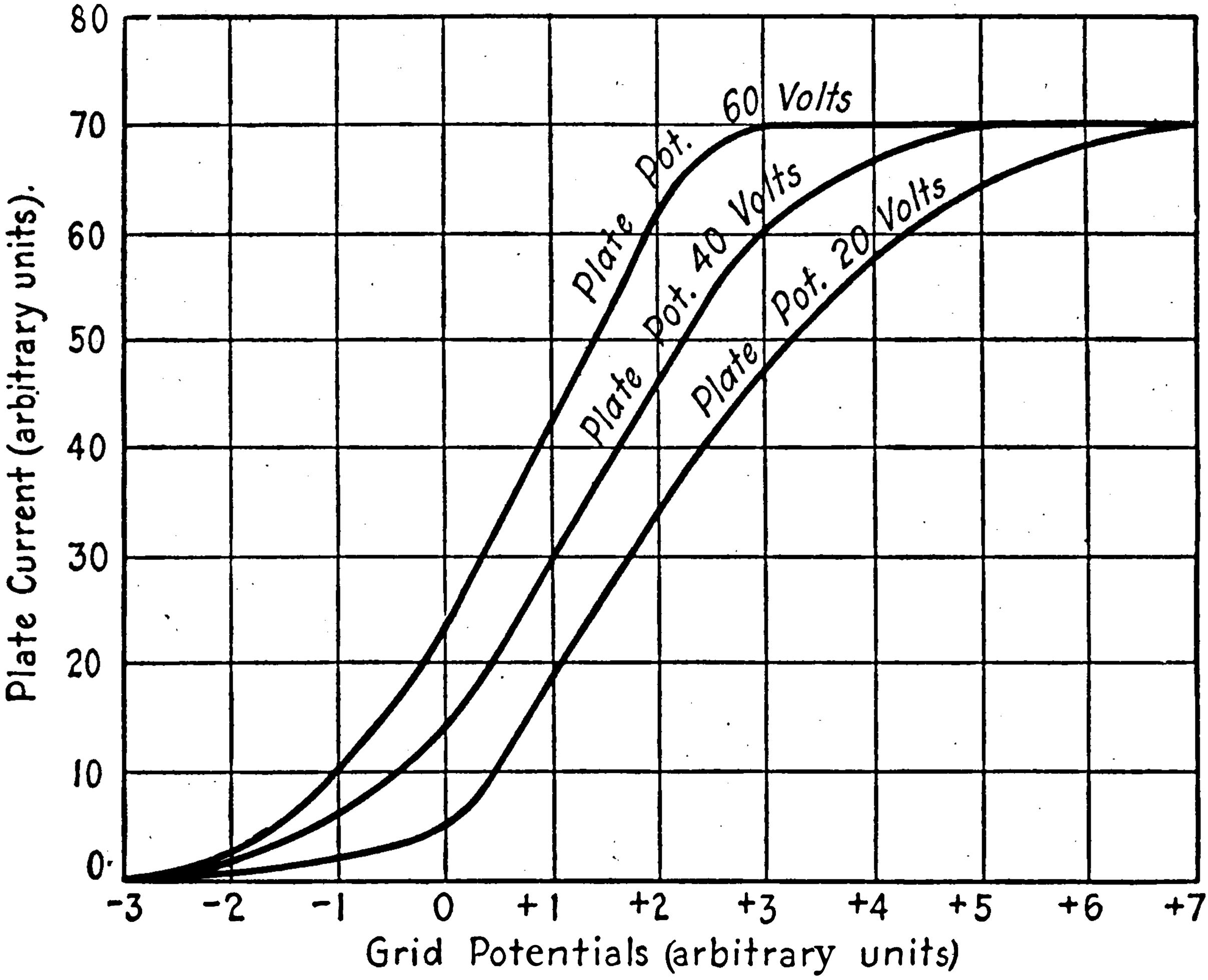

Fig. 16—Characteristic curves of grid potentials and corresponding plate current values.

reduced to zero. This value of negative grid potential is called the "cut-off" potential.

The external portion (part outside of the tube) of the grid circuit is connected at one end to the grid and at the other to the filament. Therefore when potentials are applied to the grid, they are either positive or negative with respect to the filament. That is to say, when a higher potential is applied to the grid than to the filament its potential is "positive" with respect to the filament. The reverse is also, of course, true.

A graph is shown in Fig. 16, which pictures the effect of

various grid potentials upon plate current for three different values of plate potential, the filament current being the same in all cases. It is to be noted that the variation of plate current with grid potential is not linear at all times, but that the "characteristic" graphs are curved at their upper and lower portions. This is a characteristic of vacuum tubes which is very valuable, as will be seen more clearly later on. The graph of grid potentials plotted against plate current is, therefore, called a "characteristic curve."

Relay Action

The action of a grid may be compared to that of a telegraph relay, schematic circuit of which is shown in Fig. 17. The armature of the relay is

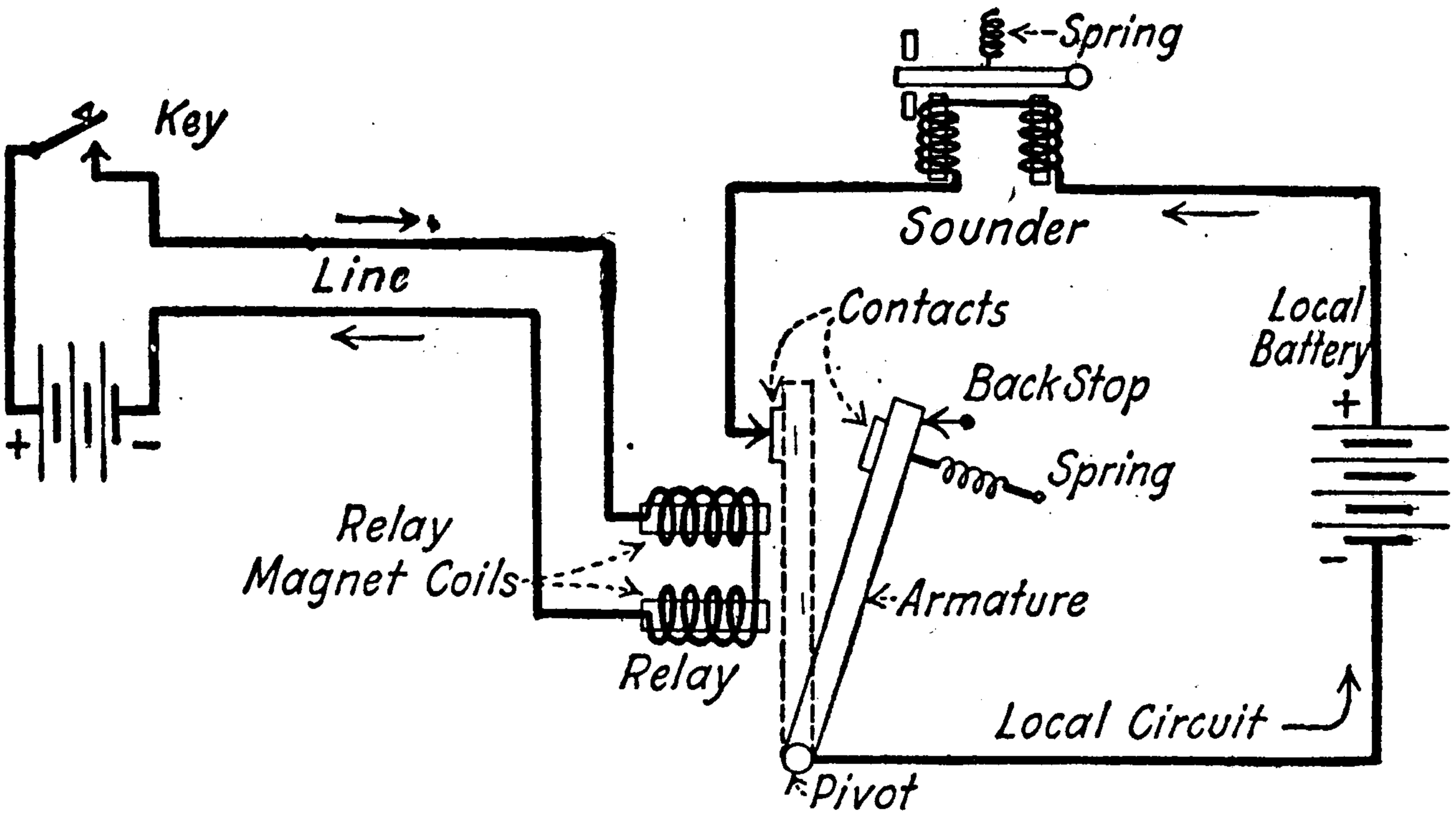

Fig. 17—Circuits of telegraph relay.

magnetically attracted over toward the poles of the electromagnets when the key in the line is closed and current flows through the magnet coils. When the armature is attracted, a

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grid is negative the plate current decreases below the normal. There are variations or alternations of plate current above and below this normal value which are in step with the grid potential variations. Note particularly, however, that the increases are, in this particular case, larger than the decreases. That is, that equal variations of grid potential cause unequal variations of plate current. This being the case, the average value of the

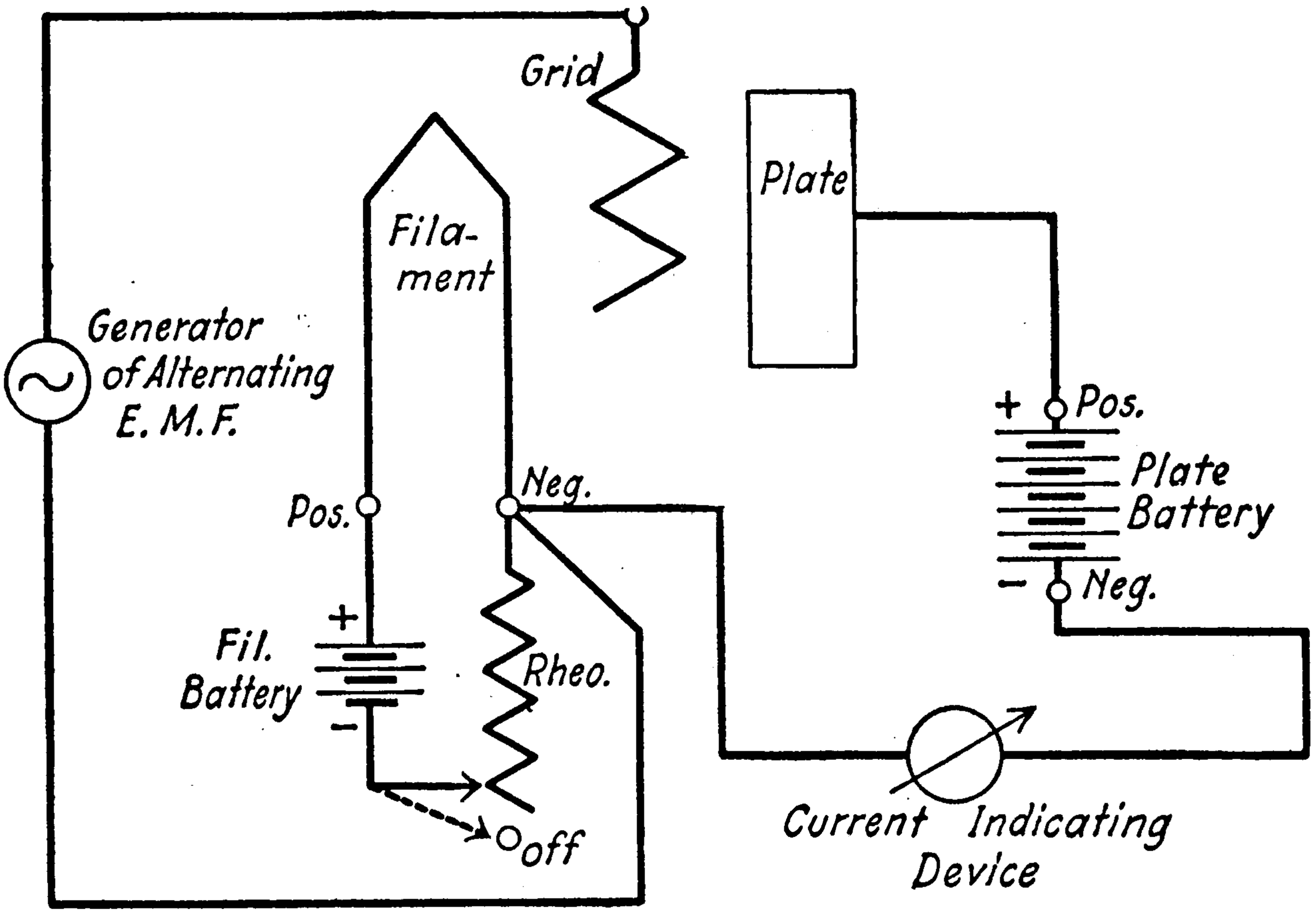

Fig. 18—Continuous variations of grid potentials.

plate current is at every instant greater than the normal value. If the generator were started and stopped periodically this average value would rise when the generator is running and fall back tc normal when the generator is momentarily stopped. There would then be periodical increases and decreases of average plate current in step with the starting and stopping of the generator. As far as this average value is concerned there appears to be what is called a "rectification" of the more rapid plate current variations. This is "apparent recti-

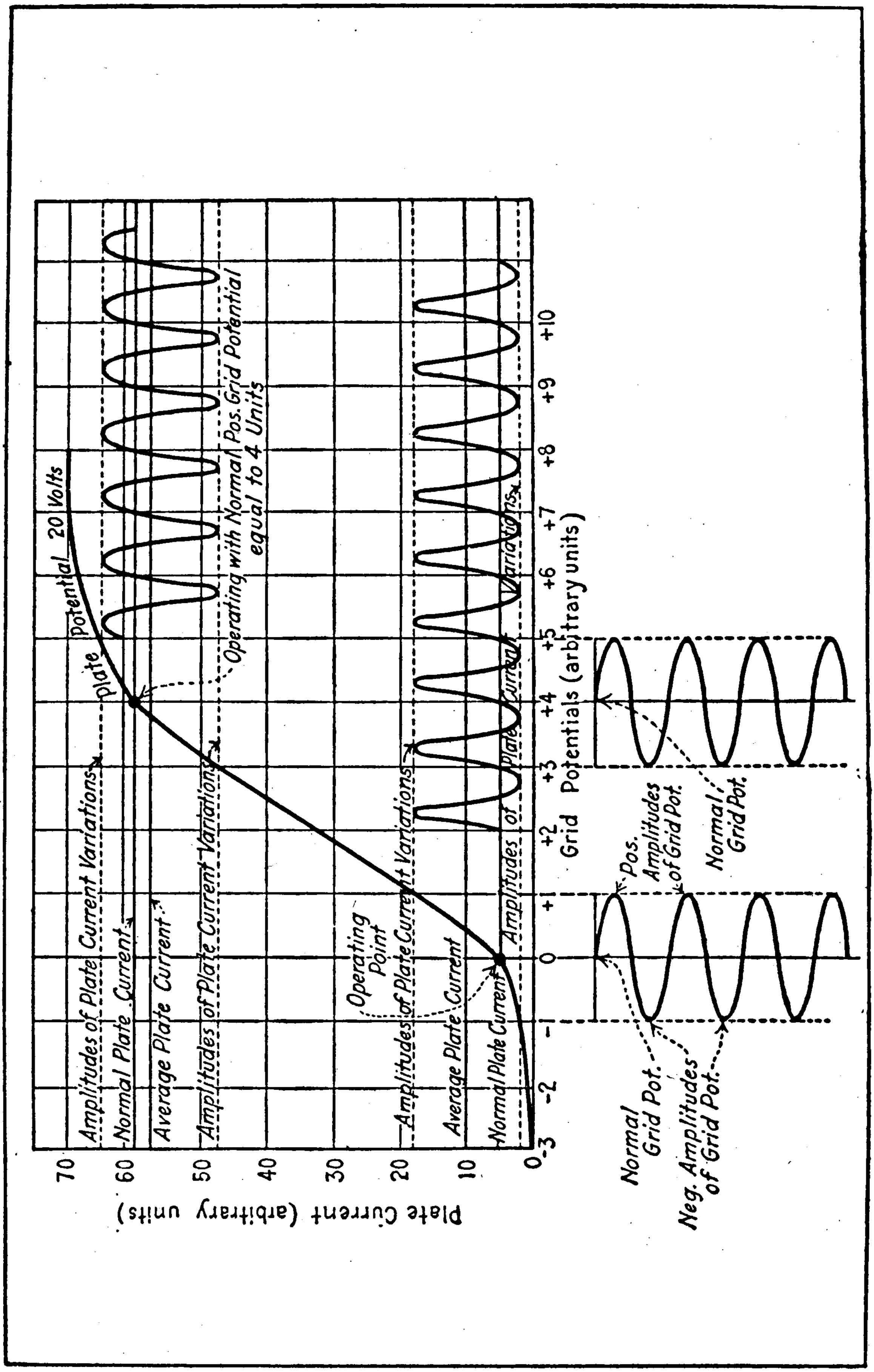

Fig. 19—Variations of plate current with variations of grid potential.

fication" of the plate current. Coincident with this action there is also an actual rectification of the grid current. That is, when the grid receives a positive charge from the generator it attracts electrons to itself and a current flows in the grid circuit. But when the grid receives a negative charge it repels electrons and no current can flow in the grid circuit. The action of the grid therefore changes the alternating current which would otherwise flow under the influence of applied alternating E.M.F. into a pulsating current. This is *actual* rectification.

If, by means of a grid battery (Fig. 20), there is a certain normal positive potential applied to the grid, the normal plate

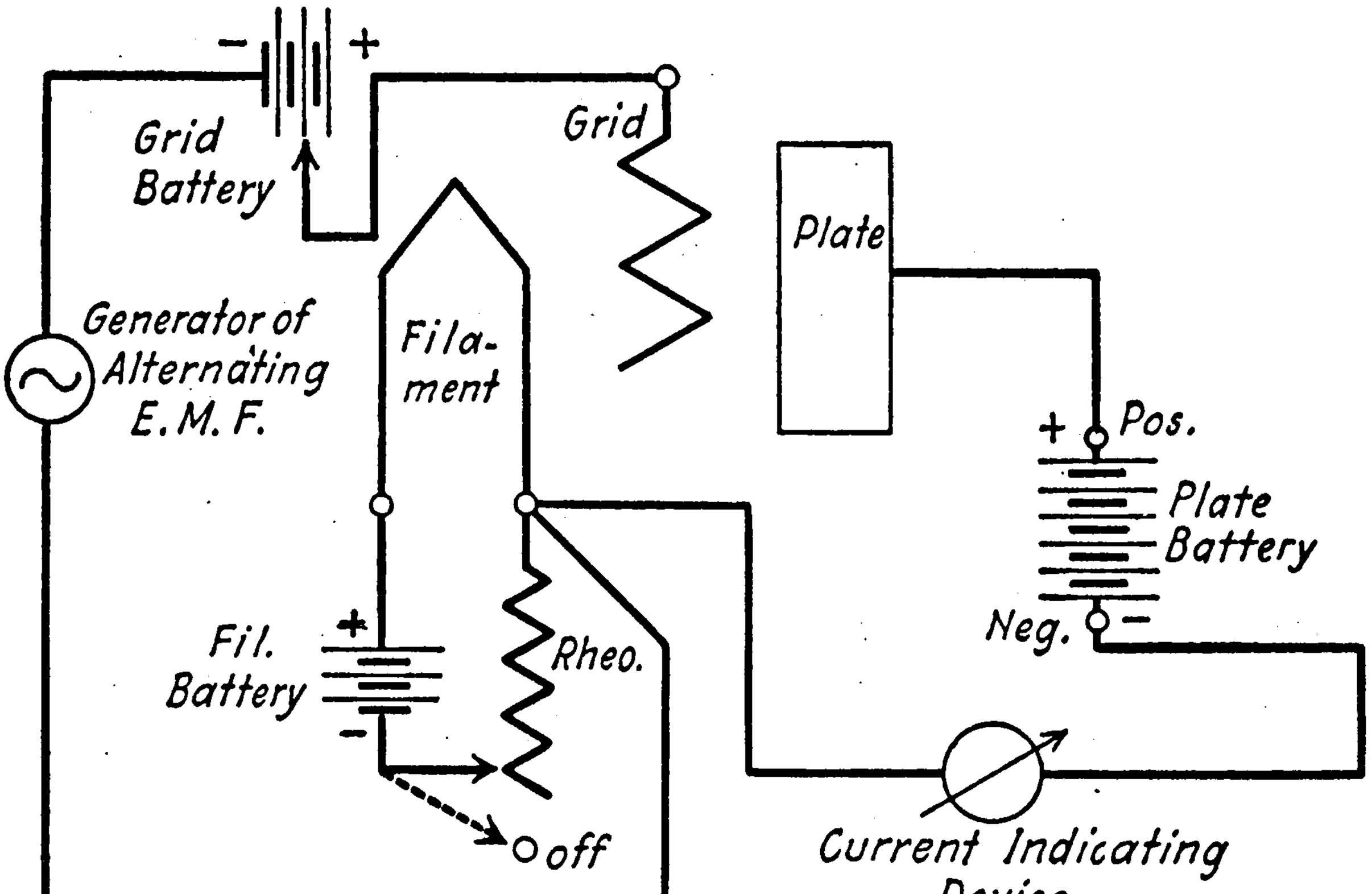

Fig. 20—One method of applying a desired normal grid potential.

current is increased to a greater steady value. In this case the same equal variations of grid potential produced by the generator alternately increase and reduce the positive potential

on the grid. This again causes unequal variations of plate current above and below the new normal value, but the decreases are greater than the increases. The variations are, however, still in step with the grid potential variations. Since a grid current is always flowing, there is no actual rectification of grid current but only an apparent rectification. There still is, nevertheless, apparent rectification of the plate current. It is interesting to note that both the more rapid variations of plate current and the slower variations of average plate current may take place in the circuit at the same time if the generator is periodically started and stopped. Under favorable conditions currents of both the higher and lower frequencies may flow in the plate circuit.

