"Spirit of Electricity."

Principles of Electricity

applied to

Telephone and Telegraph Work

A Training Course Text
Prepared for Employees of the
Long Lines Department
AMERICAN TELEPHONE AND TELEGRAPH COMPANY
November, 1938
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PREFACE

THIS book is the outgrowth of certain less formal notes used for training purposes in the Long Lines Department in earlier years. Its origin may be traced to a set of such notes bearing the title, "Elements of Electricity Applied to Telephone and Telegraph Work". These were issued in 1922 in response to a long-standing demand by Long Lines employees for text material that would demonstrate the fundamental principles of electricity and magnetism by applications to the electrical circuits and apparatus with which they worked.

Since that time technical developments in communications work have called for revisions at varying intervals, and the demand for the book has increased steadily. By 1928 the annual requirements justified its printing for the first time. Another edition, somewhat revised, was printed in 1929 and, at the instance of the Department of Operation and Engineering, was made available to all Bell System Companies and regularly carried in stock by the Western Electric Company. A more extensive revision was made in 1930.

The present edition attempts to bring within the scope of the text some of the more important technical advances that have been made since 1930. This has resulted in a substantial increase in the size of the volume. Seven chapters have been added and ten other chapters have been materially revised or enlarged.

Because of the variety and scope of the subjects covered, the book is necessarily rather voluminous, although every effort has been made to treat each subject taken up as briefly as is consistent with a reasonably adequate presentation of the theory and fields of application involved. On the other hand, the book is not intended to be in any sense a complete treatise on electrical communication. Its subject is electrical theory and such descriptions of telephone or telegraph equipment and circuits as have been included are employed primarily for illustrating some of the applications of this theory to practice. The purpose has been to cover the essential general principles of simple electrical theory and to illustrate each principle briefly by one or more of its outstanding applications, rather than to duplicate the field of the technical instructions and specifications to be found in every telephone office.

The use of higher mathematics has been avoided entirely, and even the more elementary branches have been used as sparingly as possible. A general knowledge on the part of the reader is assumed of only those branches of mathematics ordinarily taught in High Schools, including Algebra, Geometry, Logarithms and Trigonometry. There is a slight departure, however, in the chapters dealing with the solution of alternating-current circuits and with transmission theory. Here it has been thought desirable to make use of Vector Notation. Though this may involve the introduction of certain simple mathematical concepts with which some readers are not familiar, the great simplification that is thus effected more than justifies the time spent in learning these new concepts.

For anyone who has difficulty in following the derivation of formulas or in solving illustrative problems, there is available a booklet of mathematical notes which explains in a brief and simple manner the essentials of all branches of mathematics used in the text. In some cases it may be advisable for the reader to review these notes along with his study of this text, taking up each item as he needs it. A knowledge of the more elementary principles of Physics and Mechanics is also assumed, but for anyone wishing to review these subjects hurriedly, an Appendix is included giving the important fundamental definitions and concepts.

A word of caution is perhaps needed regarding the circuit drawings, tables, and other statistical data included at various points in the text. The circuit drawings are used primarily as a means of illustrating the principles under discussion. While they are reasonably representative of current practice, they may or may not conform in detail with any actual situation. Similarly, the tables and other data represent the best information available at this time, but they are subject to change and are not intended as a substitute for current data as issued in formal instructions.

C. F. Myers,
Supervisor of Instruction,

L. S. Crosby,
General Personnel Supervisor.

32 Sixth Avenue,
New York City,
November, 1938.

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Principles of Electricity

applied to

Telephone and Telegraph Work

CHAPTER I

ELEMENTARY DEFINITIONS AND OHMS LAW

1. Introductory

Electricity is well adapted to transmitting from one place to another and delivering in convenient form quantities of energy, either large or small. It enables the power engineer to harness the energy of an isolated waterfall and to transmit it to some distant city where it may be utilized in the form of heat, light, mechanical work, or to change the state of certain chemicals. Likewise, it enables the telephone engineer to transmit the human voice thousands of miles without loss of intelligibility. Although in accomplishing such feats as these electricity is used with precision, our knowledge of its exact nature is limited to the now generally accepted, though not entirely complete, electron theory.

According to this theory the electron is the smallest possible charge of electricity, just as an atom is the smallest possible chemical particle of any substance. Electrons are all identical and each has a definite negative charge and a definite mass. By means of various ingenious methods some of which involve isolating individual electrons, these values have been carefully measured. The charge is found to be about 4.79×10^{-10} electrostatic units and the mass about $\frac{1}{1800}$ part of that of the hydrogen atom. These values are so infinitesimally small as to be almost meaningless to anyone except a trained physicist.

All substances are made up of electrons and corresponding positive particles called protons. Much less is known about protons than about electrons; it has been determined, however, that they are of approximately the same size as electrons but nearly two thousand times as heavy. The most widely accepted theory of the structure of the atom postulates that it is made up of a nucleus consisting of one or more protons surrounded by an equal number of electrons, the number and arrangement of the positive and negative charges being different for each chemical element. The simplest and lightest element, hydrogen, is made up of a nucleus consisting of a single proton around which a single electron revolves in certain fixed orbits. Heavier elements have nuclei consisting of a number of protons held together and partially neutralized by about half as many electrons and the remaining half of the electrons of the atom revolve about the nucleus in various orbits. In every case the number of electrons revolving in orbits about the nucleus gives the **atomic number** of the element and the number of protons contained in the nucleus gives the **atomic weight.** The electron has the properties of a wave as well as of a corpuscle and it is therefore not entirely accurate to think of it as being located at a point in space. Nevertheless some idea of its status as a part of the atom-model that we have been considering may be obtained if we note that its magnitude and space relationships relative to the atom as a whole are comparable to those of the earth in relation to the solar system. Meanwhile we must remember that the atom itself is almost inconceivably minute.

Electrons are attracted toward the atom nucleus and are repelled by one another with tremendous forces relative to their magnitude—forces infinitely greater than the gravitational forces with which we are familiar. For this reason the electrons in the atoms are for the most part held permanently in place in fixed orbits around the atom nucleus, but in the atoms of many materials one or more of the electrons farthest out from the nucleus is attached rather loosely and may by various means be drawn away from the atom altogether. When this happens to a number of the atoms making up a substance, as for instance a piece of metal, it contains less than its normal quota of electrons and is said to be positively charged. At the same time something else must be negatively charged or contain more than its normal number of electrons, for those taken away from the original substance must of course go somewhere. The means of bringing about such a condition are too numerous to mention, although we will consider several of them in later chapters.

The electron theory explains the flow of current in a conductor as being merely a stream of electrons moving along the conductor from atom to atom in a definite direction under the influence of an outside applied force or pressure. Substances whose atoms have loosely attached outer electrons are good conductors while substances to whose atoms all electrons are tightly bound contain normally very few free electrons and are therefore poor conductors, or good insulators.

While in our study of vacuum tubes in a later chapter we will deal with electrons as such, for most of our purposes we will not need to be familiar with all the details of electron theory, nor to know exactly what electricity is. Though we cannot observe it any more than we can actually see the force of gravity, we can observe its effect on other things about us. In this way we associate it with skilfully constructed mechanisms that are set in motion at the throw of a switch or the touch of a button, and with forms of energy that may be conveyed from place to place and changed from one state to another. We learn the conditions under which certain chemicals, or work performed in a mechanical way, can produce energy in an electrical form and how, through means of intelligently controlling it, we may employ it for practical purposes. In so far as this text is concerned, **our chief interest in electricity lies—first, in the many convenient ways in which it can be produced; second, in the means of transmitting it; and third, in the simple methods by which it may in turn produce active forces.**

In what follows, then, we will be principally concerned with the study of the more important laws of electrical circuits which have been deduced from observation and with certain of the practical applications of these laws. For a proper understanding of the electrical quantities with which we will deal it is desirable that the reader have a general knowledge of the more fundamental physical quantities and for the benefit of any one who may wish to refresh his memory regarding these matters a brief review of elementary physics may be found in Appendix 1.

2. The Electrical Circuit

An electrical circuit in its simplest form consists of a source of electromotive force and a continuous conducting path through a resistance from the positive terminal to the negative terminal. The source of electromotive force may be direct or alternating. If direct, the positive and negative terminals remain unchanged, but if alternating, their polarity is changed or reversed at periodic intervals. Accordingly, the study of electricity is usually divided into two parts; first, that dealing with circuits having sources of direct electromotive force, commonly called **direct current circuits**; and second, that dealing with circuits having sources of alternating electromotive force, commonly called **alternating current circuits.**

3. Electrical Pressure or Electromotive Force

The flow of electricity through a circuit is analogous in many respects to the flow of water through a closed system of pipes. Figure 1 shows a simple electrical circuit consisting of a battery connected to a resistance *ab*. Figure 2 shows a simple water circulating system. In the water mechanism, the pump creates a difference in pressure between the points *a* and *b*. This difference in pressure, or "pressure head", will cause water to flow from the outlet pipe *a*, through the small pipe to the flow meter, and return to the low pressure side of the pump at *b*. The amount of water that will flow will depend upon this difference in pressure and upon the nature of the small pipe. In the electrical circuit, the battery supplies the electrical pressure or electromotive force which causes electricity to flow from the high potential side of the battery. The amount of electricity that will flow depends upon this electromotive force and the nature of the resistance.