It is a characteristic of vacuum tubes that the increase and decrease of plate current with variations of grid potential is not linear. This has been previously mentioned, but it may be pointed out here that this very characteristic may be made use of in operating the tube as a rectifier. Straight lines drawn to indicate values of grid potential and plate current are seen, in Fig. 19, to cross each other on the graph indicating the relation between the two. If two such lines are drawn to indicate the normal grid potential and the coincident normal plate current, the point where they cross on the characteristic curve may be called the "operating point," since variations in both take place about this point. It is obvious, therefore, that the operating point may be shifted at will by the application of the required normal grid potential.

In order to secure apparent rectification of plate current variations it then becomes necessary to have the operating point on either the upper or lower bend of the characteristic curve. It is most always brought to the lower bend to avoid grid current flow and very high values of plate current which add nothing

to the efficiency of the tube, but actually result in poorer operation.

With the characteristic curve of Fig. 19 a grid current will flow in the tube at certain times because the grid potential is allowed to become positive periodically even though the operating point is on the lower bend of the curve.

All tubes, however, do not have the same characteristics and in some cases it might be necessary to apply a normal negative potential to the grid to bring the operating point to the lower bend of the curve. If, then, the applied alternating potentials never exceed this value of negative potential, no grid current will flow at any time. There is no rectification of grid current, but there is still apparent rectification of plate current.

In the next chapter the practical application of the rectifying action to radio reception is brought out.

CHAPTER III

THE VACUUM TUBE DETECTOR

The telephone receiver—Simple detection—Detection with grid condenser—Effect of gas in a detector tube—Heterodyne action or the production of beats.

The Telephone Receiver

When ether waves are produced at a distant transmitting station and, in turn, cause oscillating electric current to flow in a receiving antenna, it is necessary to provide some kind of an indicator which will make the presence of these oscillations manifest to one of the senses. It is customary to translate these

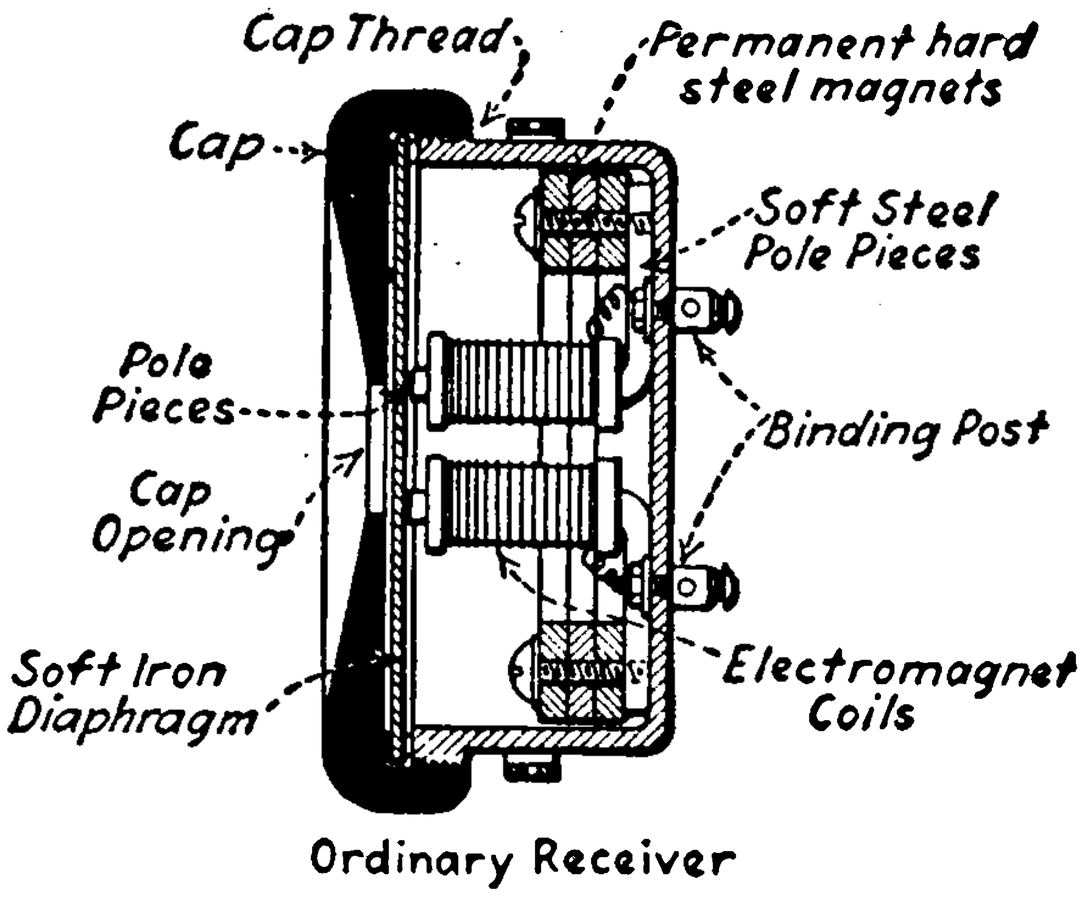

Fig. 21—Construction of a typical telephone receiver.

oscillations into audible sound so that signals may be perceived by the sense of hearing. A telephone receiver, the construction of which is shown in Fig. 21, has two coils of wire, each wound in many layers around an iron core to produce two electro-magnets. A metal diaphragm is so supported that it may be attracted by the magnet poles or released, depending upon the strength of magnetism in the poles. An increase of

electric current through the magnet windings causes the diaphragm to be attracted and a decrease of current causes it to be released, because the strength of magnetism is thereby increased and decreased. If the diaphragm is attracted and released periodically it is caused to vibrate, and if the mechanical frequency of vibration (number of attractions and releases per second) is somewhere between 15 and 15,000 vibrations per second, the air waves thereby created will produce audible sound in the human ear. The more rapid the vibrations are, the higher the pitch of the sound which is produced. The telephone receiver is a very sensitive indicator or translator and is very extensively used in radio work for this purpose.

Simple Detection

In Fig. 22 there is an antenna circuit containing a coil and a condenser, both of which are variable to provide for the tuning of the circuit. The opposite terminals of the coil are connected to the grid and filament of a vacuum tube as shown. Suppose that continuous oscillations are present in the antenna and, therefore, flowing in the coil. If the antenna is in resonance with a transmitting antenna, these oscillations will be of maximum amplitude and will set up radio frequency oscillations of potential at the coil terminals, which will also be of maximum amplitude. Now, the coil terminals are connected to grid and filament so that the oscillating potentials must be applied to the grid and filament of the tube. The oscillating potentials at the coil terminals have now replaced the alternating E.M.F. produced by the generator of Fig. 18, and their frequency is very much higher than the alternating E.M.F. then considered. The plate current variations now take place at radio frequency instead of at the frequency of generator

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ance of an ordinary telephone receiver winding is very high indeed to currents of radio-frequency. The current that does flow through the receiver windings is the average value of direct current in the plate circuit. In the case under consideration this average current is higher than the normal value and remains constant so long as the amplitudes of the antenna oscillations do not vary. Therefore, when unmodified undamped waves are radiated by a transmitting station no sound is produced in a telephone receiver at the receiving station with a simple detector circuit.

Suppose, however, that damped waves are radiated by the transmitting station. In this case it will be remembered that there are groups (or trains) of oscillations produced in the receiving antenna, each composed of radio frequency oscillations whose amplitudes decay from a maximum value to zero periodically. The grid and filament circuit of Fig. 22 then being still connected across the antenna coil, radio-frequency potential variations are applied to the grid, whose amplitudes decay from a maximum to zero during each group of oscillations, as shown in Fig. 23. As also shown in the graph of this figure, the radio-frequency plate current variations also decrease in amplitude during each group or train of oscillations and there is a variation in the average plate current which rises and falls once for each oscillation train. If the frequency of the oscillation trains is within the limits of audibility (15 to 15,000 per second) the frequency of the variations of *average* plate current is also an audible frequency or, as it is called, an "audio-frequency." Current variations of such comparatively low frequency pass through the receiver windings and cause the diaphragm to vibrate and to produce sound waves of the same frequency which, being audible, are heard by the human ear. The sound heard depends then upon the frequency of the oscil-

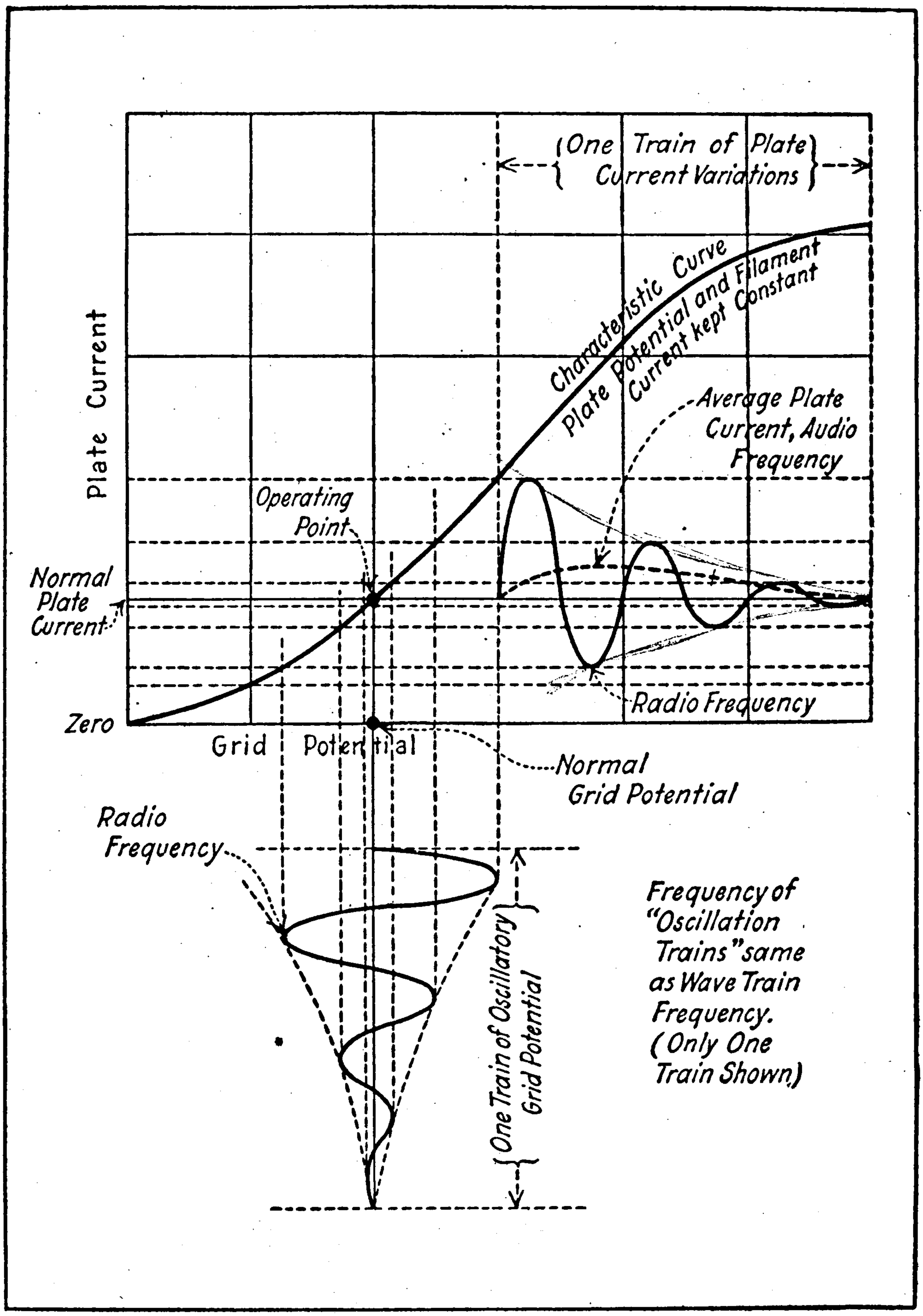

Fig. 23—Rectification effect in plate current with damped grid potential variations.

lation trains and increases in pitch with that frequency. Suppose a case in point is considered. There is a transmitter at a distant station which creates in the transmitting antenna oscillations whose frequency is 1000 per second. The transmitter could be a 500 cycle synchronous rotary gap or quenched gap spark transmitter. Ether wave trains are set up whose frequency is also 1000. These ether waves cause trains of oscillations in the receiving antenna, variations of average plate current, receiver diaphragm vibrations and, finally, sound waves, all of the some frequency, 1000 per second. If the distant transmitter were a 240 cycle set, ether wave trains of 480 per second would be created and the frequency of the sound waves produced by the receiver diaphragm would be 480 per second. The pitch of the tone would be higher in the first case than in the second, although both tones would be musical. Damped oscillations, being modified radio frequency oscillations, produce audible sound in a telephone receiver.

If the undamped oscillations generated by a transmitter are modified by auxiliary apparatus in such a manner as to vary the amplitudes of the radio-frequency oscillations at an audio-frequency rate (frequency with the limits of audible sound), air waves of the same audible frequency will be produced by the receiver diaphragm. The radio-frequency oscillations are molded into groups and that group frequency is selected which will give the most pleasing pitch of tone in the telephone receiver. Such a process of molding is called "modulation." Fig. 24 illustrates the effect of modulated continuous oscillations in a simple detector circuit. The group frequency is maintained at a constant value, usually, so that the tone does not change at any time. Different transmitting stations may, however, select different group frequencies and therefore produce tones in a receiver which differ from each other. A trans-

mitting station can then often be identified by its tone frequency.

A radio-telephone transmitter must use a generator of continuous radio frequency oscillations but, in this case, the radio

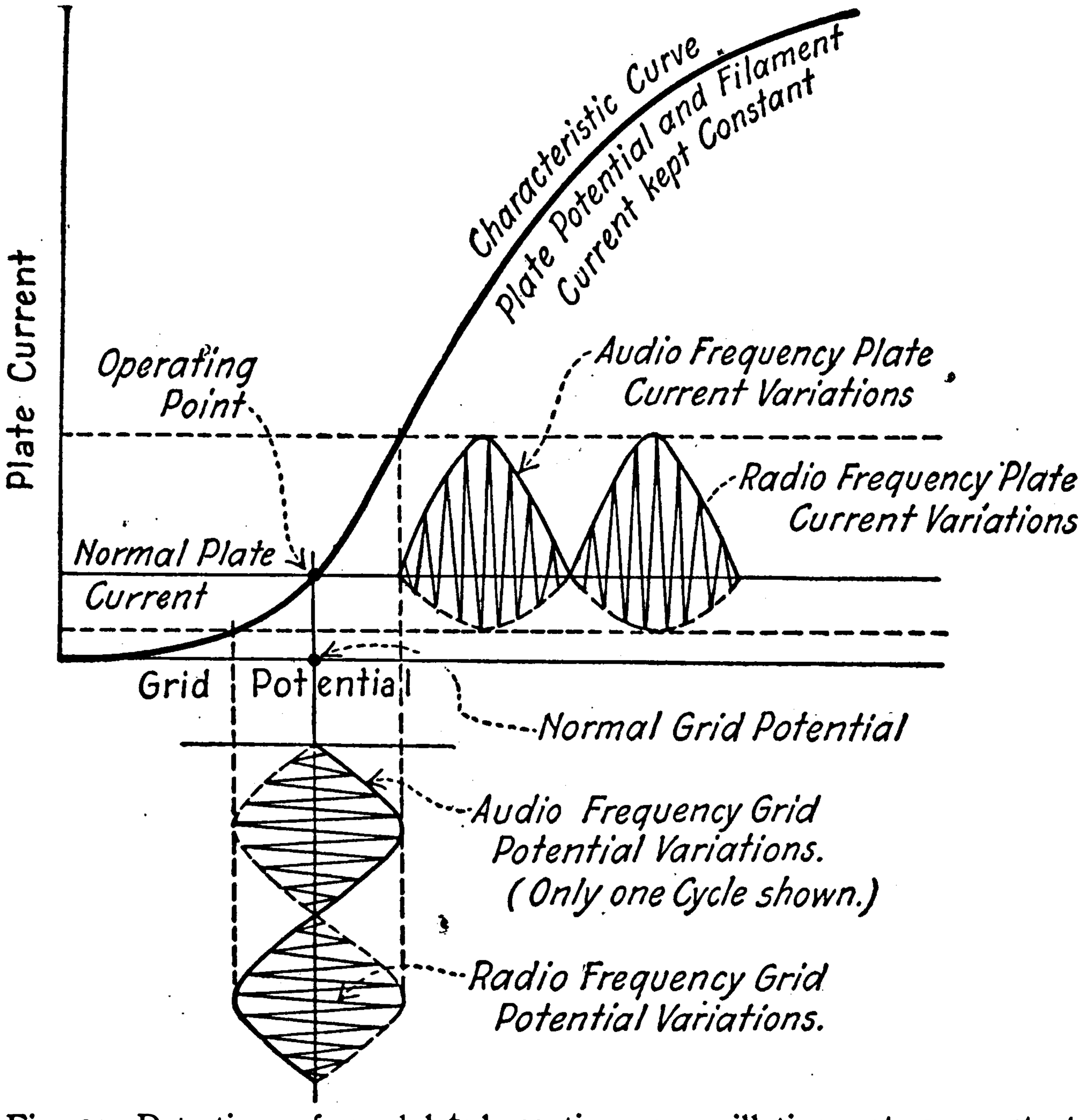

Fig. 24—Detection of modulated continuous oscillations at a constant group frequency.

frequency current amplitudes are not always varied at the same audible frequency as is usually the case with modulation for telegraphic purposes. The frequency of the sound waves created by the human voice averages around 800 per second, but constantly increases and decreases with the pitch of tone. Every change in inflection of the speaking voice and every change in

tone of the singing voice means a change in the frequency of the air waves created. In the case of music produced by various instruments, every change in tone also means a change in air wave frequency. In the operation of a radio-telephone transmitter, devices are provided which will cause the originally generated undamped radio frequency oscillations to be molded or modulated constantly in amplitude at constantly varying tone frequency. The constant changes in tone (group) frequency therefore produced in the receiving antenna cause constantly varying changes in the current flowing through a telephone receiver of the simple detector circuit. The result is, of course, air waves and sound created by the receiver diaphragm of constantly changing frequency in step with the frequency of the sound waves acting upon the distant transmitter. Fig. 25 gives an idea of how this is accomplished in the receiving circuits.

In all of the above considerations it is, of course, understood that the receiving antenna must be tuned to the radio frequency oscillations no matter what the group or tone frequency may be.

Detection with Grid Condenser

In the case of simple detection there may be actual or apparent rectification of grid current, depending upon the normal grid potential. If a small condenser is connected into the grid circuit close to the grid, however, the rectification of grid current is actual. There is also apparent rectification of the plate current variations. The mode of functioning is somewhat different, however, when a grid condenser is used.

Assume that, due to resonance with a transmitting antenna, there are damped radio frequency oscillations of maximum possible amplitudes induced in the receiving antenna. Radio

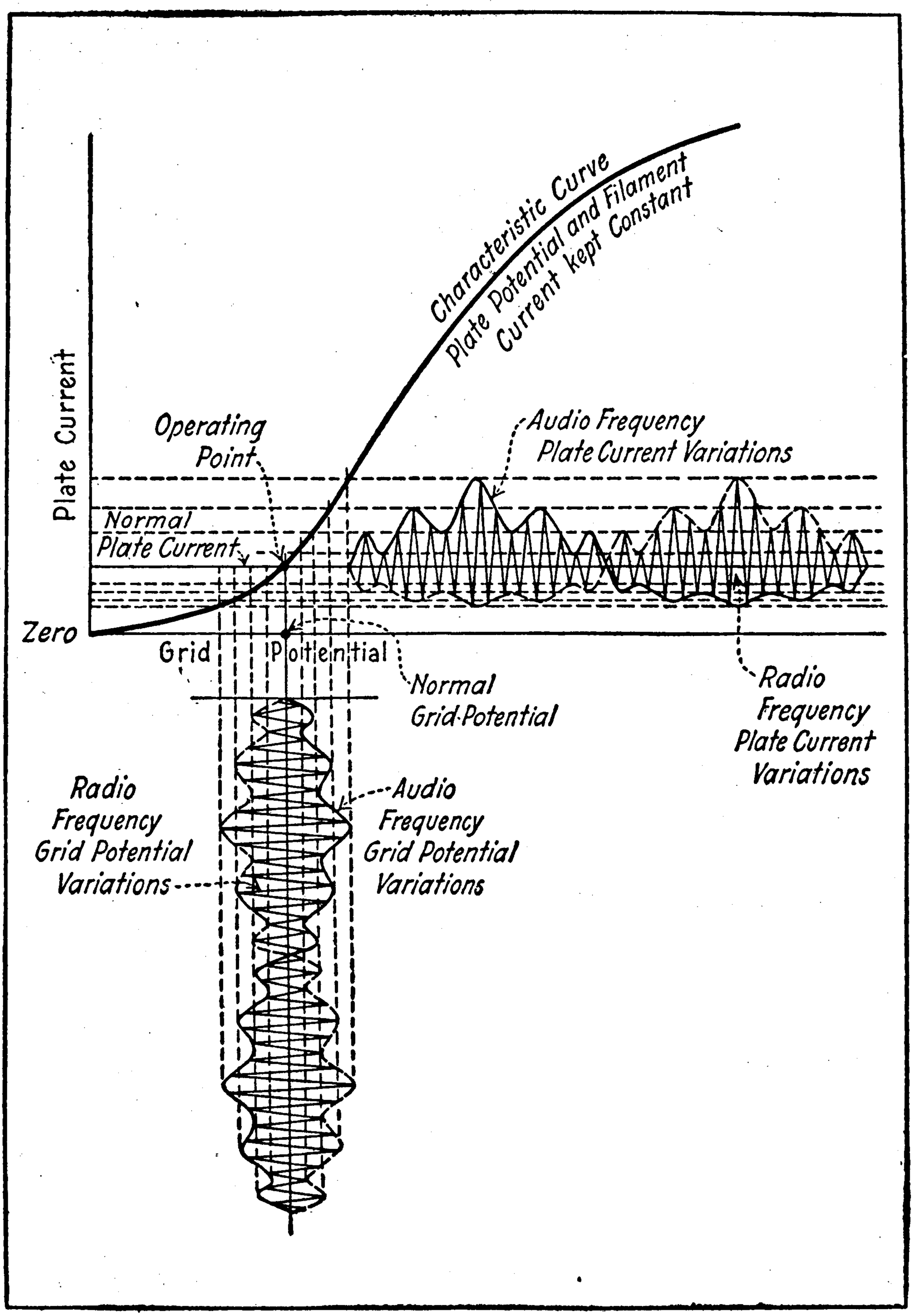

Fig. 25—Detection of voice modulated continuous oscillations at a varying group frequency.

frequency alternating potentials are applied to the grid through the grid condenser. When the grid receives a positive charge from the circuit it attracts electrons to itself, a grid current flows and the plate current is momentarily increased, since the operating point is now assumed to be on the straight portion of the curve. (Fig. 26). The grid then receives a negative charge, repels electrons, no grid current can flow and the plate current is reduced. But, when the grid was positive and electrons were attracted to it these electrons were trapped on the grid because of the "blocking" action of the grid condenser. When, during succeeding alternations of the applied potential, the grid receives a positive charge more electrons are attracted to the grid and are trapped. During one group of oscillations then, the grid accumulates electrons, its negative potential increases and the average plate current decreases. (Electrons are negative charges.) It may be pointed out here that the normal potential of the grid with respect to the filament is always zero. During a group of oscillations the negative charge on the grid is built up to a comparatively large value and, unless the charge leaks off of the grid, the grid potential will not be zero at the beginning of the next group of oscillations. During the group of oscillations just considered the operating point has slid down the characteristic curve. If this negative grid charge does not entirely leak off, the next group of oscillations will cause the negative grid potential to increase and the operating point to slide still further down the curve. It is obvious that the cut-off grid potential might be reached and the plate current stopped entirely. When this happens the tube is said to be "blocked" or "choked." It is paralyzed until the grid charge is allowed to leak off, for example by placing the fingers on the grid terminal. It is quite necessary, therefore, to provide a path

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through which the negative charge may leak when it becomes large, so that the grid potential may be returned to zero and the plate current to normal in time for the next group. This may be accomplished by connecting a resistance called a "grid leak resistance" across the grid condenser terminals or directly between the grid and the filament. The value of resistance must be high enough to prevent any great flow of current through it until the maximum charge has accumulated upon the grid. It should not be too high, however, because the charge would not then leak off quickly enough, but might accumulate until it leaks off through the glass walls of the tube, the dielectric of the grid condenser or the vacuuous space between filament and grid. This might cause a thumping noise in the telephone receiver.

In the next section tubes containing gas are described. If such a tube is used as a detector the negative grid charge may leak from the grid to the filament because of the comparatively good conducting path then offered. If the gas content of the tube is high enough no grid leak is necessary. Modern gas content tubes, however, usually require a grid leak resistance when used with a grid condenser.

In Chapter V various practical circuits are described which show the schematic connections of grid condensers and grid leaks. No grid battery is ever needed with a grid condenser. The rectification of plate current oscillations does not depend entirely upon the location of the operating point because it is the cumulative effect of the negative grid charge which causes the plate current decrease during each group of oscillations. As a matter of fact, however, it is desirable to have the normal operating point on the straight portion of the curve so that the decrease of grid potential caused by accumulation of negative charge will produce the greatest

possible change in plate current. Reference to Fig. 26 will make all these points more clear.

The effect of the grid condenser does not change the relation between the group frequency of the antenna oscillations and the group frequency of the plate current variations. The latter is still the same as the former and the frequency of air waves (pitch of sound) is still the same as the group frequency of oscillations in the antenna circuit. The detector with grid condenser may be used for the reception of damped waves, modulated undamped waves for telegraphic purposes or voice modulated undamped waves as in radio-telephony. Later on it will be shown how straight undamped waves may also be detected by modifying the radio-frequency oscillations in the receiving circuit.

Effect of Gas in a Detector Tube

Under "Tube Construction" in the preceding chapter it was stated that some tubes, called "soft" tubes, contain a small amount of gas. This gas is rarefied, of course, since the vacuum within the tube is still comparatively high, although not as perfect as it might be made. Electrons are not matter in any shape or form, but gas is most certainly a form of matter. Therefore if there is gas within a tube, the tube space is not absolutely devoid of matter, except for the electrodes, but has matter between the filament, grid and plate. Its action also cannot, therefore, be exactly like a very high vacuum, or "hard," tube.

The smallest possible particle of gas is called an "atom." It is too small to be seen but, nevertheless, has weight because it can be acted upon by gravity. Electrons do not have weight because they cannot be acted upon by gravity. Each atom of gas has a central nucleus which carries a positive charge of elec-

tricity. This nucleus is surrounded by electrons (negative charges) so that, normally, the sum of all the negative charges of the electrons equals the positive charge of the central nucleus. If an electron projected at high velocity from a filament collides with an atom of gas, it may very easily cause one or more electrons to be torn away from the atom. When such a thing occurs, the positive charge of the atom over-balances its remaining negative charges and it acts like a positive charge of electricity. In this condition it is called an "ion." That is, an atom is known as an "ion" after it has lost one or more electrons. It is quite conceivable that if there are thousands of electrons projected from the filament per second, all at high velocity, many collisions might take place between them and the gas atoms. Many ions would then be created. Such action is called "ionization by collision." Now, under the influence of a positively charged plate, the electrons emitted by the filament and those set free by collision move toward the plate and are attracted to it at a rate depending upon its potential. The ions are repelled by the plate toward the filament. Suppose that electrons are not projected in sufficient numbers per second from the filament to equal the rate of attraction of the plate. If additional electrons are produced by collision, they may make up the deficiency and cause the plate current to be increased without the increase of filament temperature. Care must be taken, however, to keep the plate potential below the value which causes too large plate current. When too much plate current flows there will be a visible blue glow inside the tube and the plate current will not be appreciably affected by the grid potential variations. The result is very erratic action of the tube and a decrease in volume of sound from the telephone receiver. The "soft" tube is more sensitive as a detector than the "hard" tube, but it has its disadvantages.

The most marked disadvantage is probably the critical adjustment of filament temperature and plate potential necessary to satisfactory operation. Another is the shortened life of the tube caused by the bombardment by the comparatively heavy ions which are driven against it when they are repelled by the plate.

Heterodyne Action, or the Production of Beats

It has been pointed out that unmodulated (unmodified) undamped radio frequency oscillations will not produce sound in

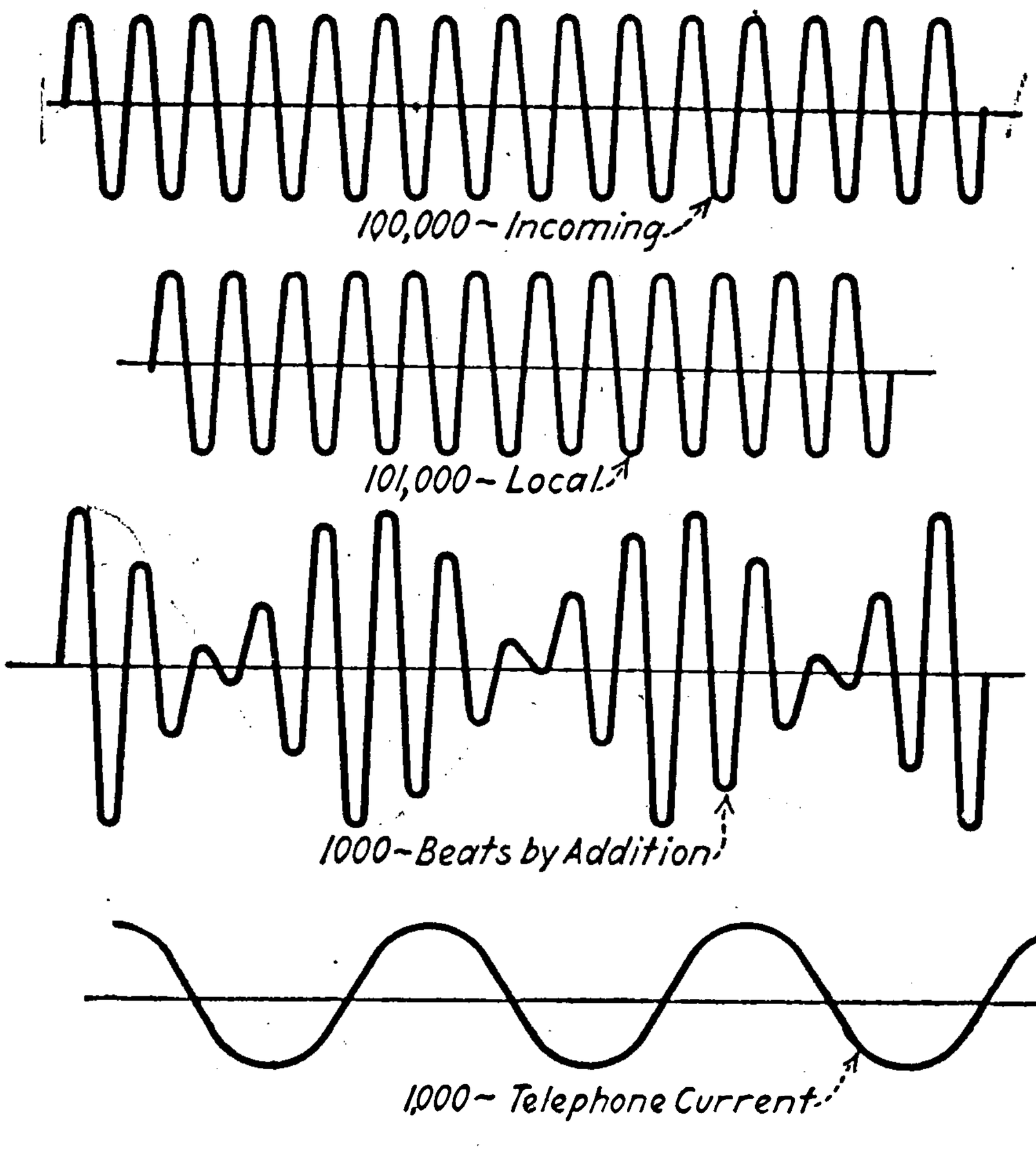

Fig. 27—The principle of heterodyne action.

a telephone receiver. If, however, oscillations of a different frequency are generated locally and forced to flow in an antenna circuit there is an interaction between the two frequencies which produces oscillations of a third frequency equal to the numeri-

cal difference between the other two. The third frequency must then, of course, be lower than either of the other two. This action is called "heterodyne action" and the oscillations of the third and lower frequency are called "beats." The curves of Fig. 27 show this graphically. There are, in this case, oscillations induced in the antenna circuit (by a distant transmitter) whose frequency is 100,000 cycles per second and oscillations

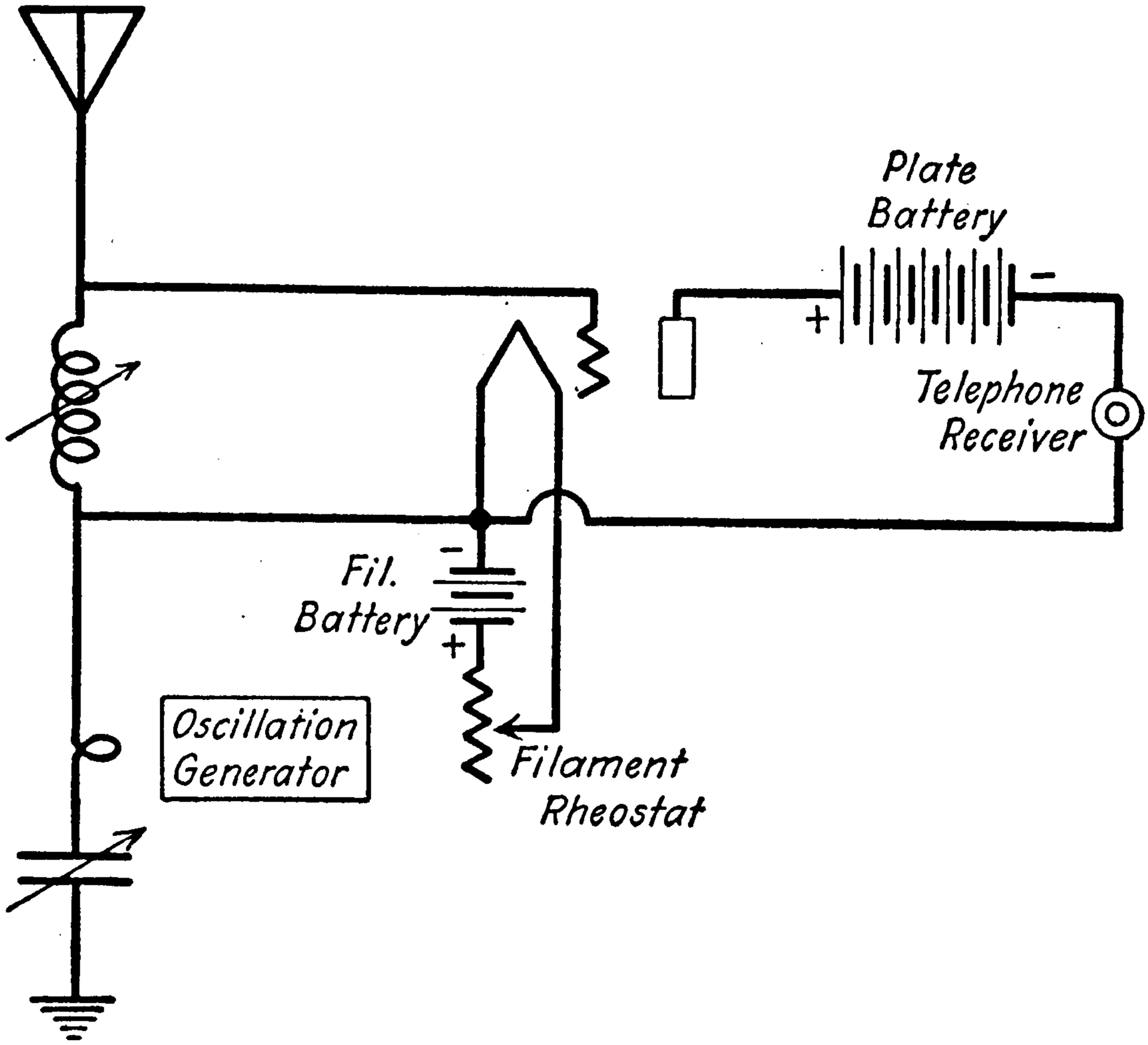

Fig. 28—Schematic circuit for the production of beats.

produced by a local oscillation generator whose frequency is 101,000 cycles per second. Both are radio frequencies and neither by itself produces any audible response in the telephone receiver. Now, the local oscillations are forced to flow in the antenna circuit although the latter is not tuned to them. This is because of a strong inducing action of the local generator upon the antenna circuit. The amplitude of the forced oscilla-

tions (of 101,000 cycle frequency) in the antenna circuit is not maximum, but that makes no difference. The frequency of the third set of oscillations in the antenna circuit is 1000 cycles per second (within the limits of audible sound) and will cause the average plate current to vary or pulsate 1000 times per second and the telephone receiver diaphragm to vibrate at the same frequency. The sound waves produced are, then, at the rate of 1000 per second and the same tone is heard as would be if the transmitter at the distant station were a 500 cycle spark set. In this manner the undamped waves are modified by heterodyning at the receiving station and made to produce an audible response in the telephone receiver.

Various schematic circuits are illustrated in a following chapter, which show how connections may be made to produce this heterodyne action. The local oscillations may be generated by an entirely separate generator, as in Fig. 28, or the detector circuit may be slightly changed so that it acts as an oscillation generator at the same time that it acts as a detector.

CHAPTER IV

THE VACUUM TUBE AMPLIFIER

General characteristics—Audio frequency amplification—Radio frequency amplification—Radio frequency regenerative amplification—Autodyne production of beats.

General Characteristics

Because of the relay action of a tube, a certain amount of amplification takes place even when the tube is functioning as a detector. Amplification may be said to be an inherent property of all vacuum tubes.

If a steady potential is applied to the grid which brings the operating point to a position on the straight portion of the characteristic curve, equal variations of grid potential will cause equal changes of plate current. No distortion of plate current is then caused, even with damped oscillations, and its variations are not only in step with the antenna oscillations but its amplitudes are proportional to the amplitudes of antenna oscillations at every instant. See Figs. 29 (a) and (b).

If radio-telegraph signals only are received, distortion of the oscillating plate current is not such a serious drawback. But when radio-telephone speech and music are received it is imperative that no distortion takes place or the sounds heard may not be accurate reproductions of the sounds at the transmitting station. They may, in fact, be so greatly distorted that they are extremely difficult to understand or absolutely unintelligible. An ideal amplifier is, then, one in which the antenna current is amplified without distortion regardless of the combination of frequencies involved.