Fig. 1. Simple Electrical Circuit

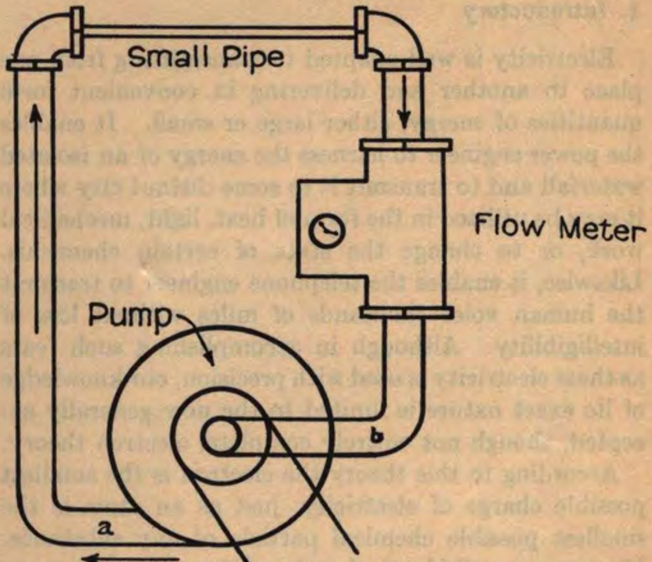


Fig. 2. Water Circulating System Analogous to Simple Electrical Circuit

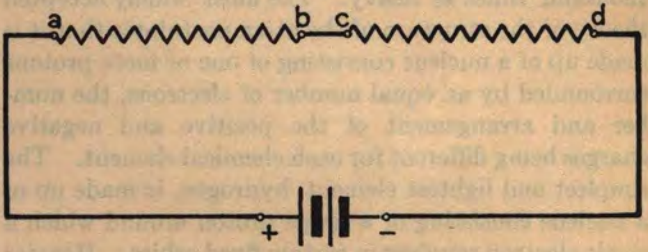


Fig. 3. Series Circuit

If a differential pressure gage were connected between the points *a* and *b* in the water system, it would register the difference in water pressure in some suitable unit such as "difference of head in feet". The electromotive force of the electrical circuit, on the other hand, is measured in terms of a unit called the **volt.**

It may be noted at this point that the terms electromotive force and difference in potential are commonly used synonymously. There is technical distinction, however, in that an electromotive force is always established by a battery or other primary source of electrical energy, whereas a difference in potential exists between any two points of a conductor through which current is flowing.

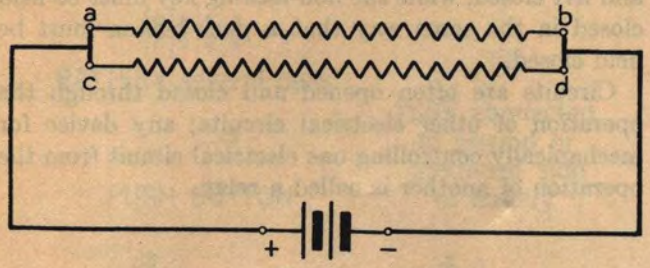


Fig. 4. Parallel Circuit

4. Resistance

In Figure 2, if the small pipe is made longer the flow of water will be decreased although the pump maintains the constant difference in pressure between the points *a* and *b*. Also, if the small pipe is decreased in size the flow of water will likewise be decreased. Though there is no simple unit for measuring this resistance to flow of water in a pipe, it is analogous to an electrical resistance in many respects. The unit of electrical resistance is called the **ohm** and is defined as **the resistance offered to electrical flow by a column of mercury one square millimeter in cross-section and 106.3 centimeters long at a temperature of zero degrees Centigrade.**

5. Current

In our water circulating mechanism we can describe the **rate of flow,** or the current, as the amount of water being circulated in gallons per second. In electrical work the current is expressed in amperes. **The measure of one ampere is the current which when passed through a solution of nitrate of silver between two silver plates under fixed conditions will cause a deposit due to electrolytic action of 0.001118 gram of silver per second.**

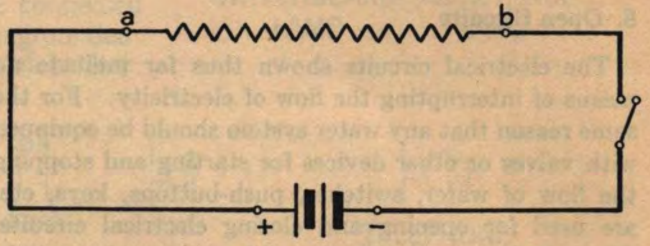


Figure 5

6. The Volt

The volt has been named as the unit of electrical pressure but its size has not been defined. **A source of electromotive force is said to have one volt of electrical pressure when it will establish a current of one ampere in a resistance of one ohm.**

7. Series and Parallel Circuits

A simple circuit may contain any number of resistances. Figure 3 shows such a circuit with two resis-

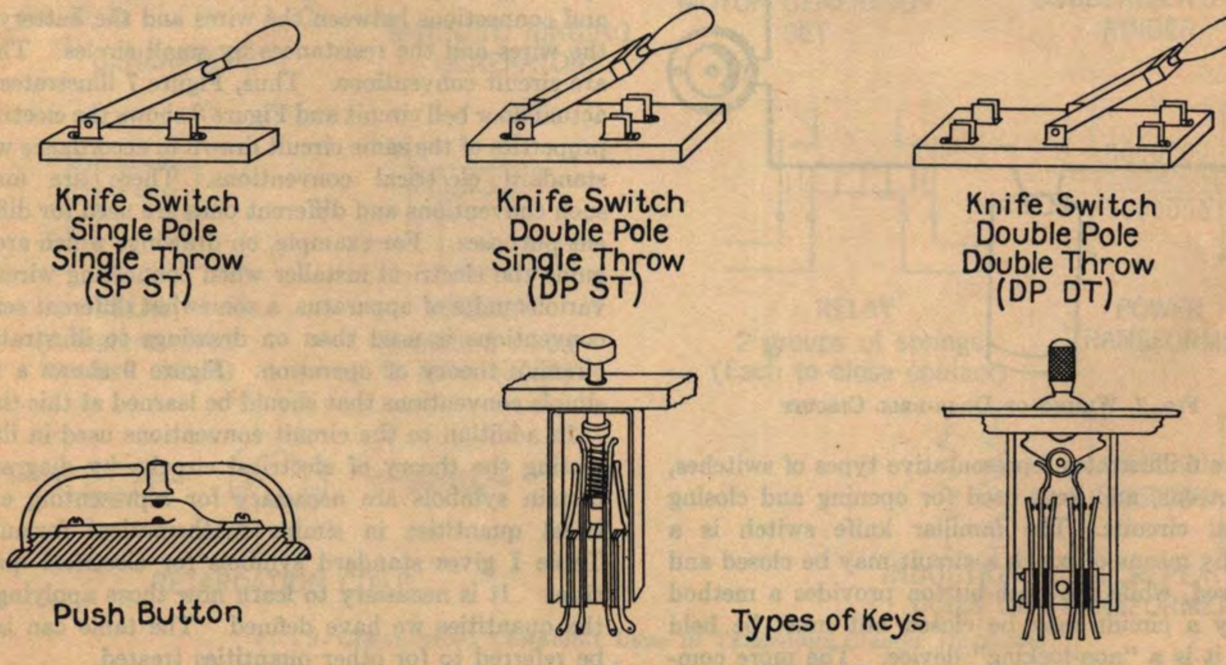


Fig. 6. Representative Devices for Opening and Closing Electrical Circuits

tances which when connected as shown are said to be "in series". Figure 4 shows another circuit with the same resistances connected "in parallel". Any number may be so connected in either case.

The current from a battery in a parallel circuit will divide between the various resistance branches but in a series circuit, as in the flow of water in a single pipe, it cannot divide and must be identical at every point. In other words, it must have an unchanged value in all parts of the circuit from the positive to the negative terminal of the battery.

8. Open Circuits

The electrical circuits shown thus far indicate no means of interrupting the flow of electricity. For the same reason that any water system should be equipped with valves or other devices for starting and stopping the flow of water, switches, push-buttons, keys, etc. are used for opening and closing electrical circuits. Figure 5 shows a circuit opened by means of a switch. Its metallic continuity is interrupted by the switch and when so interrupted there is no flow of electricity. This protects the source of electromotive force against unnecessary losses since when the circuit is open it cannot absorb any energy.