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tudes in the plate circuit are usually larger than those in the antenna. They may not, however, be large enough to create the

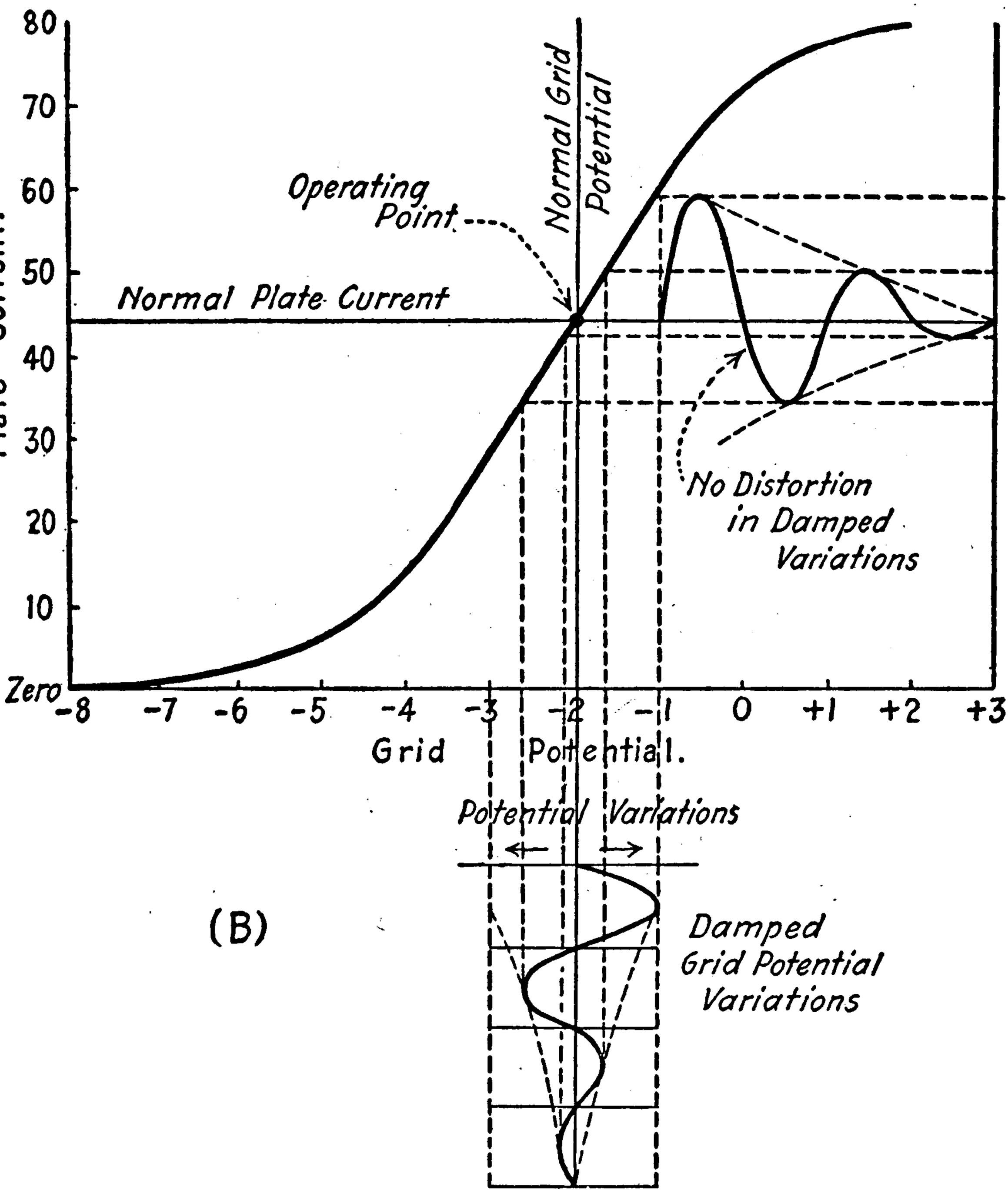

Fig. 29 (b)—Amplification of damped oscillations.

desired amplitudes of sound waves and therefore the volume of sound from the telephone receiver. Amplification must then be increased in some manner.

Amplification Factor

It has been stated that if the filament current and plate potential are kept constant, the plate current varies with the grid potential. It is also true that if both filament current and grid potential are kept constant, the plate current varies with the plate potential. There are then two possible ways to vary the plate current when the filament current is constant. But the reason the potential variations due to signals are applied to the grid rather than to the plate is that they have greater effect upon the plate current in the former case than in the latter. There would otherwise be no object in having a grid electrode. The ratio of plate potential variation to grid potential variation required to produce any given change in plate current is called the "voltage amplification factor." For example, if a certain increase in grid potential will produce a certain increase in plate current and it takes an increase of plate potential six times that of grid potential to produce the same increase of plate current, the voltage amplification factor is six.

The value of any given vacuum tube as an amplifier depends upon this amplification factor. In general, all other conditions being equal, the amplification factor of a tube depends upon two things. The first is the relation between the distance of the plate from the filament and the distance from the grid to filament. That is, with a given distance between plate and filament, the closer the grid is to the filament the greater this amplification factor will be. The second is the spacing between the grid wires (or distance between turns). The amplification factor increases with a decrease of spacing and vice versa. Tubes may thus be compared with each other and their relative values as amplifiers roughly judged.

With any given tube, the amplification factor also depends

to some extent upon the plate and grid potentials. It cannot, therefore, be considered as an actual constant. If, however, only the straight portions of characteristic curves are considered the effect of plate and grid potentials upon amplification constant may be ignored.

The value of a tube as an amplifier also depends upon the degree of vacuum and the very "hard" tubes are considered far superior to the "soft" tubes for amplification purposes.

Now, the slope of the grid-potential, plate-current curve depends upon the amplification factor, other things being equal. If this characteristic curve for one tube is steeper than that for another, grid potential variations in the first tube will produce larger plate current variations than will be produced in the second tube by the same grid potential variations. This may be seen by comparing Fig. 30 with Fig. 29 (a). In the case of an amplifier tube it is only the straight portion of any characteristic curve which is of interest, since operation on a bend of the curve would result in unsymmetrical variations of plate current.

Audio Frequency Amplification

If it is desired to amplify the audio-frequency current in the plate circuit of a detector tube, the primary of a small closed core transformer may be connected between the plate and the positive terminal of the plate battery. The secondary of the transformer is then connected into the grid circuit of another tube and the normal potential on the grid of this second tube is so adjusted that its operating point is on the straight portion of its characteristic curve. Usually a certain amount of steady negative potential must be applied to the grid of this amplifier tube to accomplish this result. This may, of course, be done by inserting a grid battery of proper voltage into the grid circuit

and connecting the negative battery terminal to the grid. Another and better method is to include a portion of the fila-

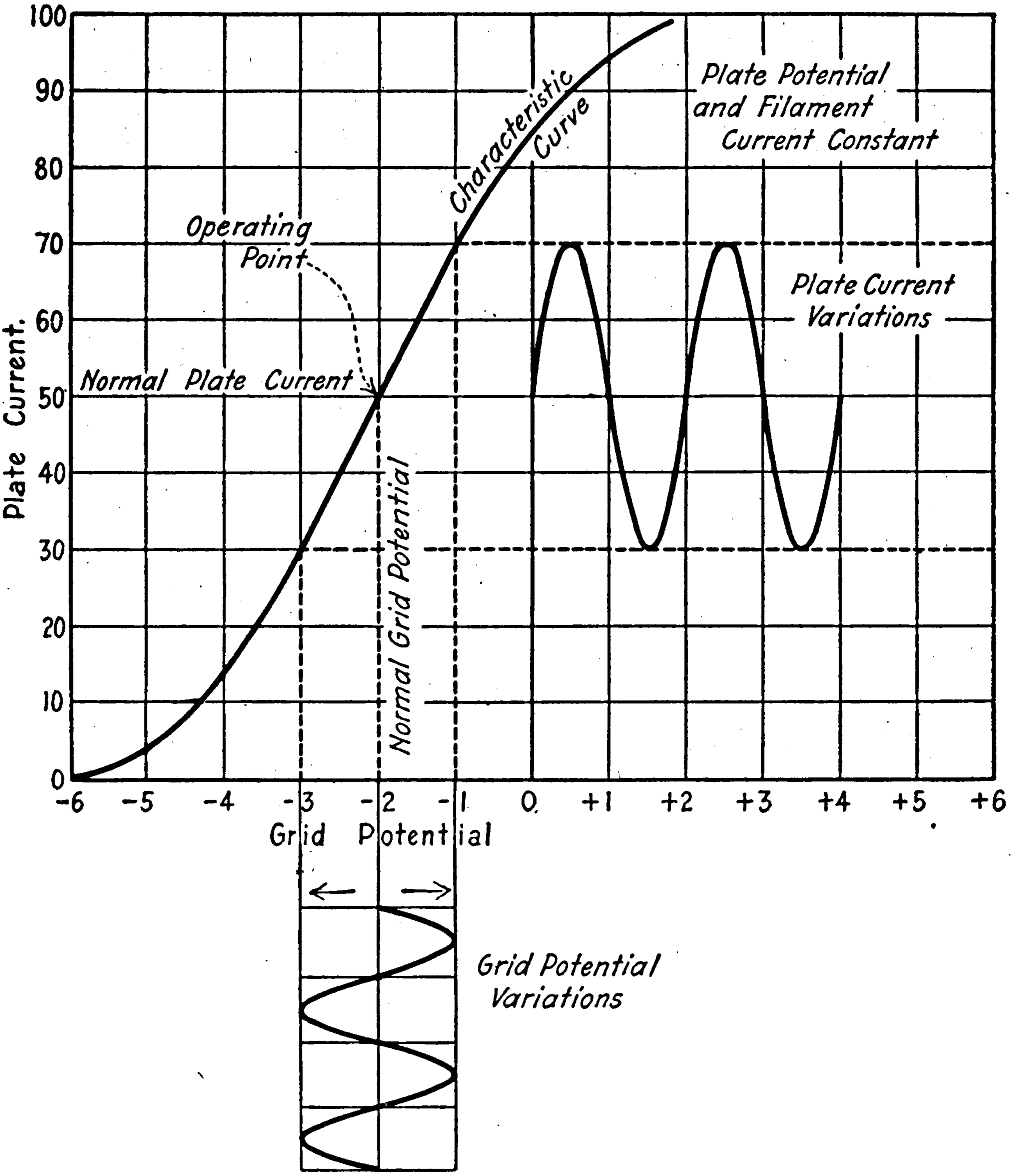

Fig. 30—Amplification of continuous oscillations

ment rheostat resistance in the grid circuit as shown in Fig. 31. This places a negative potential upon the grid which is equal to the potential difference between the points "X" and "Y."

The audiofrequency variations of plate current in the detector tube now cause grid potential variations in the amplifier tube which are larger in amplitude than the grid potential vari-

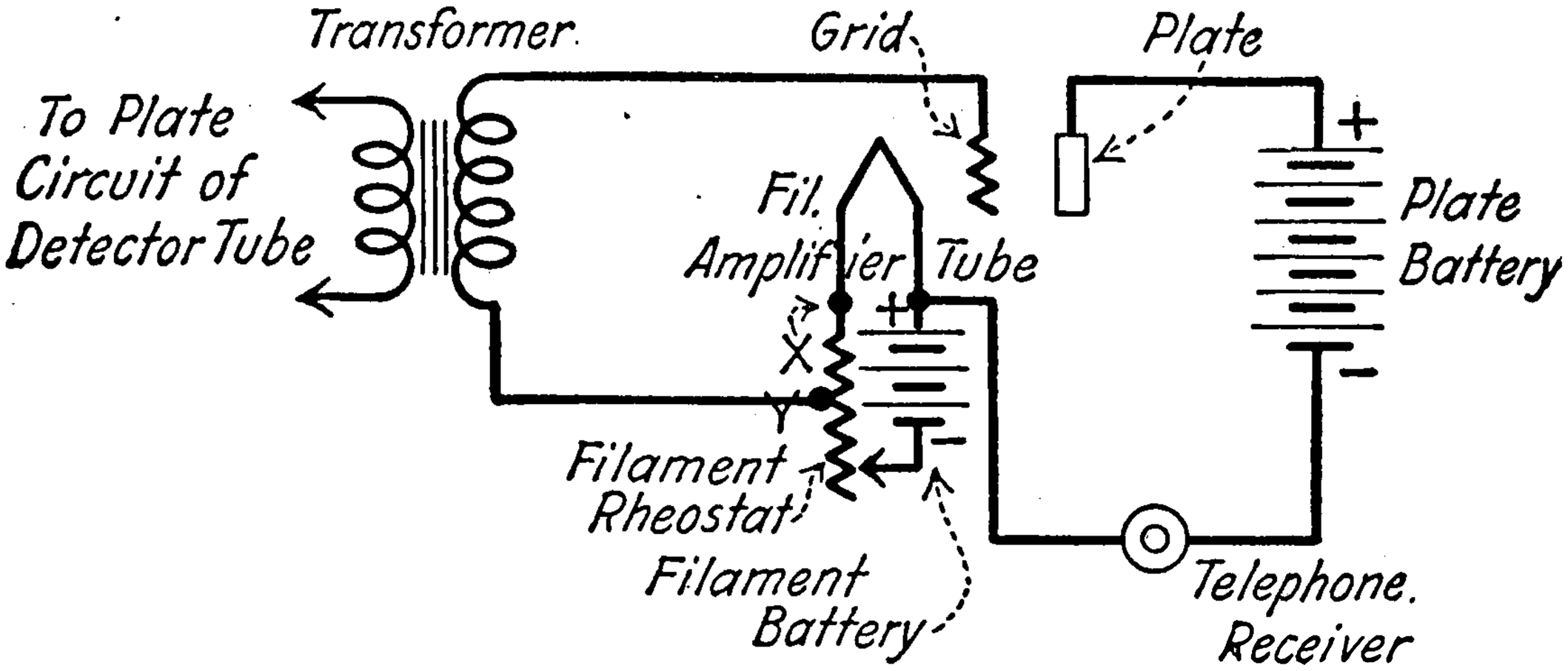

Fig. 31—Customary method of placing a normal negative potential on the grid of an amplifier tube.

ations applied to the detector tube by the antenna oscillations. These variations of amplifier grid potential will be at the audible frequency rate because radio frequency current variations cannot readily flow in the detector plate circuit due to the high reactance of the transformer primary. Audio-frequency currents will then flow in the plate circuit of the amplifier tube and through the telephone receiver. The receiver diaphragm will vibrate with greater amplitude because the current variations are of magnified amplitude and, as a final result, the sound heard in the telephone receiver is louder. This can easily be verified by plugging a telephone receiver into the jack of the detector circuit and then into the jack of the first stage of an audio-frequency amplifier.

If still further increase in audibility (or volume of sound) is required one or more "stages" of amplification may be used in the same manner. Such amplification is referred to as "cascade amplification." Usually two stages of audio frequency amplification (two amplifier tubes in cascade connection) are the

limit, although if care is taken three stages may sometimes be managed.

The signals must, of course, be put through a detector tube and rectified before they are applied to an audio-frequency amplifier. With cascade amplification sufficient current may frequently be secured in the plate circuit of the last tube to operate a relay or a device known as a "loud speaker." If the relay is used, telegraph signals may be sent over a land wire from the radio receiving station to a distant office where another relay opens and closes a local sounder circuit. If the loud speaker is used both radio telegraph signals and radio-telephone speech and music may be reproduced with sufficient volume to be heard considerable distances away from the instruments.

Radio Frequency Amplification

The amplitudes of the grid potential variations in any tube control the audio-frequency variations of average plate current. These grid potential variations of course depend upon the amplitudes of the antenna oscillations. If the antenna oscillations are weak, that is, if the signal is weak, the grid potential variations are also weak (of small amplitude) and a detector tube may not be made to function propertly and possibly not at all. This is because the sensitiveness of a detector depends upon the *square* of the potentials applied to the grid by the signal current. For example, if a certain voltage applied to the grid produces a certain change in plate current, twice the applied voltage will produce four times the change in plate current. It is obvious that the amplitudes of the antenna oscillations might at times be too small to operate the detector tube. In this case there would be no amplification of the very weak signal by means of audio-frequency amplification because the signal can not operate the detector in the first place.

When signals are very weak it is then of very great advantage to amplify them before they are rectified. That is, to amplify the antenna oscillations until the potential variations are high enough to operate a detector tube to good advantage. To do this it is necessary to amplify *radio* frequency oscillations *before* rectification.

The circuit shown in Fig. 32 may be referred to. In this circuit there is resistance inserted in the plate circuit of the first

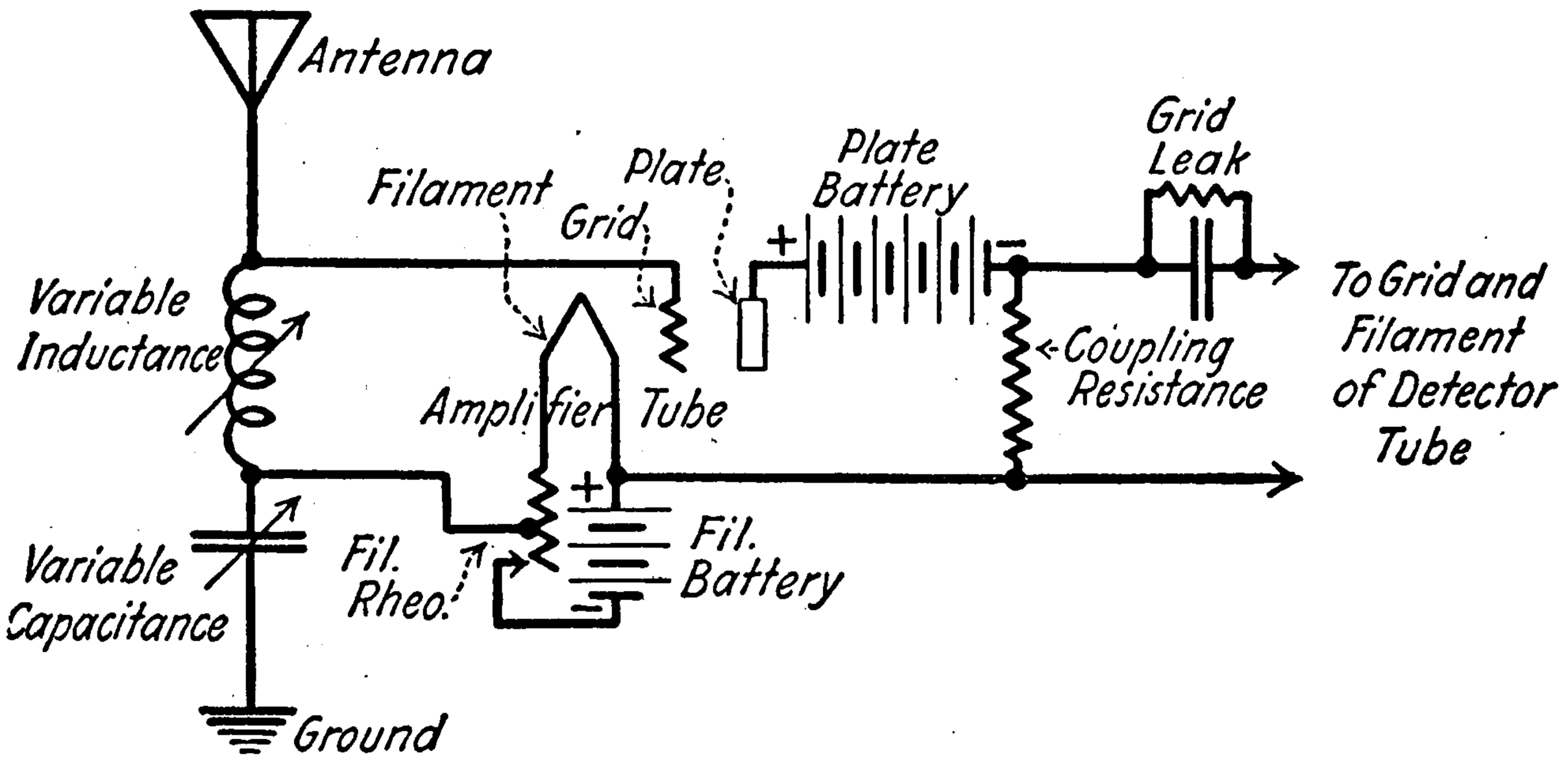

Fig. 32—Single stage of radio-frequency amplification using a coupling resistance.

or radio-frequency amplifier tube. Due to inherent amplification, the plate current variations in this first tube are greater in amplitude than the antenna oscillations. If the coupling resistance is quite large, amplified potential variations are applied to the second or detector tube. Let it be assumed that these amplified potentials are sufficient to operate the detector tube to good advantage. The rectified plate current variations will then be of audio-frequency and the telephone receiver will function providing the antenna oscillations of radio frequency are modified at an audio-frequency rate.

If one stage of radio-frequency amplification is not enough,

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in this "closed" oscillatory circuit. The oscillations in this circuit cause radio-frequency variations of potential at the terminals of the condenser "C," which are applied to the grid of the tube. Corresponding variations of plate current are therefore produced, which flow through the "by-passing condenser" (connected across the telephone receiver and the plate battery) and also through the plate coil. Being of radio-frequency, these plate current variations cannot, naturally, flow very readily through the telephone receiver. The radio-frequency variations of plate current are, of course, in step with the oscillations in the circuit "LC" and, therefore, the oscillating E.M.F. induced in that circuit by the plate coil is also in step, providing the coils are connected in the proper manner. Some of the energy of the plate circuit oscillations is transferred or "fed back" to the circuit "LC." These oscillations in "LC" are then reinforced and the potential variations across the condenser "C" are also reinforced. This in turn reinforces the potential variations on the grid and therefore the plate circuit oscillations. In this manner grid potential variations of radio frequency are increased sufficiently in amplitude until, even with a very weak signal, the detector tube will be operated to good advantage. The rectifying or detecting action of the tube goes on at the same time so that if the radio-frequency antenna oscillations are in audio-frequency groups, the telephone will respond to the audio-frequency variations of plate current and the signal is greatly amplified as well as rectified. In accordance with the characteristic action of the grid condenser, this condenser is charged in the usual manner, but its charge at the end of a group of oscillations is proportional to the resultant reinforced amplitude of grid potential variations rather than to the amplitude of radio-frequency oscillations.