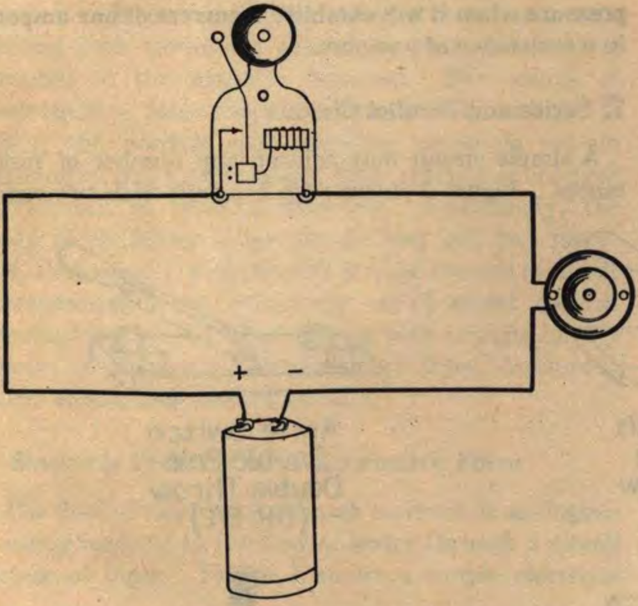


Fig. 7. Wiring of Door-bell Circuit

Figure 6 illustrates representative types of switches, push-buttons, and keys used for opening and closing electrical circuits. The familiar knife switch is a device by means of which a circuit may be closed and left closed, while the push-button provides a method whereby a circuit may be closed but must be held closed; it is a "non-locking" device. The more common designs of circuit closing apparatus used in telephone and telegraph work are called **keys.** When the circuit to be opened or closed does not carry an excessive current, these will perform the corresponding functions of the knife switch and the push-button; that is, they may be either locking or non-locking. The locking key may be operated or closed and left closed in the same way that the knife switch may be closed and left closed, while the non-locking key must be held closed in the same way that a push-button must be held closed.

Circuits are often opened and closed through the operation of other electrical circuits; any device for mechanically controlling one electrical circuit from the operation of another is called a **relay.**

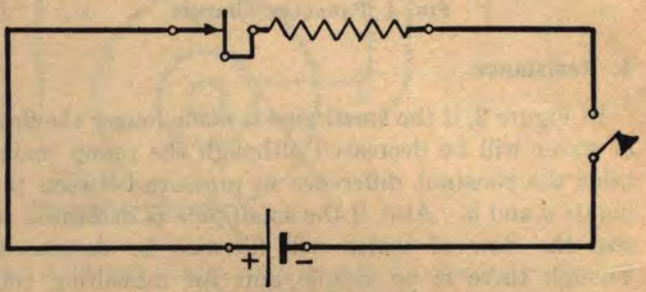


Fig. 8. Conventional Drawing for Circuit of Fig. 7

9. Electrical Symbols and Circuit Conventions

In the foregoing circuit diagrams we have represented the battery with a long and a short line, a resistance by a wavy line, connecting wires by straight plain lines, and connections between the wires and the battery or the wires and the resistances by small circles. These are circuit conventions. Thus, Figure 7 illustrates an actual door bell circuit and Figure 8 shows the electrical properties of the same circuit drawn in accordance with standard electrical conventions. There are many such conventions and different ones are used for different purposes. For example, on drawings which are to guide the electrical installer when connecting wires to various units of apparatus, a somewhat different set of conventions is used than on drawings to illustrate a circuit's theory of operation. Figure 9 shows a few simple conventions that should be learned at this time.

In addition to the circuit conventions used in illustrating the theory of electrical circuits by diagrams, certain symbols are necessary for representing electrical quantities in simple mathematical formulas. Table I gives standard symbols for electrical quantities. It is necessary to learn now those applying to the quantities we have defined. The table can later be referred to for other quantities treated.

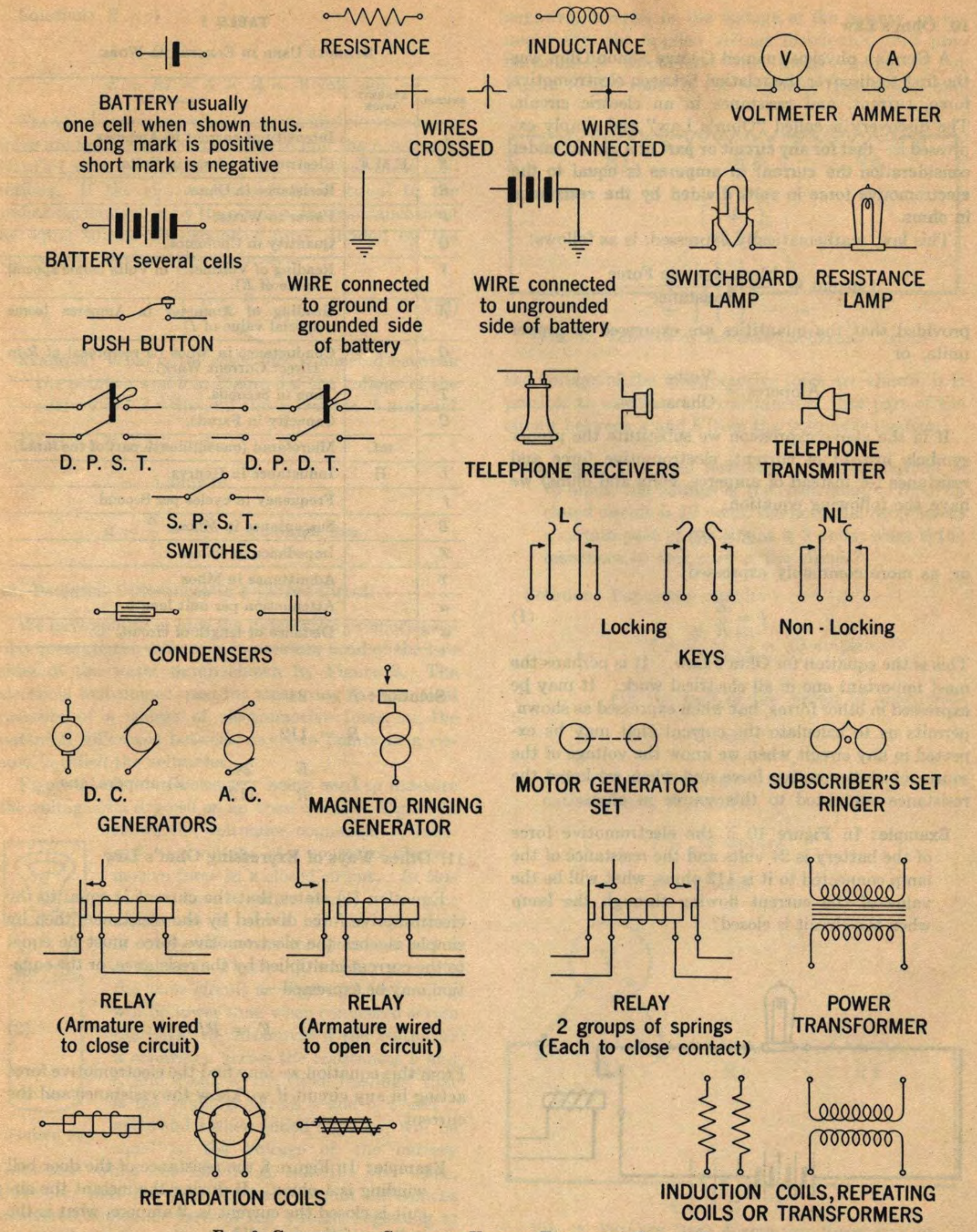


Fig. 9. Conventions Commonly Used in Telephone Circuit Drawings

10. Ohm's Law

A German physicist named George Simon Ohm was the first to discover the relation between electromotive force, current, and resistance in an electric circuit. The discovery is called "Ohm's Law" and simply expressed is—**that for any circuit or part of a circuit under consideration the current in amperes is equal to the electromotive force in volts divided by the resistance in ohms.**

This law, mathematically expressed, is as follows:

$$\text{Current} = \frac{\text{Electromotive Force}}{\text{Resistance}}$$

provided that the quantities are expressed in proper units, or

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}$$

If in the above expression we substitute the proper symbols instead of current, electromotive force and resistance (or instead of amperes, volts and ohms) we have the following equation:

$$I = E \div R,$$

or, as more commonly expressed,

$$I = \frac{E}{R} \qquad (1)$$

This is the equation for Ohm's Law. It is perhaps the most important one in all electrical work. It may be expressed in other forms, but when expressed as shown, permits us to calculate the current that may be expected in any circuit when we know the voltage of the source of electromotive force and when we know the resistance connected to this source in ohms.

Example: In Figure 10 if the electromotive force of the battery is 24 volts and the resistance of the lamp connected to it is 112 ohms, what will be the value of the current flowing through the lamp when the circuit is closed?

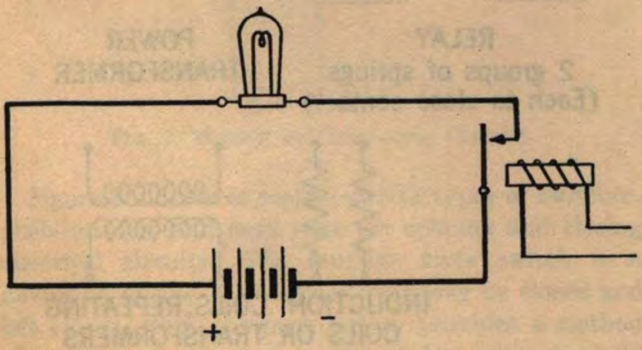


Figure 10

TABLE I

Symbols Used in Electrical Work

SYMBOL	ABBREVIATION	STANDS FOR
I		Intensity of current in Amperes.
E	E.M.F.	Electromotive force in Volts.
R		Resistance in Ohms.
P		Power in Watts.
Q		Quantity in Coulombs.
V		Reading of Voltmeter in Volts (some special value of E).
A		Reading of Ammeter in Amperes (some special value of I)
G		Conductance in Mhos (is reciprocal of R in Direct Current Work).
T		Time in Seconds.
C		Capacity in Farads.
	mf.	Microfarad (one millionth part of the farad).
L	H	Inductance in Henrys.
f		Frequency in cycles per Second.
B		Susceptance in Mhos.
Z		Impedance in Ohms.
Y		Admittance in Mhos.
α		Attenuation per unit length.
d		Distance or length of circuit.