This reinforcement of grid potential variations is called

"regeneration," and the amplification produced is "regenerative amplification." The idea is due to E. H. Armstrong, and this circuit and its many modifications are called "Armstrong circuits."

Autodyne Production of Beats

If the distance between the plate coil and the coil "L" is decreased it is said that the "coupling" between them is increased. If this coupling is sufficiently increased a click will be heard in the telephone receiver. At this instant radio-frequency oscillations begin to be self-generated in the circuit "LC," whose frequency will depend upon the inductance of the coil "L" and the capacitance of the condenser "C." An increase in either inductance or capacitance (or both) in this circuit will decrease the frequency of the oscillations. On the other hand, a decrease in either or both will increase the frequency of the oscillations.

Suppose that the frequency of the antenna oscillations is 100,000 cycles and that of the self-generated oscillations is 101,000 cycles. Currents of both frequencies flow in the circuit "LC," although the amplitude of the 100,000 cycle oscillations will not be as great as though this circuit were in resonance with the antenna circuit. Both oscillations, antenna and self-generated, are undamped (unmodified). A third oscillating current is produced in the circuit "LC" whose frequency is 1000 cycles, the numerical difference between the other two. This is the previously discussed heterodyne action except that, in this case, the local oscillations are generated by the detector tube itself. The beat frequency, in the usual manner, produces 1000 variations of plate current through the telephone receiver each second and, this being an audio-frequency, an audible response is heard in the receiver. By varying the frequency of the locally generated oscillations, the beat frequency and, there-

fore, the tone of sound in the receiver can be varied at will. Undamped ether waves thus produce undamped antenna oscillations, which are modified and rectified by the detector to produce audible signals.

This method of receiving undamped wave signals is called the "autodyne" method to distinguish it from the method in which local oscillations are generated by an entirely separate device. It is, of course, a "self-heterodyne" method, whereas that previously considered was a "separate-heterodyne" method.

If the signals are damped waves or undamped waves modulated at any audible frequency, the tone produced in the telephone receiver will be greatly distorted due to the interaction of the various frequencies, both radio and audio. In the case of speech or music reception the result is hopelessly unsatisfactory unless the frequency of the local oscillations is *exactly* the same as the antenna oscillations. In this case the speech or music will come through without much distortion, usually, and the amplification will be greatly increased. This is called "zero-beat" reception. No beat frequency is produced. When the signals are from a spark telegraph transmitter or modulated continuous wave telegraph transmitter, the natural group frequency of the oscillations will be reproduced and greatly amplified by the zero-beat method.

It is to be noted that the circuit may be exactly the same as that used for regeneration. In fact, autodyne reception is simply regeneration carried to the point where the grid potential variations are maintained at constant amplitude whether signals are being received or not.

If the coupling between the plate and grid coils is decreased to a certain point, the local oscillations will no longer be generated. Undamped (or continuous) wave signals will then no longer be heard, although radio-telephone signals, spark sig-

nals and modulated continuous wave telegraph signals may still be heard.

It is interesting to note that in the case of "beat reception" of continuous wave signals, there are two values of frequency of local oscillations which may be used to produce a beat frequency of, say, 1000 cycles. The numerical difference between 100,000 cycles, the frequency of the signal oscillations, and 9900 cycles, the frequency of local oscillations, is also 1000 cycles and an audible beat frequency. The local circuit "LC" of Fig. 32 might be adjusted so that either local frequency is produced and with a signal frequency of 100,000 cycles (wave length of 3000 meters) the audible beat frequency and, therefore, the musical tone in the telephone receiver is the same, 1000 cycles.

There are various modifications of the regenerative and self-heterodyne circuit shown in Fig. 33, but these will be considered in detail under "Practical Circuits and Their Operation."

CHAPTER V

PRACTICAL CIRCUITS AND THEIR OPERATION

Methods of coupling—The variometer—Inter electrode tube capacitance—Wave length, Frequency and Resonance—Circuits and Explanations of their arrangement and operation.

Methods of Coupling

Two circuits, each containing inductance and capacitance, may be coupled together in any one of the ways shown in Fig. 34. If oscillations are present in one of the circuits, oscillations of the same frequency will be forced to flow in the other which is coupled to it. The first circuit is called the "primary"

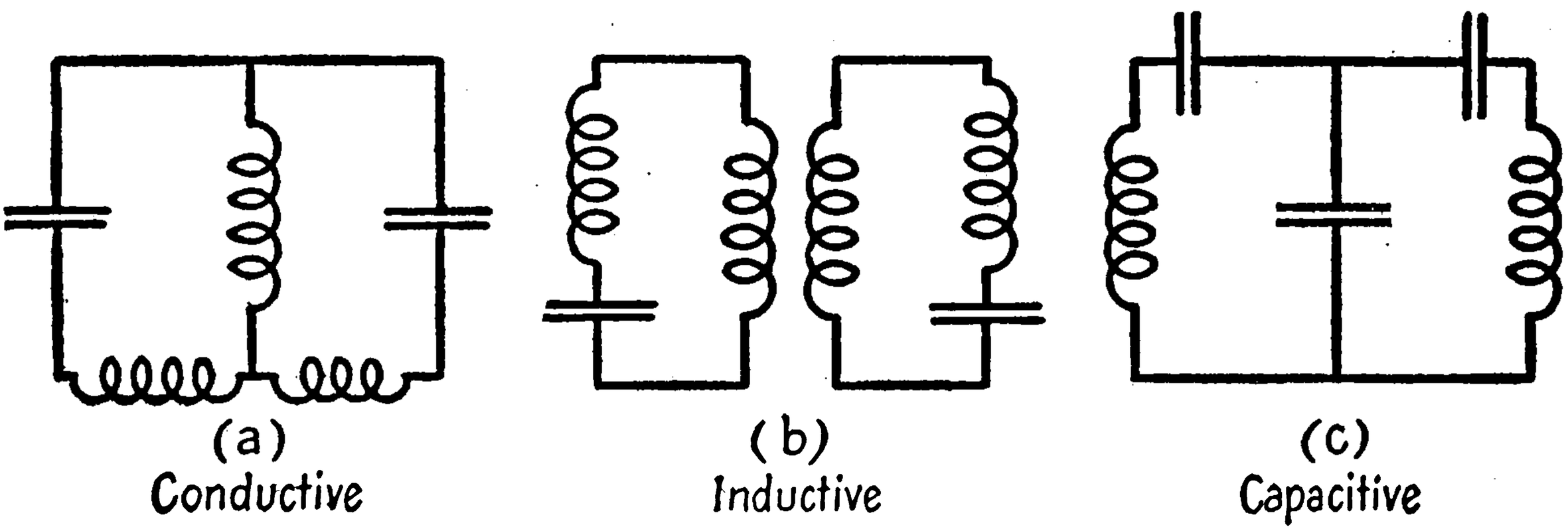

Fig. 34—Methods of coupling.

and the second is called the "secondary" circuit. The oscillations which are forced to flow in a secondary circuit are called "forced oscillations." Their amplitudes will not be maximum unless the secondary circuit is tuned to resonance with the primary. This is true no matter what kind of coupling is considered.

In Fig. 34 (a) the primary and secondary circuits are coupled through the inductance which is common to both

circuits and the coupling is called "conductive." In Fig. 34 (b) there is what is known as "mutual inductance" between the two coupling coils. In few words, there is an inductive (inducing) effect of each coil upon the other, although the coils are not necessarily physically or electrically connected with each other. This is called "inductive" coupling. Fig. 34 (c) shows a capacitance to be common to both primary and secondary circuits. The coupling between the two is made through this capacitance and is, therefore, called "capacitive" coupling.

The primary circuit may in any of the above cases be considered to be an antenna circuit, since it contains both inductance and capacitance.

The Variometer

A continuously variable inductance is quite often required for the close adjustments frequently necessary in vacuum tube circuits. If a coil of wire is tapped at every turn so that the inductance may be varied turn by turn the variation might not be smooth enough. That is, it might be necessary to secure a variation of inductance less than that of one turn on the coil. In this case a variometer may be used whose construction may be quite similar to that shown in Fig. 35. The coil which may be turned is called the "rotor" and the stationary coil is called the "stator." The inductance of a variometer may be varied by varying the coupling between the rotor and the stator which are connected together.

Inter-Electrode Tube Capacitance

The filament, grid and plate of a vacuum tube all have some surface area and, in operation, have electric charges placed

upon them. It is not hard to imagine them as being plates of small condensers with the vacuum space between them acting as a dielectric. There is thus capacitance between the tube electrodes which may have certain effects upon the circuits of the grid and plate. There is a condenser effect between

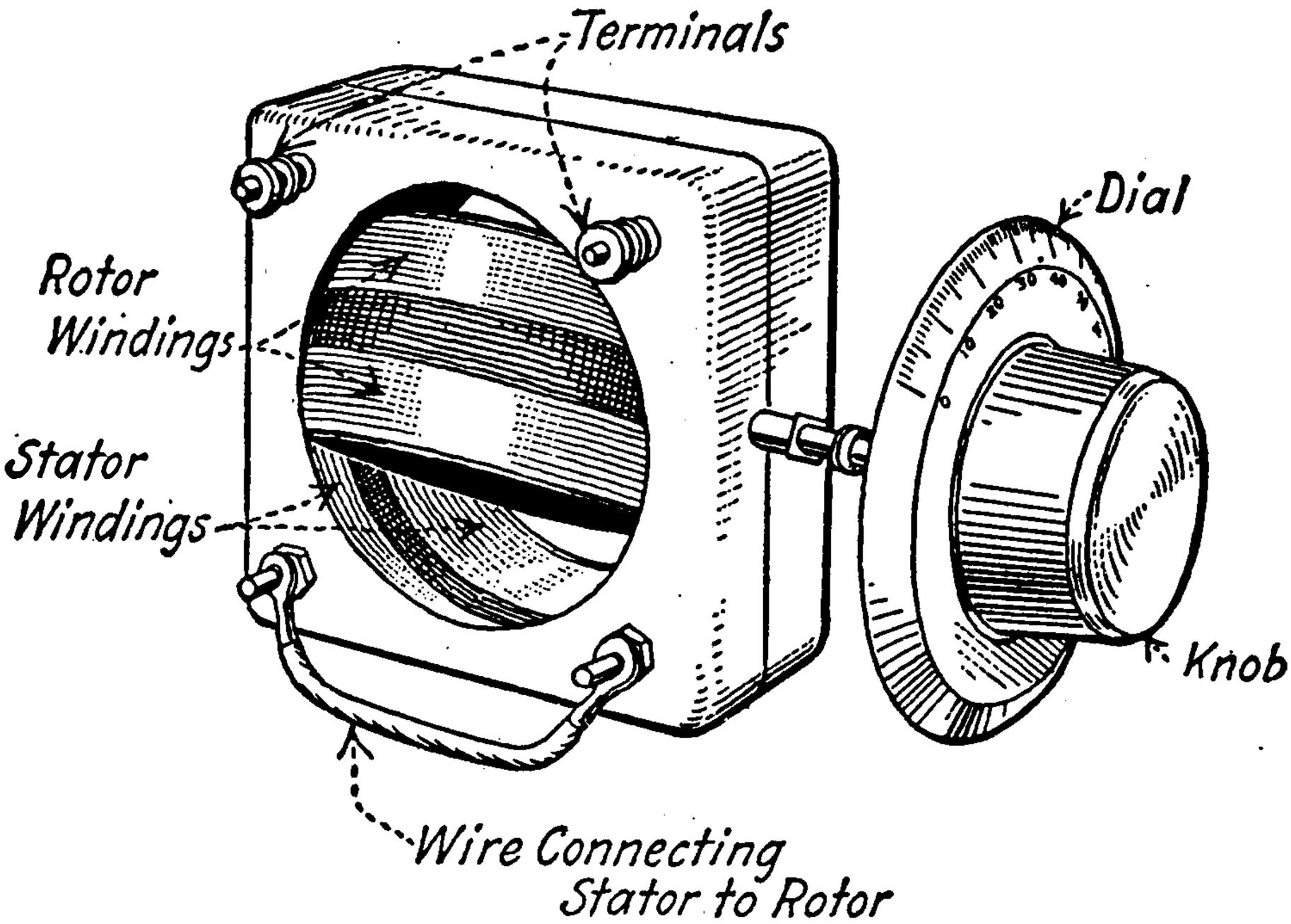

Fig. 35—Construction of a typical variometer.

the grid and the plate and another between the grid and the filament. In some cases the condenser effect may be considered, as shown in Fig. 36, where a certain amount of capacitance is common to both the grid and plate circuits. The circuits are then considered as being coupled together by "capacitive" coupling.

Wave Length, Frequency and Resonance

It will be recalled that as the frequency of ether oscillations decreases, the wave length of the oscillations increases and vice versa. When a circuit is in resonance with another at a certain frequency it may also be said that they are in resonance at a certain wave length corresponding to that particular

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inductance equals 50 units and capacitance equals 1 unit. So long as the product of the two equals 50, the circuit will, in this case, be resonant at the wave length of 300 meters. This is quite important and must be borne in mind in the consideration of circuit operation.

Circuits

The circuits schematically shown in the following diagrams are those which are probably in most common use and are entirely practicable. Many variations could be made in them

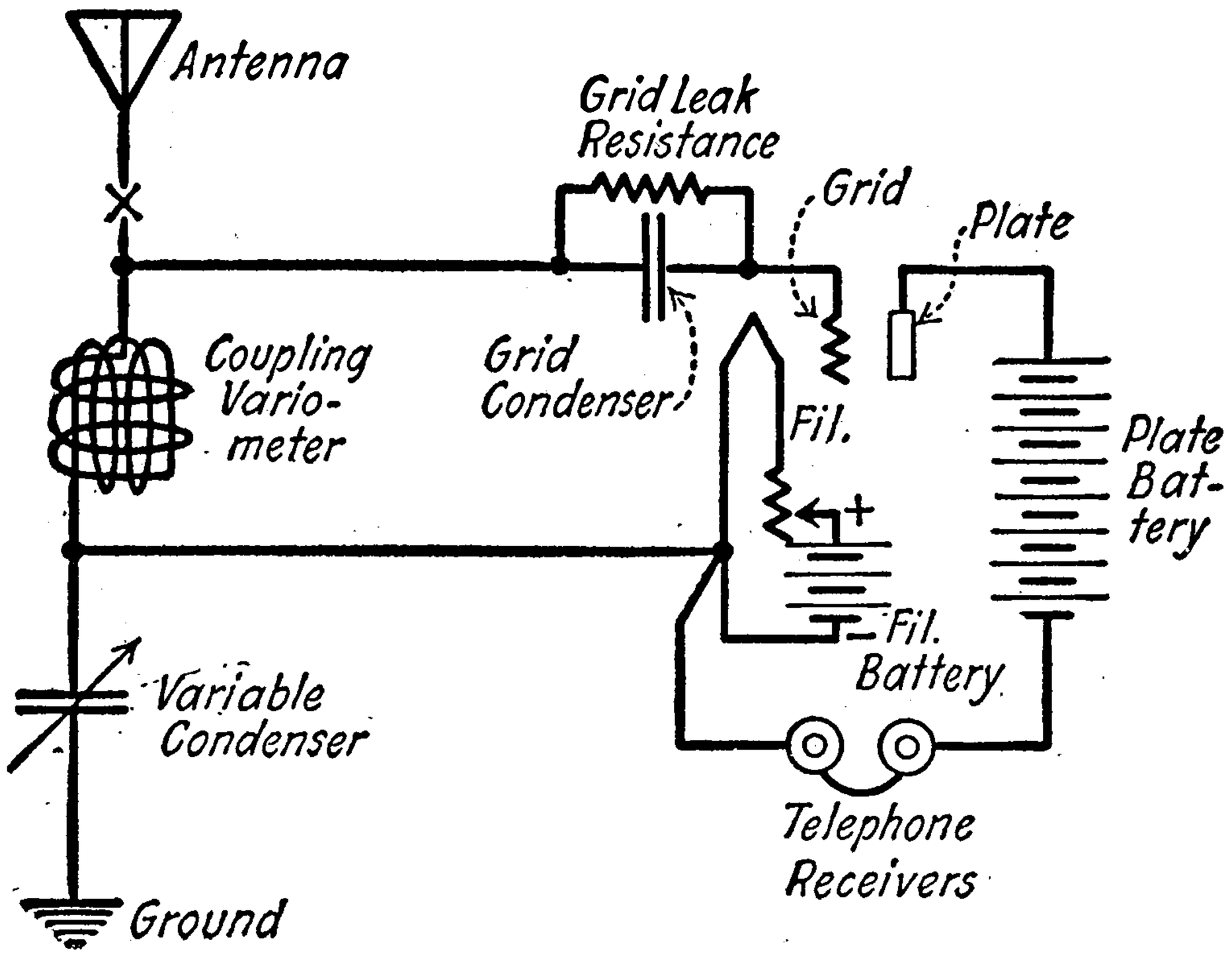

Fig. 37—Simple Single Circuit Receiver.

and there are receiving circuits almost by the hundreds which are workable but not in common use. No attempt will be made to illustrate every possible connection of vacuum tubes into detector or amplifier circuits.

Fig. 37 is a detector circuit with grid condenser in which the coupling between the antenna and grid circuit is conductive. The secondary circuit is not tuned to resonance

with the primary, although it contains both inductance and capacitance. It may be called an "untuned secondary" circuit. A receiver with such a circuit is said to be a "single circuit receiver" because only one circuit, the antenna, is tunable.

In the operation of this circuit, the antenna is tuned to resonance with the radio frequency oscillations induced in it by the transmitting station it is desired to receive from. If the plate battery voltage and filament current have been so adjusted that the normal operating point is on the straight portion of the characteristic curve, signals of maximum obtainable audibility will be heard in the pair of telephone receivers.

The circuit shows the antenna inductance to be a variometer and it will be good for the reception of short waves. To receive long waves an inductance, called a "loading inductance," may be inserted in series at point "X."

With this circuit, the ability to cut out forced antenna oscillations from a station transmitting on a different wave length will depend upon the ratio of the total antenna inductance to total antenna capacity. By increasing the inductance and simultaneously decreasing the capacitance a value of each will be found which will again put the circuit in resonance with somewhat greater freedom from interference caused by the unwanted station. This is sometimes called "stiffening" the circuit. There is a drawback to this circuit, as if the inductance of the variometer is increased, the coupling between the antenna and the grid circuit is also increased. This would counteract the value of stiffening the circuit, since increased coupling means increased liability of interference. The disadvantage could be overcome to some extent by using a loading coil. The coupling in no case, however, may be made as loose as is often desirable for the elimination of

strong interfering signals and atmospherics. Such a circuit is used for the reception of damped waves only (spark, voice, etc).

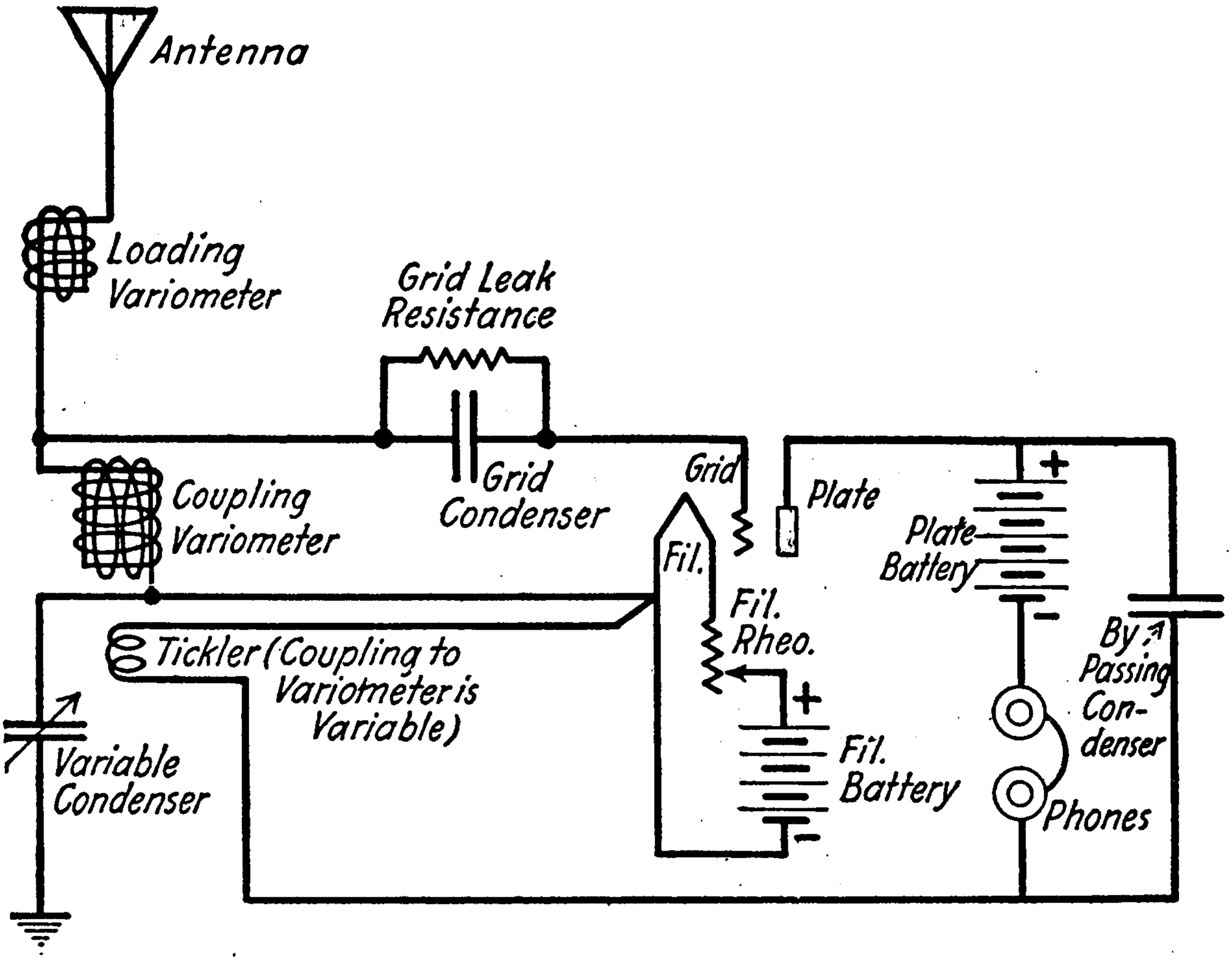

Fig. 38—Single Circuit Regenerative Receiver.