Solution: $E = 24$

$R = 112$

$$I = \frac{E}{R} = \frac{24}{112} = .21 \text{ ampere, ans.}$$

11. Other Ways of Expressing Ohm's Law

Equation (1) states that the current is equal to the electromotive force divided by the resistance; then by simple algebra the electromotive force must be equal to the current multiplied by the resistance, or the equation may be expressed—

$$E = RI \qquad (2)$$

From this equation we may find the electromotive force acting in any circuit if we know the resistance and the current.

Example: In Figure 8 the resistance of the door bell winding is 4 ohms. If during the instant the circuit is closed the current is .2 ampere, what is the voltage of the dry cell?

Solution: $R = 4$

$I = .2$

$E = RI = 4 \times .2 = .8$ volt, ans.

The third case is one where current and electromotive force are known and it is desired to find the resistance. Ohm's Law may likewise be stated to cover these conditions. If the electromotive force is equal to the resistance multiplied by the current, the resistance must be equal to the electromotive force divided by the current or, algebraically expressed—

$$R = \frac{E}{I} \qquad (3)$$

Example: What is the resistance connected between the points *a* and *b* in Figure 5 if the voltage of the battery is 1.3 volts and the current is .5 ampere?

Solution: $E = 1.3$ volts

$I = .5$ ampere

$R = \frac{E}{I} = \frac{1.3}{.5} = 2.6$ ohms, ans.

12. Potential Differences in a Closed Circuit

We have spoken of how the differential pressure gage may measure the difference in pressure head of the two sides of the water pump shown by Figure 2. The electrical instrument used for measuring the electrical pressure of a source of electromotive force, or the potential difference between any two points in a circuit, is called the **voltmeter.**

Figure 11 shows a voltmeter being used to measure the voltage of a dry cell on an open circuit. Figure 12 shows the voltmeter connected to measure the voltage of a source of electromotive force in a closed circuit. In this case we have a simple circuit with three resistances in series. If the voltmeter is connected across the points *a* and *b* as shown in Figure 13, which represents the same circuit as Figure 12, its reading will be lower than when connected across the battery. Moreover if the voltmeter is connected across the resistances *b* and *c*, *c* and *d*, the three readings, that is the readings across *a* and *b*, *b* and *c*, and *c* and *d* when added together, will be equal to the voltage of the battery (measured while the circuit is closed). We learn, therefore, that **the sum of the potential differences measured across all parts of the circuit, beginning at the positive pole of the battery and returning to the negative, is equal to the voltage of the battery,** or we might say, the applied voltage distributes itself proportionately throughout the series circuit. If in Figure 13 the value of the resistance from *a* to *d* and the voltage of the electromotive force are known, it is possible to calculate the resistance of that part of the circuit between *a* and *b* from the voltmeter reading.

FIGURE 11

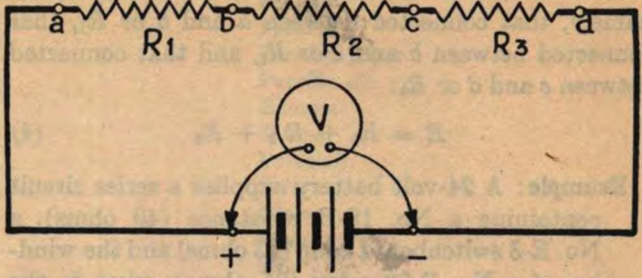


FIG. 12. VOLTAGE OF BATTERY ON CLOSED CIRCUIT

Example: The total resistance of a series circuit is 15 ohms, the voltage of the electromotive force on closed circuit is 10 volts, the potential drop across a certain part of the circuit is 3 volts; what is the resistance of this part of the circuit?

Solution: For entire circuit:—

$$I = \frac{E}{R} = \frac{10}{15} = .67 \text{ ampere.}$$

For the part of the circuit in question—

$E = 3$ volts.

I of series circuit is same in any part of circuit as for entire circuit, therefore,

$I = .67$ ampere

$E = 3$ volts

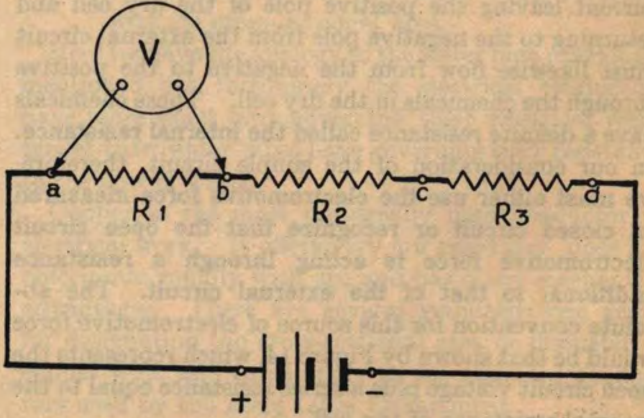


FIG. 13. VOLTAGE DROP ACROSS ONE RESISTANCE OF CLOSED CIRCUIT

$$R = \frac{E}{I} = \frac{3}{.67} = 4.5 \text{ ohms, ans.}$$

The total resistance of a series circuit is equal to the sum of all the individual resistances. In Figure 12 the total resistance is the sum of the three resistances; namely, that connected between *a* and *b* or R_1, that connected between *b* and *c* or R_2, and that connected between *c* and *d* or R_3:

$$R = R_1 + R_2 + R_3 \tag{4}$$

Example: A 24-volt battery supplies a series circuit containing a No. 18-B resistance (40 ohms), a No. E-3 switchboard lamp (43 ohms) and the winding of a No. B-22 relay (95 ohms); what is the total resistance of the circuit and what current will flow through the switchboard lamp?

Solution: $R = R_1 + R_2 + R_3$

$$= 40 + 43 + 95 = 178 \text{ ohms, ans.}$$

$$E = 24 \text{ volts}$$

$$I = \frac{E}{R} = \frac{24}{178} = .13 \text{ ampere, ans.}$$

13. Internal Resistance

If a dry cell, as shown in Figure 11, is placed in a closed circuit like that of Figure 3 and its voltage again measured with a voltmeter, a reading will be obtained which will be somewhat less than the reading on open circuit. This means that the electromotive force of the dry cell depends to some extent upon the value of the current it is furnishing. As the current is increased the electromotive force is decreased. This is due to a potential drop within the cell itself, which is merely a drop across a resistance in the same way that the potential measured across the terminals *ab* in Figure 12 is a drop across a resistance, excepting that in this case the resistance is inside the dry cell. Any electrical current leaving the positive pole of the dry cell and returning to the negative pole from the external circuit must likewise flow from the negative to the positive through the chemicals in the dry cell. These chemicals have a definite resistance called the **internal resistance.** In our consideration of the simple circuit, therefore, **we must either use the electromotive force measured on closed circuit or recognize that the open circuit electromotive force is acting through a resistance additional to that of the external circuit.** The absolute convention for this source of electromotive force would be that shown by Figure 14, which represents the open circuit voltage plus a series resistance equal to the internal resistance of the cell.

The ordinary dry cell has an internal resistance averaging about one ohm, but this greatly increases with the aging of the cell. In the telephone central office where storage batteries are used almost exclusively, the internal resistance is negligible for most direct current considerations.

14. Electrical Power

In the simple circuits we have thus far considered we have only dealt with resistance, electromotive force, and electrical current, but each of these circuits is actually converting energy from chemical to heat or some other form. They, therefore, have a definite power consumption or represent a definite transfer of power to some external device. The scientific unit for work is the joule, equal to about $\frac{3}{4}$ths of one foot-pound, and the scientific unit for rate of doing work or power is the watt, which is equal to about $\frac{3}{4}$ths of one foot-pound per second. The electrical units have been so derived as to facilitate convenient calculations in transforming expressions for power and energy from mechanical to electrical units. **In the electrical circuit if we multiply the electromotive force in volts by the current in amperes we have an expression for the power in watts.** The watt may, therefore, be defined as an electrical unit as well as a mechanical unit and is the power expended in a circuit having an electromotive force of one volt and a current of one ampere.

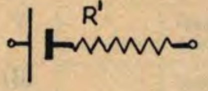


FIGURE 14

Because the watt is the connecting relation between mechanical units and electrical units, its value in terms of horsepower should be committed to memory (see Appendix I), and the following formula should be considered second only to Ohm's Law in importance:

$$P = EI \tag{5}$$

A somewhat more convenient form for determining the power expended in any given resistance is—

$$P = I^2R \tag{6}$$

This latter equation is apparent from Ohm's Law, which states that $E = IR$ and we may, therefore, substitute IR for E in Equation (5), which gives us I^2R.

Example: In Figure 12, what is the power expended in the resistance between terminals *a* and *b* if the potential difference is equal to 10 volts and the resistance is 5 ohms?

Solution: $P = EI$, and

$$I = \frac{E}{R} = \frac{10}{5} = 2,$$

then $P = EI = 10 \times 2 = 20$ watts, ans.

15. Quantity of Electricity

In Figure 2 we may say that the amount of water that will pass through the small pipe in a given interval of time is a definite number of gallons; thus the gallon is a unit of quantity of water. The amount of electricity that flows through an electrical conductor in one second when the current intensity (or rate of flow) is one ampere is called a **coulomb**. This is the unit for measuring quantities of electricity.

TABLE II

RESISTIVITY OF VARIOUS METAL CONDUCTORS AT 0°C.
(Compared to pure copper of same length and cross section)

KIND OF METAL	TIMES THE RESISTANCE OF PURE COPPER
Silver	.941
Copper (pure)	1.000*
Copper (annealed)	1.018
Copper (hard drawn)	1.025
Gold	1.423
Aluminum	1.679
Magnesium	2.788
Zinc	3.449
Tungsten (hard drawn)	3.474
Nickel	4.442
Iron (pure)	5.673
Platinum	6.301
Tin	6.730
Steel (soft)	7.564
Tantalum	9.359
Lead	12.692
German Silver	21.218
Steel (hard)	29.294
Mercury	60.301
Cast Iron (hard)	62.692

* Resistivity of pure copper 1.56 microhms per cm^3.

16. Properties of Electrical Conductors

A column of mercury was used to define the standard unit of resistance, the ohm. Other metals could have been used for this fixed standard but their dimensions would have been different from that of mercury. Dr. Ohm investigated the conducting properties of various kinds of metals and called those offering very high resistance to the flow of electricity "poor conductors" and those offering comparatively little resistance to the flow of electricity "good conductors". There is another classification for material having extremely high resistance, in fact so high as to give an open circuit for all practical purposes. These are called **insulators.**

TABLE III

INSULATING MATERIALS
(Given in the order of their approximate insulating properties)

Dry air
Shellac
Paraffin
Paraffin paper
Paraffin oil
Ebonite
Rubber
Porcelain
Sulphur
Glass
Mica
Silk
Varnish
Dry paper
Celluloid
Dry wood
Slate
Fiber
Distilled water
Alcohol

Table II shows a few conductors in the order of conductivity. Those offering the least resistance are at the top of the list. Table III shows a list of materials which are commonly used as insulators. There are many other good insulators but they are not all adaptable for use as such in practice.

In addition to the law showing the relation between electromotive force, current, and resistance, Ohm investigated the properties of conductors and established in addition to their relative values the following laws:

a. The resistance of any conductor varies directly with its length.

b. The resistance of any conductor varies inversely with its cross-sectional area.

Here we have the analogy to the water pipe previously mentioned but fortunately the electrical conductors have more exact laws governing their electrical resistances than water pipes have governing their resistance to the flow of water.

Copper is the most universally used conductor in electrical work. It offers very low resistance, does not deteriorate rapidly with age and has many mechanical advantages. There are several standard wire gages for designating the cross-sectional area or diameter of copper wire, and three apply to the standard conductors used by the Long Lines Department.

Table IV shows the standard gages of wire used by the Long Lines Department and their resistance values.

TABLE IV

Electrical Properties of Copper Conductors Standardized by Long Lines Department

CONDUCTORS	NO.	SIZE		WEIGHT	RESISTANCE		INDUCTANCE	CAPACITY
		Gage	Diameter in Inches	Lbs. per Wire Mile	*Ohms per Loop Mile	Ohms per 1,000 feet (single wire)	Henrys per Loop Mile	Mfs. per Loop Mile
Open Wire (12-inch spacing)	8	B.W.G.	.165	435	4.02 (use 4)	.381	.00337	.00915
	10	N.B.S.G.	.128	264	6.68	.632	.00353	.00871
	12	N.B.S.G.	.104	174	10.12 (use 10)	.959	.00366	.00837
Cable (side circuits of standard quadded cable)	10	A.W.G.	.102	168	10.55	.999	.001	.062
	13	A.W.G.	.072	82.6	21.15	2.003	.001	.062
	16	A.W.G.	.051	41.2	42.41	4.016	.001	.062
	19	A.W.G.	.036	20.5	85.01	8.05	.001	.062
	22	A.W.G.	.025	10.2	170.44	16.14	.001	.062

* These resistance values are for 20° C or 68° F; add 2/10 of 1% per degree Fahrenheit for higher temperatures.

Note: A.W.G. is American Wire Gage and is same as B. & S. which is Brown and Sharpe Gage. B.W.G. is Birmingham Wire Gage and N.B.S.G. is New British Standard Gage.

Simple rules for remembering the approximate constants of the **cable conductors** are as follows:

a. Five sizes of cable conductors are standard for the Long Lines Department and all are A.W.G. (or B and S).

b. The largest size is #10 A.W.G. Add three gages for successive smaller sizes,—thus #10, #13, #16, #19 and #22.

c. The diameter of #10 A.W.G. is slightly greater than one-tenth inch and its resistance is slightly greater than ten ohms per loop mile.

d. Smaller sizes double resistance by the addition of each three gages beginning with #10 as a base.

e. In cables, conductors are slightly longer than the cable lengths due to the spiraling effect. This will average about 5%.

f. Three sizes of conductors are standard for open wire; 104 (#12 N.B.S.G.), 128 (#10 N.B.S.G.) and 165 (#8 B.W.G.)

g. A #10 is the nearest A. W. Gage to 104 (#12 N.B.S.G.) but is slightly smaller.

CHAPTER II

THE SOLUTION OF D.C. NETWORKS

17. Parallel Circuits

Figure 15 shows two resistances connected in parallel. If we apply Ohm's Law to either of these, we shall find that the current in it must be equal to the potential measured across the particular resistance divided by its value in ohms; and for this particular circuit, the potential measured across either resistance is the potential of the battery. The battery is in reality supplying two currents, one through the resistance *ab* and the other through the resistance *cd*. These two currents are united and flow together in the conductors connecting the poles of the battery with the junctions of the two resistances. Likewise, for any circuit having two resistances connected in parallel, the current supplied to the combination must be greater than the current supplied to either of the resistances. If we think of the combination of resistances in Figure 15 as equivalent to a single resistance that might be substituted in their stead, we may say accordingly that the value in ohms of two resistances in parallel is less than that of either resistance taken singly.

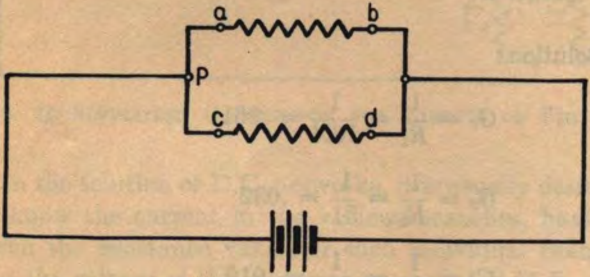


FIG. 15. TWO RESISTANCES IN PARALLEL

We may make calculations for determining the current in a parallel circuit such as is shown by Figure 15, but these are more complicated than for a simple series circuit having more than one resistance, such as is shown in Figure 3. The solution of a parallel circuit is accomplished with the aid of Kirchoff's Laws in addition to Ohm's Law.

18. Kirchoff's First Law

Kirchoff's First Law states that at any point in a circuit there is as much current flowing to the point as there is away from it. This applies regardless of the number of branches that may be connected to the point in question. The law can be interpreted by its application to point P in Figure 15. If I is the current being supplied by the battery to the combination of the two resistances in parallel, and I_1 and I_2 are the respective currents through the two parallel resistances, then—

$$I = I_1 + I_2 \qquad (7)$$

If we apply Ohm's Law to the entire circuit and let R represent the value of **the combined resistances in parallel**, we have—

$$R = \frac{E}{I} \quad \text{or} \quad R = \frac{E}{I_1 + I_2}$$

But

$$I_1 = \frac{E}{R_1} \quad \text{and} \quad I_2 = \frac{E}{R_2}$$

Therefore,

$$R = \frac{E}{\frac{E}{R_1} + \frac{E}{R_2}}$$

But in this latter equation, the E's can be cancelled and the equation written—

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

and if we simplify this compound fraction by simple algebra—

$$R = \frac{R_1 R_2}{R_1 + R_2} \qquad (8)$$

This gives an equation for calculating the combined value of two parallel resistances. Expressed in words it may be stated as follows: **To obtain the combined resistance of any two resistances in parallel, divide their product by their sum.**

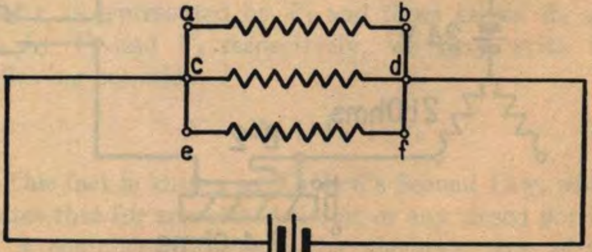


FIG. 16. THREE RESISTANCES IN PARALLEL

Example: What is the combined resistance of the inductive and non-inductive windings of a type-B relay used in a local A-board cord circuit if the inductive winding measures 16.4 ohms and the non-inductive winding measures 22 ohms?

Solution:

$$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{16.4 \times 22}{16.4 + 22} = 9.4 \text{ ohms, ans.}$$

Figure 16 shows a circuit having three resistances in parallel. A formula similar to (8) can be worked out for combinations of this kind, or calculations can be made to obtain the combined resistance of *ab* and *cd* and this value then combined with *ef*. But for problems involving more than two resistances in parallel, it is usually simpler to use the conductance method.