Fig. 38 is practically the same as Fig. 37, with the exception that a plate coil is inductively coupled to the antenna variometer. The coupling between the variometer and plate coil is variable, so that the degree of grid potential reinforcement may be controlled. This plate coil is usually referred to as a "tickler," since it "tickles" the grid potential variations, due to antenna oscillations. If the coupling between the tickler and the variometer is sufficiently increased, oscillations whose frequency will be determined by the antenna inductance and capacitance will be self-generated to produce beats. This is the autodyne action previously discussed. If the coupling is reduced below the point where oscillations are self-generated,

there is amplification by regeneration and this receiving circuit can be made quite sensitive to weak signals.

In all other respects the circuit is quite similar to that of Fig. 37. When the autodyne action is used for the reception of unmodulated undamped waves, or "C. W." (continuous waves), the tuning is much sharper than when the regenerative effect is used for damped waves. For example, suppose the frequency of the desired signal to be 100,000 cycles (wave length 3000 meters) and forced oscillations in the antenna from an interfering station to be 200,000 cycles per second (wave length 1500 meters). The frequency of local oscillations is assumed to be 101,000 cycles. The beat frequency produced by the interaction of frequencies of 100,000 and 101,000 cycles is 1000 cycles, an audible frequency. But the beat frequency, due to oscillations of 200,000 and 101,000 cycles, is 99,000 cycles, an inaudible frequency. The signal on the 3000 meter wave would be heard but that on the 1500 meter wave would not be heard at all. Both might be heard with a single circuit receiver, however, if they were modified at an audio-frequency rate (or were damped oscillations), although the receiver might be only in resonance at the 3000 meter wave.

A receiver having such a circuit may be called a "single circuit, regenerative receiver."

The inductance and capacitance are sometimes operated by one tuning knob so that both are variable at the same time. In such a case the single circuit, regenerative tuner may be made very simple to operate and the tuning will be fairly sharp so long as the ratio of antenna inductance to capacitance is high for all wave lengths. Selectivity, or sharpness of tuning, has to be sacrificed to some extent, however, for increased simplicity of operation.

In Fig. 39 the antenna is inductively coupled to the

grid circuit of the detector tube and a condenser is connected across the secondary coil and variometer. The coupling coils may have fixed inductance and the variometers may be used for inductance variations. When the plate potential and filament current of the tube have been adjusted the antenna

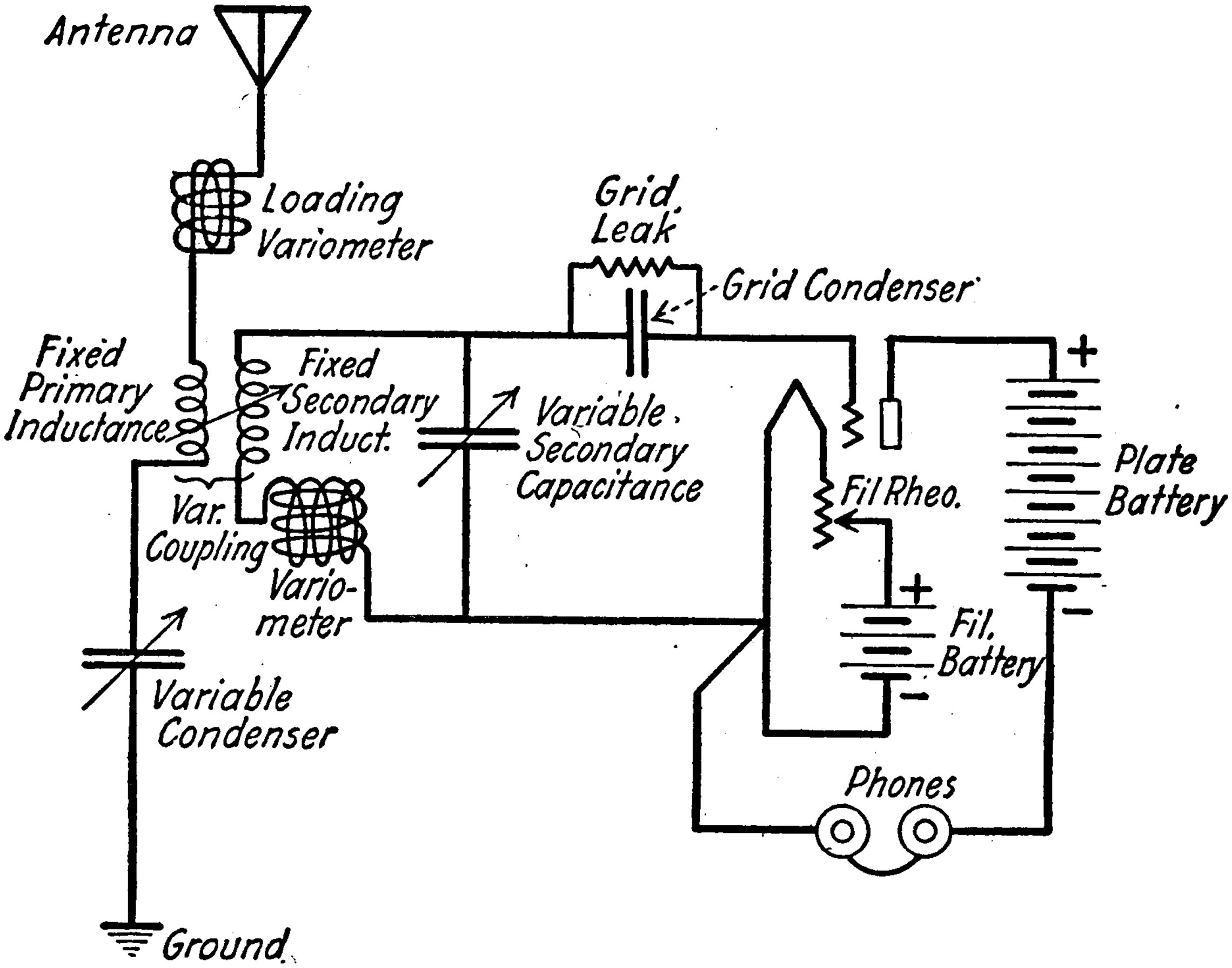

Fig. 39—Two Circuit Receiver, Inductive Coupling.

may be tuned to resonance with a signal by varying either the inductance of the variometer or the capacitance of the condenser in that circuit. Large values of inductance and small values of capacitance should be used for sharp tuning. Oscillations are then induced in the secondary circuit and their amplitudes made maximum by tuning the circuit to resonance with the antenna. The secondary variometer and condenser are used for this purpose. Large values of inductance and small values of capacitance for resonance should also be used here. A decrease of coupling decreases the amplitudes

of the secondary oscillations, but increases the sharpness of tuning. The object is, then, to use as little coupling as possible without reducing the signal too greatly. When coupling adjustments are made it will be found necessary to slightly alter the resonance adjustments of both the antenna and secondary circuits. Variations of coupling have an effect upon the inductance values.

With this circuit the sharpness of tuning may be increased very materially over that possible with any single circuit. A receiver having this sort of circuit might be called a "two-

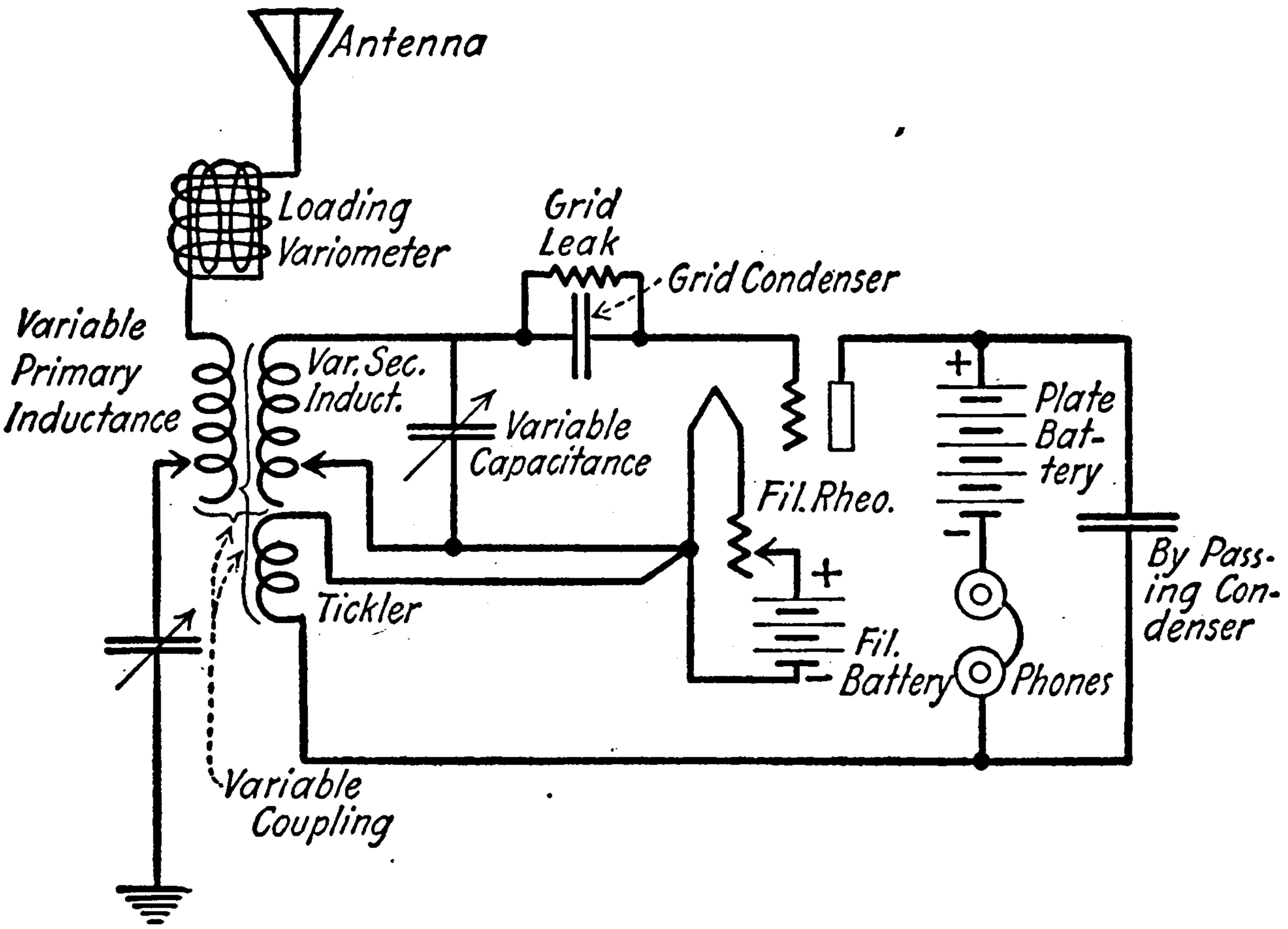

Fig. 40—Two Circuit Regenerative Receiver, Inductive Coupling.

circuit receiver," because there are two circuits to tune.

Oscillations in the secondary circuits, of course, cause oscillating potential variations to be applied to the grid of the tube, but there is no regeneration and it is possible for a signal to be too weak to operate the detector. The circuit is not adapted

to the reception of unmodified continuous waves, but may be used for damped waves (spark, radio-telephone, etc.).

Fig. 40 is almost exactly the same circuit as in Fig. 39, except that regeneration may be had by means of the tickler coupling. Here again the unmodified continuous wave signals may be received by the beat method if local oscillations of the proper frequency are generated. The frequency of the local oscillations is controlled by the adjustment of secondary inductance and capacitance. Sharpness of tuning may still be had because of beat reception in the same manner as set forth in the discussion of Fig. 38.

When regeneration is used the signals may be continuously amplified by increasing the tickler coupling up to the point where local oscillations start. Just before the oscillations start the undamped wave signals will be loudest, but after that degree of coupling is passed the locally generated oscillations will distort the tone if beats are produced. In the case of radio-telephone reception this would make speech either hard to understand or even unintelligible. Beats may be avoided, even though local oscillations are generated, by tuning the secondary to exact resonance with the antenna circuit. Reception is then accomplished by the zero-beat method. This will give maximum amplification of all damped wave signals, but in the case of voice or music there may be some slight distortion, due to the varying tone frequency.

In the reception of straight undamped waves there are, of course, locally generated frequencies both above and below the signal frequency which will give beat reception. The following is an interesting experiment. Adjust the tickler coupling until local oscillations are fairly strong. Then, starting with a secondary circuit adjustment such that the frequency of generated oscillations is somewhat above that of

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than it is for the longer because of the small inter-electrode capacitance of the tube.

In the reception of damped wave signals (spark, voice, etc.) the antenna is tuned to the signal wave and the grid circuit tuned to the antenna in the usual manner. As the plate variometer inductance is increased from a minimum value the oscillating grid potentials become more and more greatly reinforced until a certain inductance value is reached which puts the plate circuit in resonance with the grid circut. The rectifying action goes on at the same time as does the amplification due to regeneration. The result in the telephone receivers is then maximum when all three circuits are in resonance.

An autodyne action may also be secured for the production of a beat frequency when the reception of continuous waves is desired. Local oscillations may be generated in the tube circuits, providing the capacitive coupling between plate and grid circuits is large enough. The frequency of the self-generated oscillations, in the circuit under consideration, will not depend very closely upon the inductance and capacitance of the grid circuit because the plate circuit will exert a somewhat greater influence. By adjusting both the grid and plate variometers, however, a local oscillation frequency will be secured which will produce the desired beat tone in the telephone receivers. One circuit has a tendency to pull the other into step with it in a manner quite similar to that of the synchronization of two alternating current generators at a power station.

Fig. 42 is quite similar to that of the preceding circuit with the exception of a variable capacitance used to couple the grid and plate circuits. This capacitance may be used to increase the tube capacitance and therefore the coupling between the tube circuits. By increasing this capacitance

(switch closed) the operation becómes more effective at the longer waves (lower frequencies).

In all other respects this circuit is practically the same in operation as the preceding one.

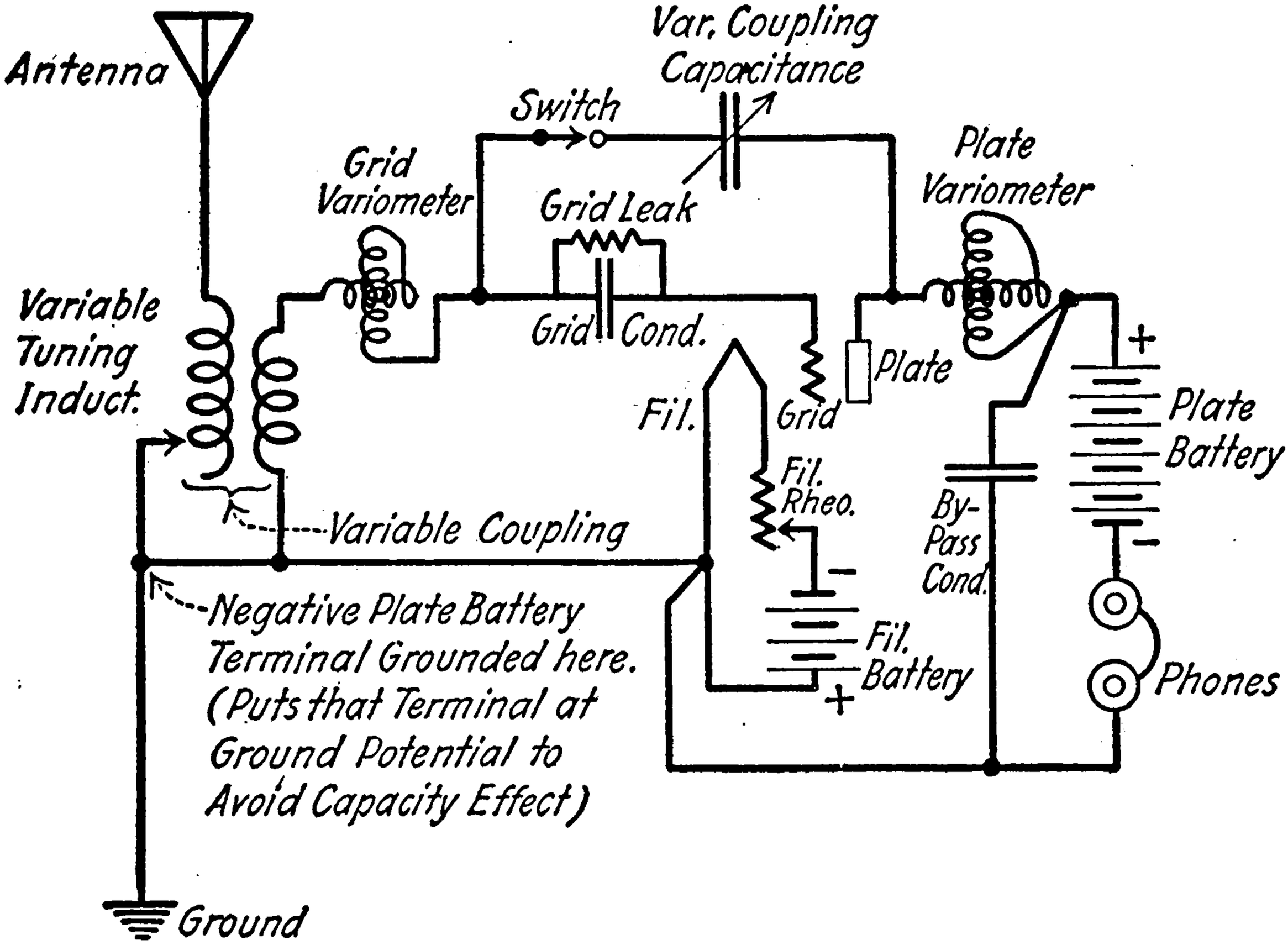

Fig. 42—Three Circuit Regenerative Receiver for Short and Medium Waves.