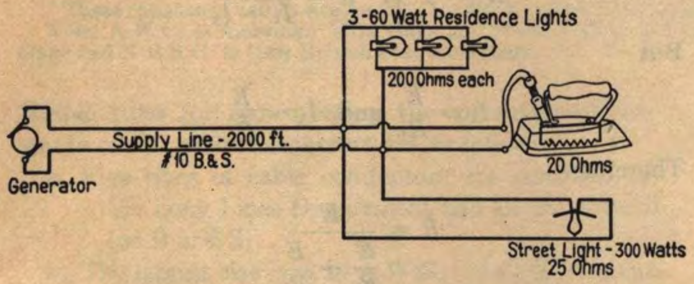


FIG. 17. SMALL ELECTRICAL POWER SYSTEM

19. Conductance

Conductance is defined in direct current work as the reciprocal of resistance. It is expressed by the symbol *G*, and for any single resistance—

$$G = \frac{1}{R} \qquad (9)$$

For a combination of resistances in parallel, such as is shown by Figure 16, the conductance of the combination is equal to the sum of the individual conductances, or—

$$G = G_1 + G_2 + G_3 \qquad (10)$$

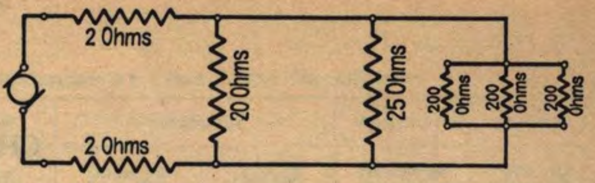


FIG. 18. CONVENTION FOR CIRCUIT OF FIG. 17

In a circuit having a number of resistances in parallel, it is often of advantage to solve for the total conductance of the circuit and then find its total resistance by taking the reciprocal of the total conductance.

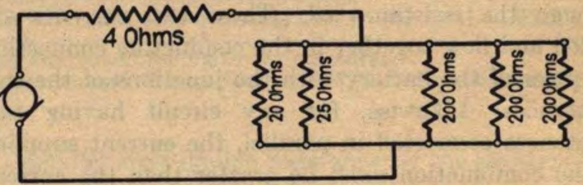


FIGURE 19

Example: If a B-3 relay has an inductive winding of 16.4 ohms, a non-inductive winding of 31 ohms, and these are shunted by an 18-U resistance (of 100 ohms), what is the resistance of the combination?

Solution:

$$G_1 = \frac{1}{R_1} = \frac{1}{16.4} = .061$$

$$G_2 = \frac{1}{R_2} = \frac{1}{31} = .032$$

$$G_3 = \frac{1}{R_3} = \frac{1}{100} = .010$$

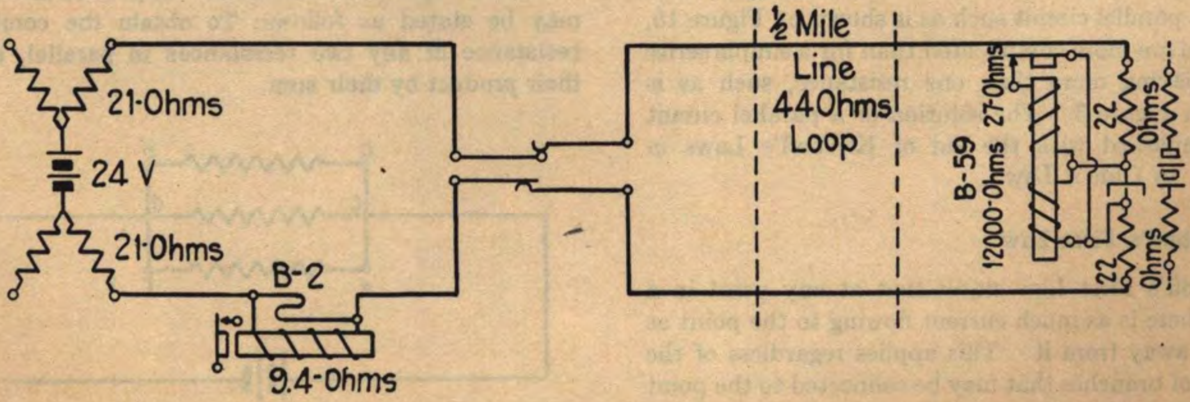


FIG. 20. CORD CIRCUIT AND SWITCHING TRUNK OF LOCAL TELEPHONE CONNECTION

$$\begin{aligned} G &= G_1 + G_2 + G_3 \\ &= .061 + .032 + .010 = .103 \end{aligned}$$

$$R = \frac{1}{G} = \frac{1}{.103} = 9.7 \text{ ohms, ans.}$$

20. Direct Current Networks

Several resistances may be connected in such manner as to form very complicated networks. In practice many circuits are of this type. For example, Figure 17 illustrates a 110-volt power distribution line supplying a residence and a street light. We may represent the electrical characteristics of such a circuit by the network shown by Figure 18, and can further simplify this network as shown by Figure 19. Power supply systems are usually complicated networks of this sort.

In the same way, many telephone circuits may be analyzed by drawing their equivalent network diagrams. Figure 20 represents an A-board local cord circuit connected to a local switching trunk having ½ mile of 19-gage cable. The equivalent network is shown by Figure 21.

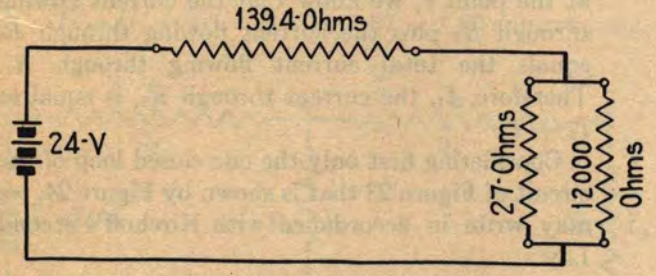


Fig. 21. Simplified Convention for Circuit of Fig. 20

In the solution of D.C. networks, it is usually desired to know the current in the various branches, having given the resistance values of each individual branch and the voltage of the source or sources of E.M.F.

Example: What is the value of the current through each winding of the B-59 relay in Figure 20?

Solution: We must first find the total current through both windings and have: $I = \frac{E}{R}$ where E is 24 volts and

$$R = 139.4 + \frac{R_1 R_2}{R_1 + R_2} = 139.4 + \frac{27 \times 12000}{27 + 12000}$$

$$= 139.4 + 26.9 = 166.3 \text{ ohms}$$

Then $I = \frac{24}{166.3} = .144$ ampere.

But the potential drop V across the two windings is equal to the current times the combined resistance of the two windings, or

$$\begin{aligned} V &= I \times \frac{R_1 R_2}{R_1 + R_2} \\ &= .144 \times 26.9 \\ &= 3.88 \text{ volts.} \end{aligned}$$

Then, applying Ohm's Law to each winding independently, we have—

$$I_1 = \frac{V}{R_1} = \frac{3.88}{27} = .144 \text{ ampere, ans.}$$

and

$$I_2 = \frac{V}{R_2} = \frac{3.88}{12000} = .00032 \text{ ampere, ans.}$$

21. Kirchoff's Second Law

When a current flows through a resistance there is always a difference in potential between the ends of the resistance, the value of which depends upon the current flowing and the value of the resistance. This difference in potential is commonly called the IR **drop** since it is equal to the product of the current and the resistance. This IR drop acts in the opposite direction to, or opposes, the E.M.F. which drives the current through the resistance.

In a closed circuit, such as is shown in Figure 22, the sum of the IR drops across the three resistances must be equal to the impressed E.M.F. Thus if the drop across the resistance R_1, as measured by the voltmeter, is represented by V_1 and those across R_2 and R_3 by V_2 and V_3 respectively, we may write the following equation—

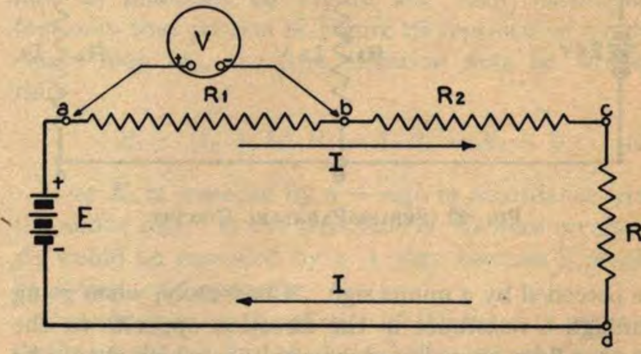


Figure 22

$$E = V_1 + V_2 + V_3 \tag{11}$$

This fact is known as Kirchoff's Second Law, which states that for any closed circuit or any closed portion of a complicated circuit, the algebraic sum of the E.M.F.'s and the potential drops is equal to zero.

In the case of Figure 22, Kirchoff's Second Law may be written as follows:

$$E - R_1I - R_2I - R_3I = 0 \qquad (12)$$

In solving any network problem, the first thing to do is to draw a good diagram. When the problem is to be solved by Kirchoff's Laws, the next step is to assign letters to all the unknowns in the circuit and to put arrows on the circuit diagram to indicate the **assumed** directions of current flow. If Kirchoff's First Law is applied at the junction points of a network, the number of unknowns may be kept down. Thus, if three wires meet at a point, and I_1 and I_2 have already been assigned to the currents in two of them, the third current may be designated as their sum or difference, depending upon the assumed direction of current flow. That is, instead of using a third unknown I_3, we will have $(I_1 + I_2)$ or $(I_1 - I_2)$. This will eliminate one equation. However, at least as many equations as there are unknowns must be written.

In the practical applications of Kirchoff's Laws, the correct use of algebraic signs is fundamentally important. When one sign has been given to the electromotive force in the direction of current flow, the opposite sign must be given to the IR drops in the direction of current flow. In other words, when going through a resistance in the same direction as the current flow, there is a drop in voltage and this voltage should be preceded by a minus sign. Conversely, when going through a resistance in the direction opposite to the current flow, there is a rise in voltage which should be preceded by a plus sign. We may for convenience accept the clockwise direction as positive, or accept as positive **all E.M.F.'s which tend to make a current flow in a clockwise direction, and as negative all potential drops due to this flow of current as well as any E.M.F.'s in the circuit tending to make current flow in the opposite direction.** It is immaterial whether the directions of current flow assumed are actually correct as long as they are consistent throughout the network. The signs of the answers will show whether or not the assumed directions are correct. When the value of a current found by solving the equations is preceded by a – sign, it merely means that the actual direction of flow is opposite to the direction which was assumed.

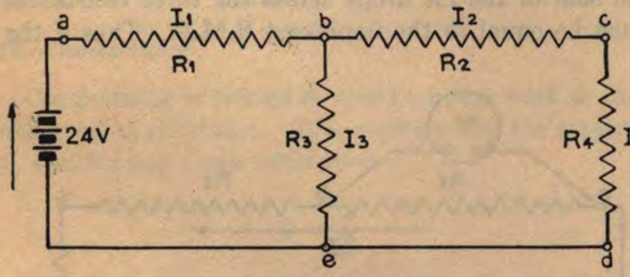


Fig. 23. Series-Parallel Circuit

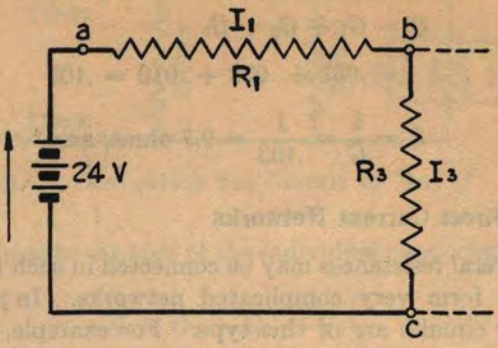


Figure 24

Example: Find the current values in each branch of Figure 23, if the resistance of $R_1 = 5$ ohms, $R_2 = 10$ ohms, $R_3 = 15$ ohms, and $R_4 = 20$ ohms, and the voltage $E = 24$ volts.

Solution: We may first assume that the direction of current flow is clockwise through both branches of the network. Applying Kirchoff's First Law at the point b, we know that the current flowing through R_3 plus the current flowing through R_2 equals the total current flowing through R_1. Therefore, I_1, the current through R_1, is equal to $I_2 + I_3$.

Considering first only the one closed loop of the circuit of Figure 23 that is shown by Figure 24, we may write in accordance with Kirchoff's Second Law:

$$E - R_1(I_2 + I_3) - R_3I_3 = 0 \qquad (a)$$

and for the closed loop shown by Figure 25—

$$E - R_1(I_2 + I_3) - R_2I_2 - R_4I_2 = 0 \qquad (b)$$

We thus have two independent equations containing two quantities which are unknown, namely, I_2 and I_3. Substituting the known values of E, R_1, R_2, R_3, and R_4, these equations may be written as follows:

$$24 - 5(I_2 + I_3) - 15I_3 = 0 \qquad (a)$$

$$24 - 5(I_2 + I_3) - 10I_2 - 20I_2 = 0 \qquad (b)$$

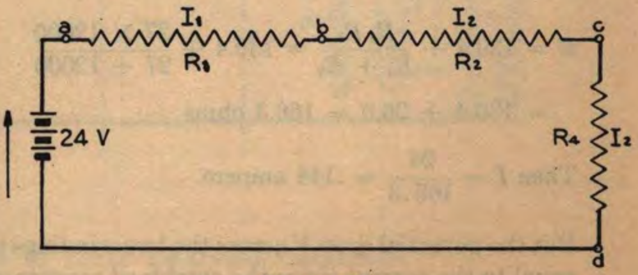


Figure 25

Simplifying, the equations become—

$$24 - 5I_2 - 20I_3 = 0 \tag{a}$$

$$24 - 35I_2 - 5I_3 = 0 \tag{b}$$

Multiplying equation (a) by seven, and subtracting equation (b) from it, we have—

$$\begin{array}{rl} 168 - 35I_2 - 140I_3 = 0 & \text{(a)} \\ 24 - 35I_2 - \quad 5I_3 = 0 & \text{(b)} \\ \hline 144 \qquad\quad - 135I_3 = 0 & \end{array}$$

or,

$$I_3 = \frac{144}{135} = 1.07 \text{ amperes, ans.}$$

Then, substituting this value in Equation (b), we have—

$$24 - 35I_2 - 5\,(1.07) = 0$$

or,

$$I_2 = \frac{24 - 5.35}{35} = \frac{18.65}{35} = 0.53 \text{ ampere, ans.}$$

and finally, the main current,
$I_1 = (I_2 + I_3) = 0.53 + 1.07 = 1.60$ amperes, ans.

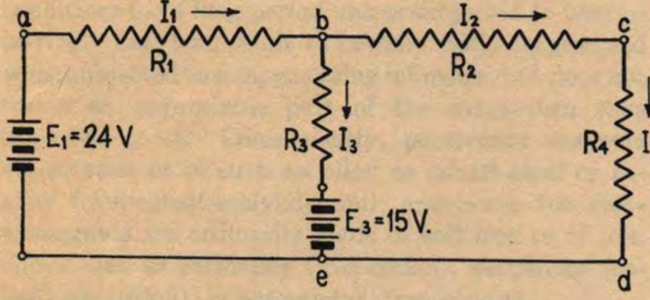


FIG. 26. CIRCUIT CONTAINING MORE THAN ONE SOURCE OF E.M.F.

22. Networks Containing More Than One Source of E.M.F.

If a network contains more than one source of E.M.F. it may be solved by either of two distinct methods. The first of these is to solve for current values in each branch of the circuit considering only one E.M.F. at a time, and to add or subtract as the case may be, the current values thus obtained for the individual branches. If we have, for example, a network such as is shown by Figure 26, containing the sources of E.M.F., E_1 and E_3, we may imagine that E_3 is omitted and the solution under this condition would be similar to that for Figure 23. The current values thus obtained would be those due to the E.M.F. designated as E_1. Those due to the E.M.F. designated as E_3 could be solved by assuming E_1 short-circuited and solving the network shown by Figure 27. The values obtained for branches 1 and 3 in the two cases would be subtracted and the values for branches 2 and 4 would be added.

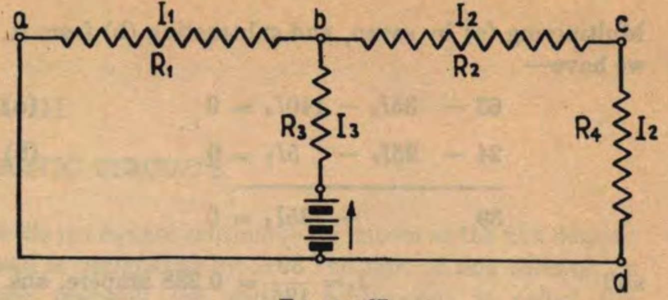


FIGURE 27

The second method is to apply Kirchoff's Laws, taking all E.M.F.'s into consideration in each equation. This is the more general method. In this case, we have two sources of E.M.F. which oppose one another. In applying Kirchoff's Second Law to this network, we would consider the main source of electromotive force, or E_1, as positive, and the second source, or E_3, as negative. A good rule to remember in this connection is: The potential due to the battery electromotive force rises in passing through a battery from the − to the + terminal and should, therefore, be preceded by a + sign. Conversely, in passing through a battery from the + terminal to the − terminal, the potential due to the battery drops and should be preceded by a − sign.

In this case, we may assume the directions of current flow as indicated on Figure 26. Now, considering first only that portion of Figure 26 represented by the closed loop *abe*, the first equation may be written thus—

$$E_1 - (I_2 + I_3)\,R_1 - I_3R_3 - E_3 = 0 \tag{a}$$

Here E_3 is preceded by a − sign in accordance with the above rule. If the terminals of E_3 were reversed, E_3 would be preceded by a + sign because it would be aiding, not opposing, E_1.