In Fig. 43 is shown the schematic circuit of a two stage audio-frequency amplifier coupled to a detector. If in any of the previous circuits the grid circuit of the first amplifier tube is connected into the plate circuit of the detector tube (through the transformer) in place of the telephone receivers, the detector energy at audio-frequency may be amplified. The connections are only shown for one type of detector circuit. The operating point must be adjusted to the straight portion of the characteristic curve in the case of each of the amplifier tubes in order to avoid distortion effects. This is done by applying a normal negative potential to the grids in the manner

shown and by adjusting the plate battery voltage and filament current to the proper values. It is customary to burn the filament at a constant voltage rather than at a constant current, since this increases the life of the filament. It may then be

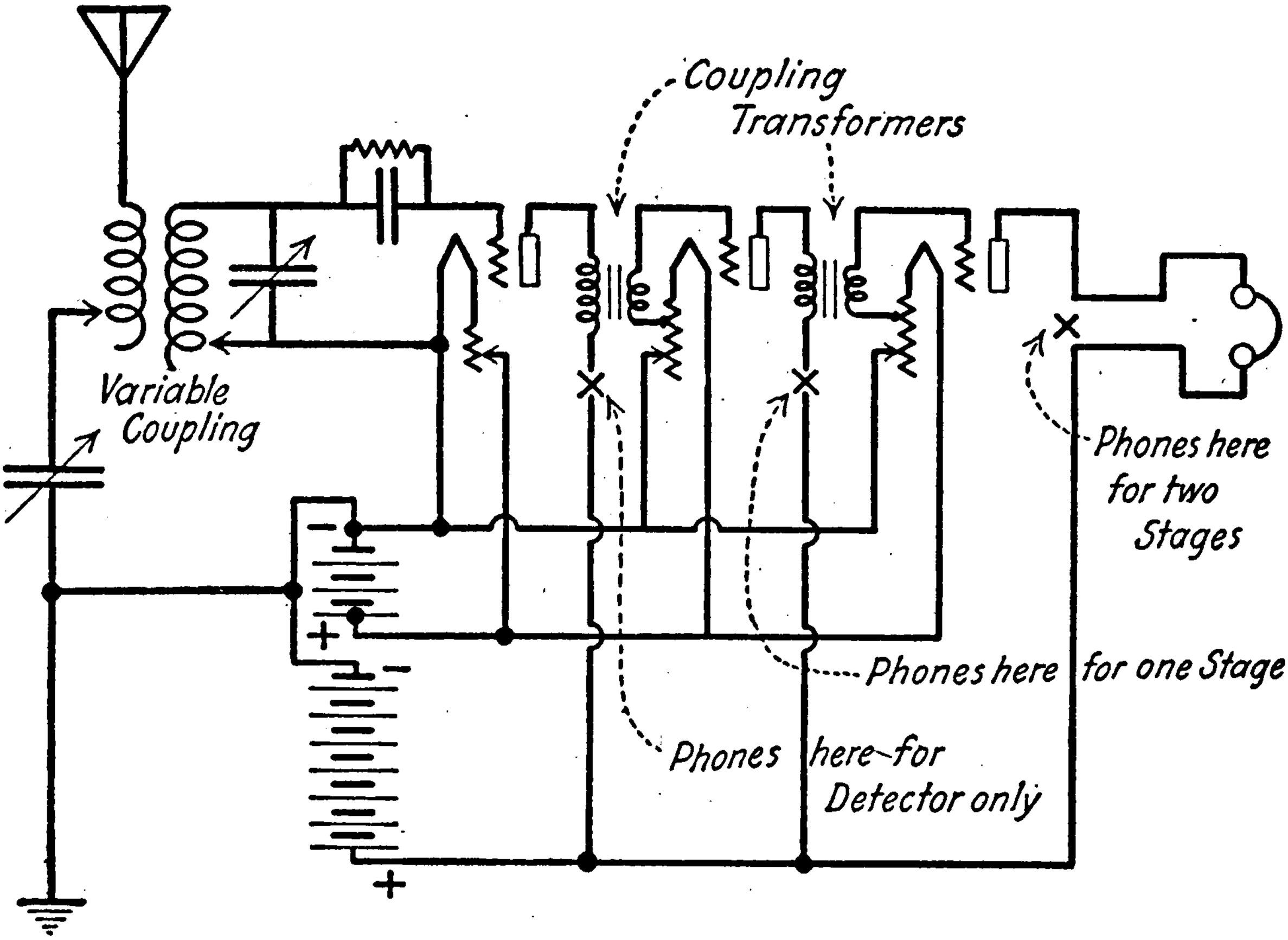

Fig. 43—Two Circuit Receiver with Two-Stage Audio-frequency Amplifier. No Regeneration.

necessary to vary the plate battery voltage from time to time as the filament ages.

The coupling transformers have closed iron cores like the illustration of Fig. 44.

The upper Fig. 45 shows a two stage resistance coupled radio-frequency amplifier connected to a detector circuit. The antenna and secondary circuits are tuned to the signal wave and the oscillating potentials applied to the grid circuit of the first amplifier tube are of radio-frequency. The oscillating potentials applied to the grid circuit of the detector tube are thereby amplified and result in greatly amplified plate current

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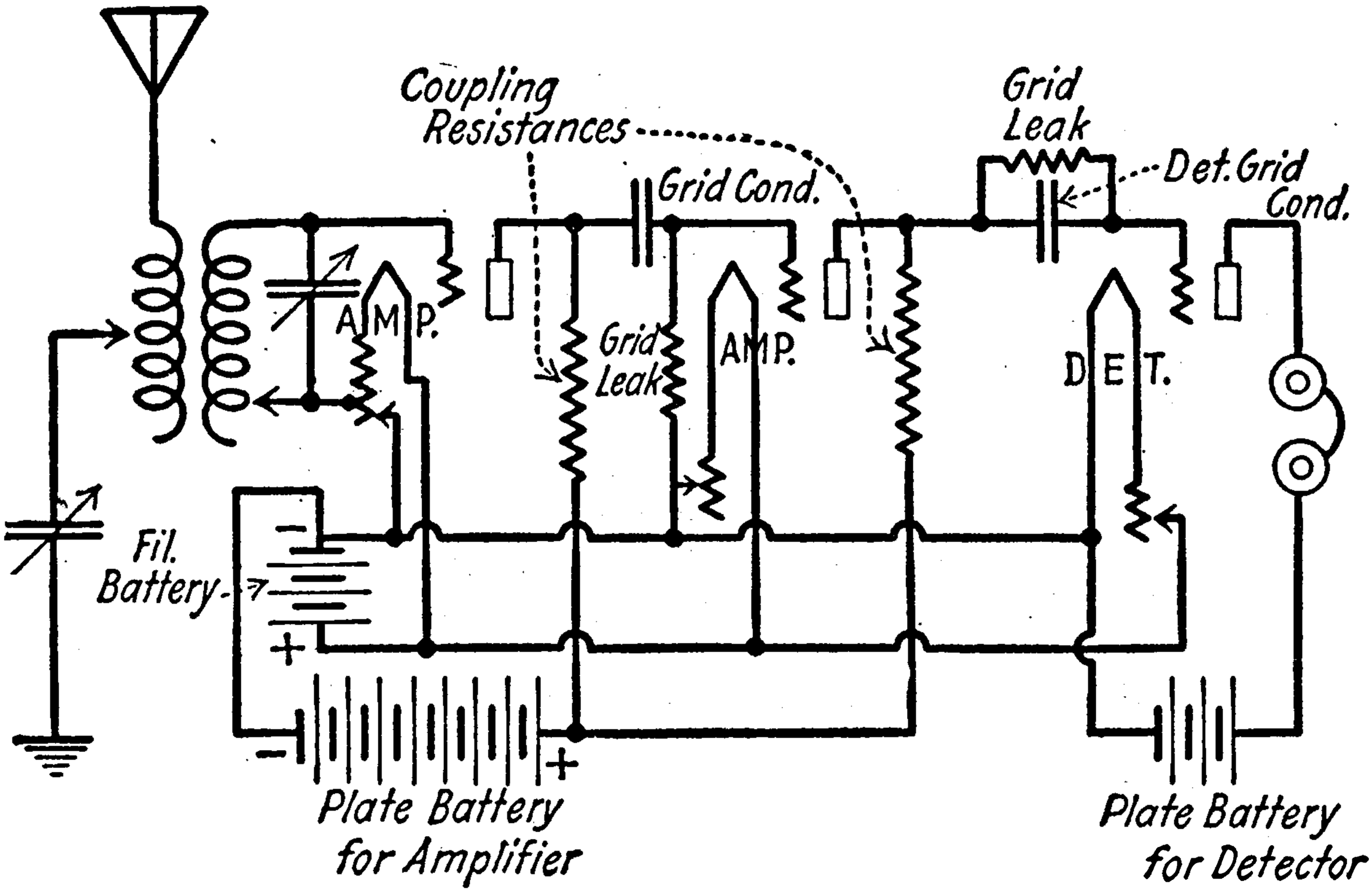

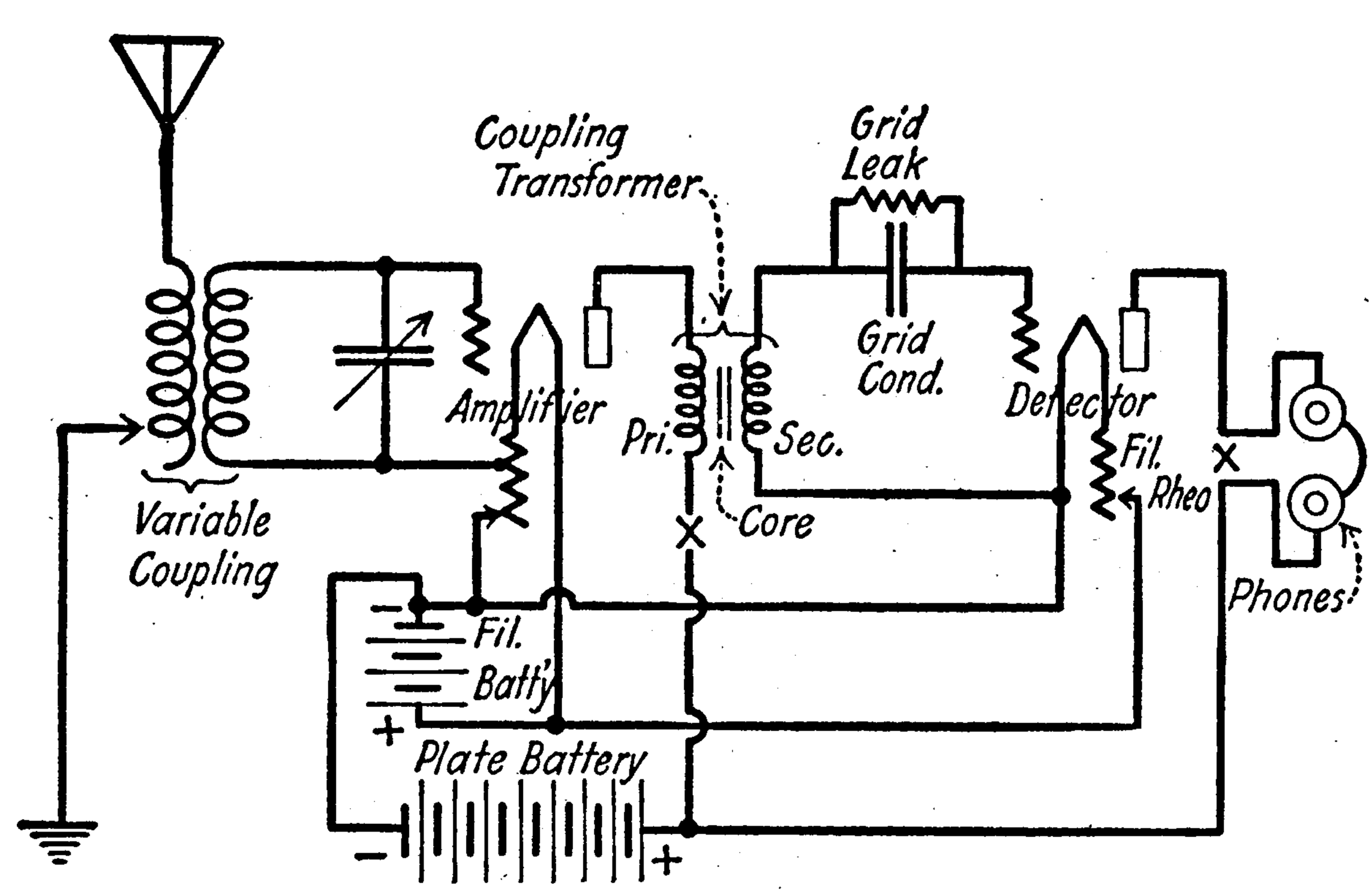

Fig. 45—Two circuits for radio-frequency amplification and detection. Two Circuit Receivers in Each Circuit.

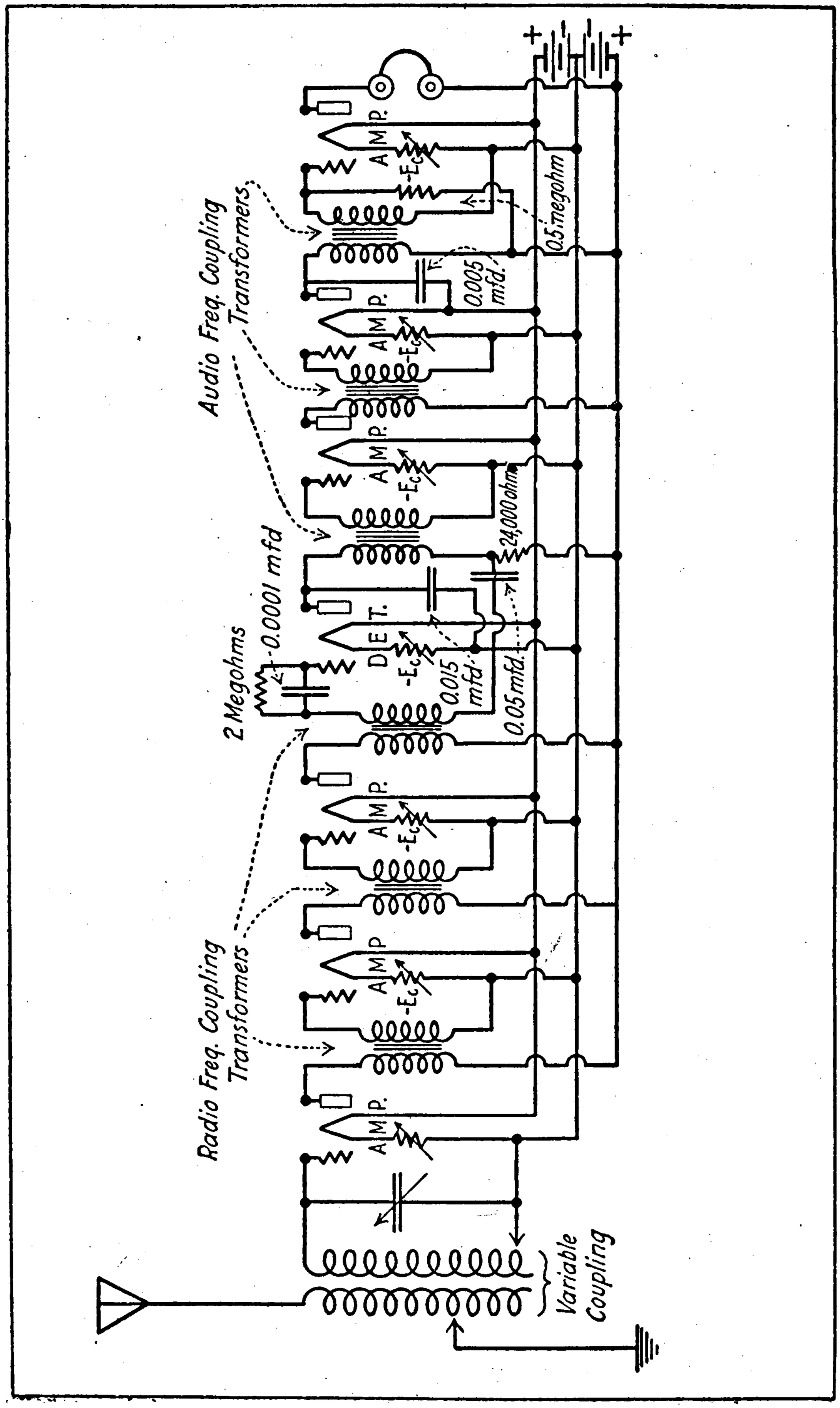

Fig. 46—Radio Frequency Amplifier, Detector and Audio-frequency Amplifier connected to Two Circuit Receiver.

frequency amplifier, detector and three stage audio-frequency amplifier are shown. If distortion is to be avoided in such a circuit (or circuits) great care must be taken to have the proper potentials applied to the grids of the amplifier tubes. Enormous amplification can be secured, however, and enough current variation produced in the plate circuit of the last audio-frequency stage to operate a relay or a "loud-speaker"

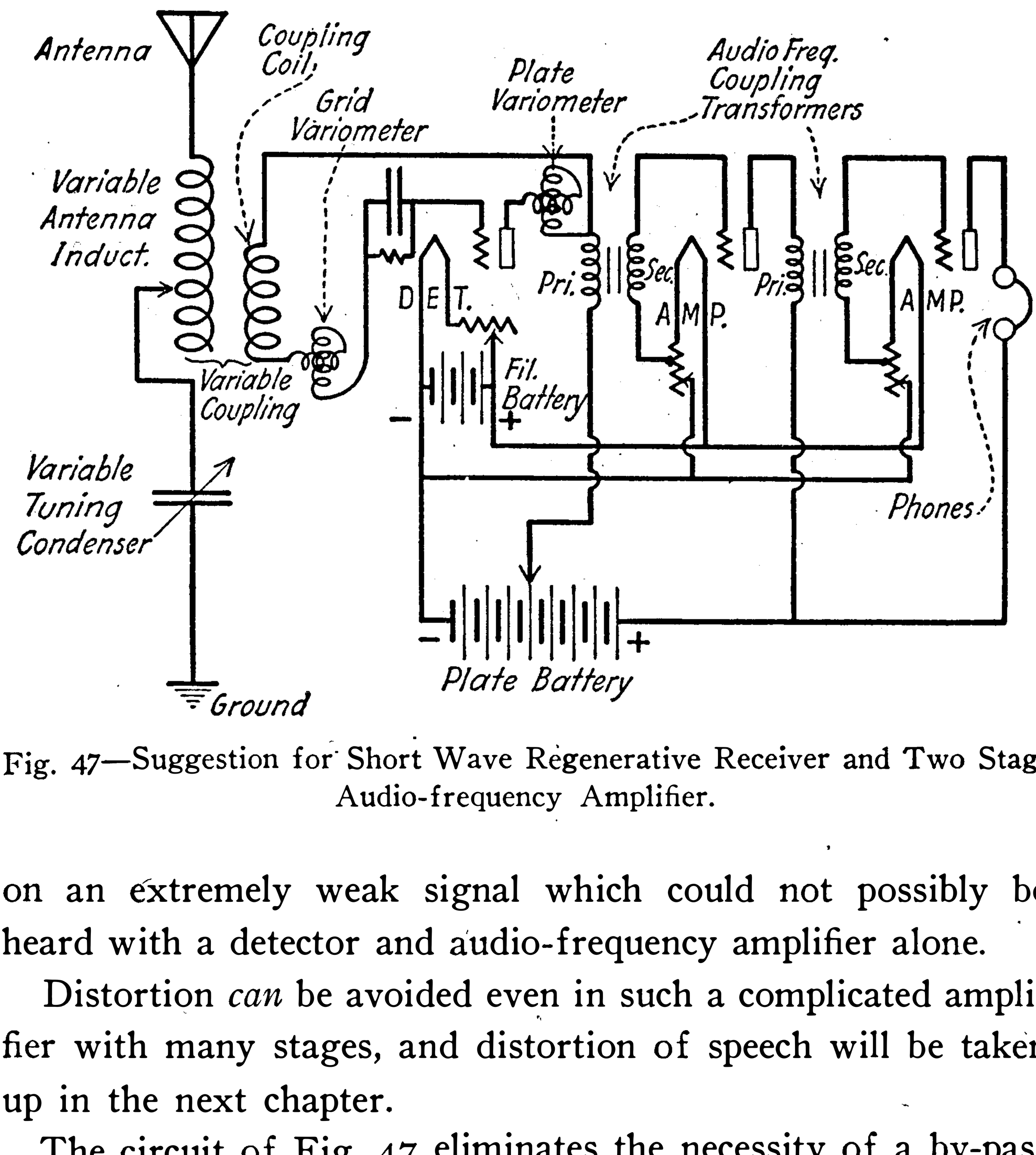

Fig. 47—Suggestion for Short Wave Regenerative Receiver and Two Stage Audio-frequency Amplifier.

on an extremely weak signal which could not possibly be heard with a detector and audio-frequency amplifier alone.

Distortion *can* be avoided even in such a complicated amplifier with many stages, and distortion of speech will be taken up in the next chapter.

The circuit of Fig. 47 eliminates the necessity of a by-pass condenser in the plate circuit. In the usual circuit this by-pass condenser is required to permit the plate circuit oscillations,

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since, without it, the inductive reactance of the telephone receivers would be too great to pass these oscillations.

The circuit is very effective and operates in a manner almost identical with that of previous tuned plate circuits.

It may be said, in this connection, that all circuits in which the plate is also tunable are called "tertiary tuned circuits" and that receivers so designed are called "three circuit receivers."

The circuit is shown connected to a two stage audio-frequency amplifier.

CHAPTER VI

Voice Distortion

Amplifier transformers—Normal grid potential—Too great regeneration—Telephone receiver.

If speech and music are received from a given station without distortion on a crystal detector and distortion is encountered when the crystal is replaced by vacuum tube circuits, it may be easily assumed that the distortion is caused in the receiving circuits. It may, therefore, be of interest to consider some of the causes of voice distortion in a receiver and amplifier.

Amplifier Transformers

Distortion is often due to a poorly designed coupling transformer in the case of either audio or radio-frequency cascade amplification. The distortion will in this case be produced regardless of the degree of care taken to prevent it in other directions. The remedy is, of course, a properly designed transformer.

Grid Potential

It has already been pointed out that in the case of either audio or radio-frequency cascade amplification it is quite necessary to have the operating point of each amplifier tube on the straight portion of the characteristic curve. Moreover, it should be as nearly as possible at the middle of the straight portion, so that neither a large positive or a large negative value of applied

grid potential (due to the signal) will swing the resultant grid potential down to the "cut-off" value or up to the value where plate saturation takes place. In order to accomplish these desired results in practice, it is desirable to have a sufficiently large plate battery voltage (normal plate potential) and a sufficiently large normal negative potential on the grid. The desired grid potential is preferably secured by including a sufficient amount of the filament rheostat resistance in the grid circuit. The manner of accomplishing this has been previously pointed out.

In some cases, however, the input (applied) grid potential variations may be too great in amplitude, even though the above precautions are taken. This is a result, usually, of too much regeneration, even though local oscillations may not be, at the same time, produced. With a regenerative receiver it quite frequently happens that operation will be without distortion until a loud tone causes the grid potential to shoot up and a loud blaring noise to be heard. In this case, sacrifice some audibility by reducing the tickler coupling (or readjusting the plate variometer) and with it the degree of regeneration. More nearly distortionless reception will result. This kind of distortion (due to too great input voltage) may also be caused by using too many stages of amplification with too little plate voltage in the circuits of the last amplifier tubes. Increase of plate voltage will frequently correct the trouble, but if not, then a small power amplifier tube may be used and large plate voltage applied to it. This is one reason why more than two or three stages of audio-frequency cascade amplification are inadvisable.

If the signal is very weak, serious distortion may be caused by a flow of grid current when the resultant grid potential periodically reaches a positive value. This would cause actual rectification in the grid circuit and, therefore, distortion of

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be to use the power tubes, which will permit of the large plate voltages without overloading. It is understood that the use of power tubes for amplification means extra expense for both the tubes and the plate batteries, but the result is usually worth the investment.

Telephone Receiver

Some telephone receivers are inherently prone to cause distortion, but this is a matter of selection of equipment. Also, if the audio-frequency plate current variations are of too great amplitudes the receiver diaphragms may rattle. The rattling is often directly due to such strong vibrations that the diaphragm hits the magnet poles. Sometimes, but not always, this rattling may be stopped by screwing the receiver cap on tighter to prevent the diaphragm from "jumping." Another cause of distortion in a telephone receiver is the resonance had at times between the natural period of vibration of the diaphragm and the tone frequency. This is again, however, a matter of selecting a pair of receivers to avoid the effect. Some "loud speakers" are made of a telephone receiver connected with a horn. In such cases resonance effects may be had in the diaphragm or in the horn itself if it is of metal. The design of an ideal loud speaker is still a goal to be attained, although some types approach the ideal quite closely.

Conclusion

Absolute absence of all distortion is almost impossible, since mechanical and electrical devices cannot be made absolutely perfect reproducers of the human voice. Perfection may be, and is, however, closely approximated when care is taken in

the design *and* operation of apparatus. This must not be taken to mean that very fine practical results in voice reproduction are only accomplished with great difficulty. Very fine results may indeed be obtained with present equipment if the comparatively few precautions are observed in operation. There probably will always be room for some improvement, however, as is the case with most things.

CHAPTER VII

PRACTICAL QUESTIONS AND ANSWERS

1. Can insulated wires be used in an antenna (or aerial)?

Ans. Yes, since the ether waves pass through insulating materials very readily.

2. How many wires are necessary in a receiving antenna?

Ans. Only one wire is necessary and there is no practical advantage in using more than one.

3. What kind of wire should be used?

Ans. Any kind of copper, aluminum, phosphor bronze or silicon bronze wire may be used. Even iron wire may be used in some cases, although it is not recommended. The wire used should have sufficient tensile strength to stand the strains imposed upon it by the weight of a span and the wind pressure against it. It should be of low resistance to high frequency alternating current. Since the radio-frequency oscillations in an antenna travel mostly upon the surface of the conductor, a copper clad wire may be used. A stranded phosphor bronze or silicon bronze wire has good tensile strength and is a very good conductor of high frequency current.

4. Is it absolutely necessary to insulate an antenna?

Ans. In dry weather an uninsulated antenna may be used without much leakage. In damp weather, however, it is quite necessary to have the antenna insulated at all points of support. Ordinary porcelain insulators are suitable.

5. Is it necessary to have the antenna as far as possible from metallic objects and structures?

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and 300 feet for the long waves. The antenna should not be over about fifty or sixty feet high from the ground or from the top of a building with the above lengths. If the height is reduced the wire may be made somewhat longer. A total length of wire (horizontal part plus lead-in) may well be about 150 or 160 feet for short wave reception.

9. How high should the antenna be?

Ans. This is partially answered in the above. In general, the higher the better. The height of an antenna erected upon a roof should be reckoned from the roof upwards, unless only a comparatively small portion of the antenna is directly above the roof. If the antenna is in an open space with no buildings or only small sheds beneath it, the height may be reckoned from the ground, providing the receiving apparatus is at or near the ground level.

10. Can a gas pipe, fire escape, drain pipe, and so forth, be used for an antenna?

Ans. In some cases any one of them might be used, providing efficient receiving apparatus is used at the same time. A gas pipe has been known to equal a rather poor antenna for receiving, but vacuum tubes and not a crystal detector were used. Bed springs may be sometimes used for antenna, providing the transmitting station is not too far away. The regular antenna gives better results usually in all cases.

11. How shall the ground be arranged?

Ans. A counterpoise ground composed of wires insulated from the earth and radiating from the receiving station at a height of about ten feet from the earth makes a very fine ground because of its comparatively low resistance. This is not possible in many cases, and even when possible the results sometimes do not justify the trouble and expense. This kind of a "ground" is highly desirable for transmitting, however.

The next best arrangement is connection to the cold water pipe. The connection should be well made. If this is not possible the ground wire may be connected to a radiator pipe and very good results are often had.

12. May a loop antenna be used to good advantage?

Ans. A loop may be used to very good advantage, providing it is of the proper dimensions for the wave lengths to be received, and providing the proper receiving equipment is used with it. Usually it is necessary to use radio-frequency cascade amplification if the transmitting station is some distance away. The loop antenna may be used to eliminate much of the interference encountered with a regular antenna and the loop should be arranged to rotate so that its position may be set for reception from a particular station. The loop is very directional.

13. May a loading coil be used to increase the wave length of the antenna?

Ans. Yes, a loading coil may be used, and if the amount of inductance required is not too great a variometer makes a very fine loading coil. If the antenna is "loaded" it is usually also necessary to load the secondary circuit of the tuner, if it is of the two circuit type. If there is a tertiary circuit (tuned-plate circuit) it is sometimes necessary to load that circuit also.

14. Why is a variometer better for a loading inductance than a tapped coil or one with a slider?

Ans. Because finer variations of inductance may be secured with the variometer.

15. What is the advantage of using a condenser in series with the antenna?

Ans. If the condenser is variable the wave length of the antenna may be made closely variable within certain limits. Another advantage is that the ratio of inductance to capacitance may be increased when tuning to a given wave length. An

increase in this ratio means increased selectivity or less liability to interference from stations transmitting on different wave lengths. Close tuning is very desirable, but the necessary adjustments are, of course, increased.

16. Is a vario-coupler better than a loose-coupler for use in a receiving circuit?

Ans. A vario-coupler usually gives the better results because it generally allows a variation of coupling without much separation of the two coils.

17. Is it advisable to use low values of capacitance (capacity) in the secondary condenser for tuning to a given wave length?

Ans. Yes; a predominance of inductance in this circuit for any given wave length is advisable when a vacuum tube detector is used. In any case, the increase in ratio of inductance to capacitance makes for sharper or closer tuning. In the case of very short waves it is often advisable to eliminate the secondary condenser entirely and use a variometer for tuning the grid circuit of a vacuum tube detector. In the case of crystal detector reception the elimination of the secondary condenser will often increase the signal strength but decrease to some extent the sharpness of tuning.

18. Will the use of a loading coil decrease the range of reception?

Ans. Not so long as the resistance of the winding is not too high. In practice it will not reduce the range, nor will it increase it.

19. Is it advisable to burn a vacuum tube filament very brightly?

Ans. No, it is not advisable to burn it any more brightly than is absolutely necessary. Burning it less brightly increases its life and very often a weaker signal in the head-phones is

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Ans. It increases the strength of the signals heard in the head-phones by feeding back energy from the plate to the grid circuit and reinforcing the potential variations applied to the grid. If the regeneration is great enough, local oscillations are self-generated, and undamped wave telegraph signals may be made audible by the beat method.

24. What is the disadvantage of regeneration in the reception of voice and music?

Ans. The delicate overtones and harmonics are usually lost, and if too much regeneration is used the voice and music are distorted.

25. What is the squealing noise sometimes heard with a regenerative receiver?

Ans. It is usually caused by too much regeneration and is the result of beat production produced by oscillations of different frequencies. These oscillations are self-generated in the circuits. Howling may be caused by circuits being run too close to each other. The wiring of plate and grid circuits should be separated from each other. Howling is often caused by incorrect adjustment of plate battery voltage.

26. Is a soft tube better than a hard tube for a detector?

Ans. The soft tube is more sensitive, but requires a very critical adjustment of filament current and plate battery voltage. The hard tube is somewhat less sensitive, but is very much easier to maintain in adjustment.

27. Why is it that a whistling noise is sometimes noticed when receiving from a radio-telephone station, no change having been made in the receiver or amplifier adjustments?

Ans. This is invariably caused by another station radiating continuous waves just different enough from those being received to produce a beat tone which sounds like a whistle. Sometimes these interfering oscillations are produced by a

nearby receiving station which is using regeneration and radiating some of the energy of the locally generated oscillations.

28. Why does placing the hands near the panel of a regenerative receiver change the signals?

Ans. Because there is a capacity effect of the body added to that of the receiver circuits. This changes the tuning. If the receiver were properly shielded this effect would not be noticed. Instead of shielding, circuits are often arranged in such a manner as to obviate the difficulty. No properly designed regenerative receiver will give this kind of trouble.

29. How can the "frying" noise sometimes heard with a soft detector tube be avoided?

Ans. By never allowing the filament to burn too brightly.

30. Will one filament lighting battery be sufficient for a vacuum tube detector and two stage amplifier?

Ans. Yes, one storage battery of the proper voltage and ampere-hour capacity is all that is required. The voltage should be six volts and the capacity either sixty or eighty ampere-hours. The larger battery is preferable if the receiver is to be used much and will not have to be charged as often as the smaller. A 100 ampere-hour battery is not too large, but it is more expensive.

31. In a simple tube detector circuit (no regeneration) why is the negative plate battery lead sometimes connected to the positive filament lead?

Ans. The filament battery voltage adds somwhat to the plate battery voltage and the plate potential is thereby increased.

32. What is the difference between a damped and an undamped wave?

Ans. The amplitudes of the damped waves decrease from a maximum to zero value, whereas those of an undamped wave do not decrease but are always the same.

33. What is meant by a wave train or group of damped waves?

Ans. It is a group of oscillations which diminish in amplitude to a zero value. The amplitudes diminish because they are damped, that is because energy is lost during each reversal of current.

34. Why is normal negative potential applied to the grid of an amplifier tube?

Ans. To avoid a grid current and to bring the operating point to the straight portion of the characteristic curve with a moderate value of plate potential. In the case of some tubes it is not necessary to do this if the plate potential and filament current are properly adjusted.

35. Why is a grid condenser used?

Ans. To avoid the use of a grid battery or other means of fixing the normal grid potential and also to operate the tube on the straight portion of the tube without eliminating the detector action. The latter would reduce the possibility of tube blocking because of large grid potential amplitude in the negative direction.

36. Why is it necessary to tune a receiving antenna circuit?

Ans. In order to produce in it the maximum possible amplitudes of signal current. In other words, to increase the strength of the received signal.

37. Why is it necessary to tune a secondary circuit?

Ans. To secure resonance between it and the antenna circuit and thereby increase the effect of the received signal upon a detector. Also to increase the selectivity of the receiver, providing the coupling is not too great.

38. Why is it desirable to have variable coupling between an antenna and secondary circuit?

Ans. To vary the selectivity of the receiver and to make

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formers. They may also be coupled by means of air core choke coils or air core coupling coils.

47. How may the tubes of an audio-frequency cascade amplifier be coupled together?

Ans. Usually by means of iron core transformers, although iron core reactances (choke coils) may also be used.

48. Is it advisable to operate a tube filament with constant current or constant voltage?

Ans. The latter because the filament life is thereby increased.

49. How is the filament current controlled?

Ans. By means of the filament rheostat.

50. What effect upon the current has an increase of resistance in a circuit?

Ans. The current decreases with increase of resistance providing the E. M. F. is kept constant.

51. What are electrons?

Ans. They are negative charges of electricity, the smallest possible particles of negative electricity. They are also current carriers when in motion between two points of different potential in any circuit.

52. What happens when the plate voltage is increased so that it will attract electrons as rapidly as they are emitted by the filament?

Ans. If the filament temperature is constant the plate current stops increasing no matter how much more the plate voltage is increased.

53. What happens when the plate voltage is kept constant and the filament temperature is gradually increased?

Ans. Up to a certain value of filament temperature the plate will attract electrons to it as fast as they are emitted. There will come a time, however, when the plate is unable to attract them at any greater rate unless its voltage increased.

Then, no matter what the increase in filament temperature, the plate current will not be any further increased.

54. If the plate is already attracting electrons at as great a rate as possible will an increase of grid potential affect the plate current?

Ans. No; because there can be no further increase in plate current due to attractive force exerted upon electrons.

55. How is the filament temperature increased or decreased?

Ans. By increasing or decreasing the filament current.

56. How is the plate potential increased or decreased, regardless of the grid?

Ans. By increasing of decreasing the plate battery voltage.

57. Why is it necessary to operate an amplifier tube with the proper value of plate potential and normal grid potential?

Ans. So that the operating point may be brought to the straight portion of the characteristic curve where equal variations of grid potential will produce proportional or symmetrical variations of plate current.

58. In this case why may the filament current not be varied?

Ans. Because, as has been stated, it is advisable to operate the filament at a constant potential and variations of any consequence should not be made in filament current unless they result in its reduction.

59. Is it desirable to have a step up of voltage from primary to secondary of an amplifier coupling transformer?

Ans. Yes, this is desirable, and the transformer should be designed to operate best with the particular tubes to be used.

60. What happens when the plate battery voltage is increased too greatly without any other changes being made?

Ans. The normal plate current may be made so great that saturation is reached and the grid potential variations have no effect upon it. Or, the operating point may be upon the upper

bend of the characteristic curve and distortion may take place in the case of amplification. In any event there is considerable useless drain on the plate battery. If the normal potential of the grid were made negative or more negative the operating point would be brought lower and, with it, the normal plate current.

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Continue

Dielectric, 24
Dielectric Constant, 24
Direct Current, 18
Distortion, Caused by Improper Grid Potential, 111
Distortion, Caused by Overloading of Tubes, 113
Distortion, Caused by Too Great Regeneration, 113
Distortion, in Amplifier Transformers, 111
Distortion in Amplifier Tube, 76
Distortion, in Telephone Receiver, 114

E

Edison Effect, 42
Effect of Gas in a Detector Tube, 71
Electrical Battery, 16
Electrical Circuit, 15
Electrical Current, 15
Electrical Pressure, 17
Electrical Resistance, 18
Electrical Resonance, 27
Electro-motive Force, 17
Electro-motive Force, Pulsating, 19
Electro-motive Force, Steady, 18
Electron, 44
Electron Emission from a Heated Filament, 44
E.M.F. (Electro-motive Force), 17
Ether, 32
Ether Oscillations, 32
Ether Vibrations, 32
Ether Waves, 32

F

Feed-back, 85, 86
Filament Battery, 43
Filament Construction, 39
Filament Current, Influence on Plate Current, 47
Filament Temperature Dependant Upon Filament Current, 43
Forced Oscillations, 90
Frequency, 20
Frequency, Audio, 62
Frequency, Resonance, 34
Frequency, Tone, 65

G

Gas in a Detector Tube, 71
Grid Battery, 49
Grid Charge, 49
Grid Charge, Leakage of, 68
Grid Condenser, 66
Grid Construction, 40
Grid Leak Resistance, 70
Grid Potential, Influence on Plate Current, 49
Grid Variometer, 101

H

Heterodyne Action, 73
Heterodyne, Self, 88
Heterodyne, Separate, 73, 88

I

Inherent Amplification, 76
Inductance, 21
Inductance, Loading, 95
Inductance, Mutual, 91
Induction, 30
Inductive Coupling, 91
Inductive Reactance, 22
Inter-electrode Tube Capacitance, 91
Ion, 72
Ionization, 72

L

Leakage, of Air Into Tube, 42
Leakage of Grid Charge, 68
Loading Inductance, 95

M

Modulation, 64
Methods of Coupling, 90
Mutual Inductance, 91

N

Normal Grid Potential, 56, 82
Normal Plate Current, 53

O

Ohm, 18
Ohm's Law, 18
Operation of Practical Circuits, 94
Operating Point, 57
Oscillations, 28
Oscillations, Continuous, 28
Oscillations, Damped, 29

Oscillations, Forced, 90
Oscillations in Ether, 32
Oscillations, Undamped, 28

P

Plate Battery, 42
Plate Construction, 40
Plate Current Dependent Upon Filament Current, 47
Plate Current Dependant Upon Grid Potential, 49
Plate Current Dependant Upon Plate Potential, 46
Plate Current, Normal, 53
Plate Potential, Influence on Plate Current, 46
Plate Variometer, 101
Potential, 44
Potential, Negative, 44
Potential, Positive, 44
Practical Circuits, 94
Primary Circuit, 90
Principle of Heterodyne Action, 73
Pulsating Current, 19

Q

Questions and Answers, 116

R

Radio Frequencies, 21
Radio Frequency Alternating Current, 28
Radio Frequency Amplification, 83
Radio Frequency Amplifier, Resistance Coupled, 104
Radio Frequency Amplifier, Transformer Coupling, 105
Radio Frequency Amplifier with Detector and Audio-frequency Amplifier, 107
Radio Frequency Regenerative Amplification, 85
Rate of Flow of Electric Current, 17
Reactance, 21
Reactance, Capacitive, 23
Reactance, Inductive, 22
Receiver for Weak Signals, a Suggestion, 109
Receiver, Single Circuit, No Regeneration, 94
Receiver, Single Circuit, Regenerative, 96
Receiver, Telephone, 59
Receiver, Three Circuit Regenerative for Short and Medium Waves, 102
Receiver, Three Circuit Regenerative for Short Waves, 101
Receiver, Two Circuit, Inductive Coupling, No Regeneration, 98
Receiver, Two Circuit, With Radio Frequency Amplifier, 106
Receiver, Two Circuit, with Two Stage Audio Frequency Amplifier, 103

R

Receptacles, 42
Rectification, 53
Rectification, Actual, 56
Rectification, Apparent, 54
Regenerative Amplification, Radio Frequency, 85
Relay Action, 52
Resistance, 18
Resistance, Grid Leak, 70
Resistance, Variable, 43
Resonance, 27
Resonance Frequency, 34
Rheostat, 43
Rotor, of Variometer, 91

S

Saturation Point, 50
Secondary Circuit, 90
Secondary, Untuned, 95
Self-heterodyne, 88
Self-inductance, 21
Sensitiveness of Detector Tube Dependant on Applied Potential, 83
Seperate Heterodyne, 88
Simple Detection, 60
Single Circuit Receiver, No Regeneration, 94
Single Circuit, Regenerative Receiver, 96
generative Receiver, 96
Space Charge, 48
Space Charge Effect, 48
Speed of Light, 32
Sockets, 42
Stator, of Variometer, 91
Stiffening a Circuit, 95

T

Telephone Receiver, 59
Tertiary Circuit, 101
Three Circuit Regenerative Receiver for Short and Medium Waves, 102
Three Circuit Regenerative Receiver for Short Waves, 101
Tickler, 96
Tone Frequency, 65
Train of Damped Oscillations, 29
Transformer Coupling, 80, 105
Two Circuit Receiver, Inductive Coupling, No Regeneration, 98
Two Circuit Receiver With Two Stage Audio-frequency Amplifier, 103
Two Circuit Regenerative Receiver, Inductive Coupling, 100
Tube Blocking, 68
Tube Capacitance, 91
Tube Choking, 68
Tube Construction, 38
Tuning the Receiving Antenna, 33

U

Undamped Oscillations, 28
Untuned Secondary, 95

V

Vacuum, 38
Vacuum Tube, 38
Vacuum Tube Amplifier, 76
Vacuum Tube as a Rectifier an Relay, 38
Vacuum Tube Detector, 59
Variable Capacitance, 24
Variable Resistance, 43
Variometer, 91
Variometer, Grid, 101
Variometer, Plate, 101
Velocity of Ether Waves, 32
Voice Distortion, 111
Volt, 18
Voltage, 18
Voltage Amplification Factor, 79

W

Wave Length, 32

Z

Zero Beat, 88