Considering now the portion of the network without the *be* branch, we find the loop similar to that shown in Figure 25 and we may write the following equation—

$$E_1 - (I_2 + I_3)\,R_1 - I_2R_2 - I_2R_4 = 0 \tag{b}$$

Substituting the known values of E_1, E_3, R_1, R_2, R_3, and R_4, these equations may be written as follows:

$$24 - (I_2 + I_3)\,5 - 15I_3 - 15 \quad = 0 \tag{a}$$

$$24 - (I_2 + I_3)\,5 - 10I_2 - 20I_2 = 0 \tag{b}$$

Simplifying, the equations become—

$$9 - \quad 5I_2 - 20I_3 = 0 \tag{a}$$

$$24 - 35I_2 - \quad 5I_3 = 0 \tag{b}$$

Multiplying (a) by seven, and subtracting (b) from it, we have—

$$\begin{array}{rrrl} 63 - & 35I_2 - & 140I_3 = 0 & \quad \text{(a)} \\ 24 - & 35I_2 - & 5I_3 = 0 & \quad \text{(b)} \\ \hline 39 & & - 135I_3 = 0 & \end{array}$$

and $$I_3 = \frac{39}{135} = 0.288 \text{ ampere, ans.}$$

Substituting this value of I_3 in the simplified form of equation (a) above, we have—

$$63 - 35I_2 - 40.3 = 0$$

from which

$$I_2 = \frac{22.7}{35} = 0.648 \text{ ampere, ans.}$$

Then, $(I_2 + I_3) = .648 + .288 = .936$ ampere, ans.

CHAPTER III

MAGNETS AND MAGNETIC CIRCUITS

23. Nature of Magnetism

Magnetism is a peculiar property of iron, nickel, and cobalt and is most pronounced in iron and certain of its alloys. As with electricity, our knowledge of its exact nature is incomplete. Our study here will be confined to those laws concerning the magnetic properties of materials learned through observation and to the behavior of such materials under practical conditions.

The early Greeks were familiar with a natural stone that would attract bits of iron. It was a form of iron ore, now known as magnetite, and the power of attraction possessed by it was called "magnetism". It was later learned that this magnetic property could be artificially given to steel or iron by means of an electrical current.

Magnets as we know them may be classed as **permanent magnets** and **electromagnets.** A hard steel bar when magnetized becomes a **permanent** magnet because it tends to retain its magnetism under normal conditions for a long period unless subjected to heat or jarring. Soft iron tends to become easily magnetized when subjected to a magnetizing influence, but does not retain an appreciable part of the magnetism thus imparted to it. Consequently, **permanent magnets** are of **steel** or of such an alloy as **cobalt-steel** or **realloy** (iron-cobalt-molybdenum), and cores for **electromagnets** are ordinarily made of **soft iron** or of iron alloys such as **permalloy** (iron-nickel), **perminvar** (cobalt-iron-nickel), or **permendur** (iron-cobalt).

24. Permanent Magnets

Figure 28 represents a rectangular steel bar magnet which will attract bits of iron brought near to either end, and will exert a force of either repulsion or attraction upon other magnets in its vicinity. The influence of a magnet may be detected in the space surrounding the magnet in various ways, and is found to vary inversely as the square of the distance from the magnet. To account for this phenomenon, the magnet is said to establish a magnetic field, which is represented by the curved lines in Figure 28. These curved lines are merely a convention for illustrating the effect of the magnet. They are commonly known as "lines of magnetic induction". All the lines as a group are referred to as the "flux", and designated by the symbol ϕ. The unit of flux is one line and is called the "maxwell". The flux per unit area, or the number of maxwells per square centimeter, is known as the flux density and is designated by B. The unit of flux density, or one maxwell per square centimeter, is called the "gauss".

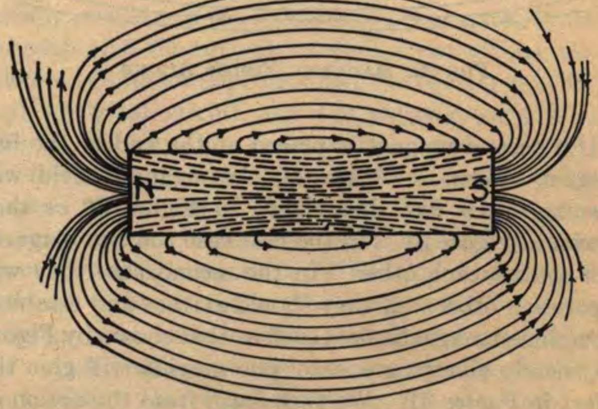


FIG. 28. MAGNETIC FIELD AROUND BAR MAGNET

The lines of magnetic induction, previously mentioned, are thought of as passing through a magnet from the south to the north pole, leaving the magnet at its north pole and reentering the magnet at its south pole. This is the significance of the arrows shown on the lines of magnetic induction in Figure 28.

Lines of magnetic induction are always closed loops. Each line or loop may be thought of as acting within itself somewhat like a stretched rubber band in that it tends to become as short as possible. Yet each of these lines or loops has a repelling effect upon its neighbors, tending to keep them separated from each other. A vivid graphical demonstration, not only of the presence

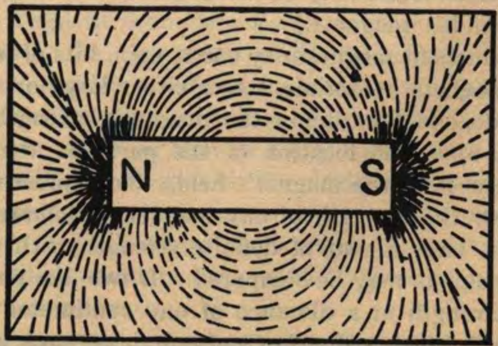


FIGURE 29

of the magnetic field but of the arrangement of the lines of magnetic induction, may be had by sprinkling iron filings upon a glass plate placed above a magnet. Figure 29 shows how the filings arrange themselves under such a condition.

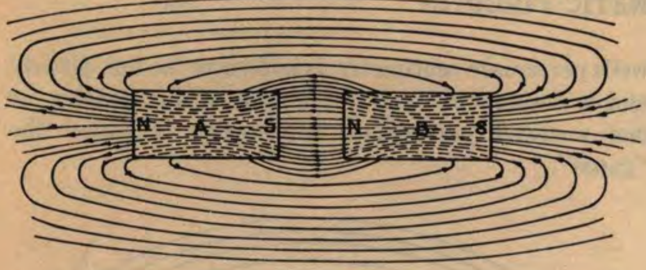


FIG. 30. MAGNETIC FIELDS AIDING

If a second magnet is placed at the end of the bar magnet shown in Figure 28, the magnetic field will become either like that shown in Figure 30 or that shown in Figure 31. In the first case the two magnets will attract each other. In the second case they will repel each other. If they should attract and establish a combined magnetic field such as that shown by Figure 30, merely changing ends of one magnet will give the effect in Figure 31. We then learn from the action of one magnet toward another that the two ends of any magnet are unlike. These two ends are called the **poles** and for convenience, the pole having one influence is called the **north pole** and that having the opposite influence is called the **south pole**. The distinction comes from the earth, which is itself a magnet. If a bar magnet is suspended so as to swing freely, that pole which tends to point toward the north is called the north seeking or north pole; the other is called the south pole. The needle of the surveyor's compass is an application of a bar magnet free to swing on its pivot and its north pole will point to the earth's magnetic pole located near the geographical north pole. (However, since the earth is itself a magnet, it may be noted that with this conventional definition, the pole nearest the geographical north is the earth's south magnetic pole inasmuch as it attracts unlike or north seeking poles of suspended magnets.)

A permanent magnet may exert, upon bits of iron or other magnetic materials, forces either large or small. These depend first, upon the magnet's strength and second, upon the location of the particles attracted with respect to the magnet's field. To express quantitatively the strength of any magnet, it follows that we must have a unit of definite strength with which other magnets may be compared. **If two like poles of equal strength at a distance of one centimeter apart repel each other with a force of one dyne, each is said to be a pole of unit strength or is called a "unit pole".** The unit pole is very small but if we can imagine one end of a small magnet sufficiently isolated from the other end and placed in the magnetic field about the magnet in Figure 28, it will tend to move in the path of the curved line nearest it and in the direction designated by the arrow if it is a north pole, and opposite to the direction designated by the arrow if it is a south pole. While the force one magnet exerts upon another depends upon the nature of their combined fields, there is an approximate law which states that the force of attraction or repulsion varies inversely as the square of the distance separating the poles in question and directly as the strength of the magnets. Expressed as an equation this law may be written—

$$f = \frac{m_1 m_2}{d^2}$$

Here f is in dynes, d in centimeters and m_1 and m_2 are the strength of the magnets in unit poles.

If the strength of the magnet in Figure 28 is doubled, the magnetic field will be strengthened in proportion, and may be represented by a more congested arrangement of lines of magnetic induction. The force that will be exerted upon a unit pole located at any point in the magnetic field will depend upon the **intensity** of the field, or the **extent to which the lines of magnetic induction at that particular point are crowded.** The unit of field intensity is that field which will exert a force of one dyne upon a unit pole. It is therefore usually expressed in dynes per unit pole and represented by the symbol H. It follows that if a pole of K units be placed in a magnetic field of intensity H, the force acting on the pole will be $f = K \times H$.

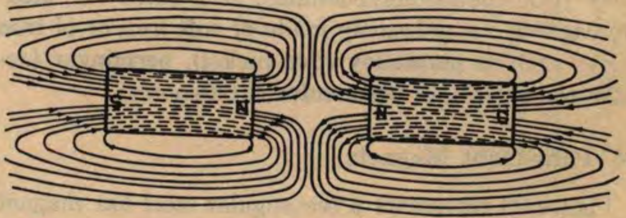


FIG. 31. MAGNETIC FIELDS OPPOSING

We have said in a preceding paragraph that the flux density B is the number of lines of magnetic induction passing through a unit area. By definition, unit flux density is one line of magnetic induction per square centimeter. We have also said that lines of magnetic induction are merely conventions for illustrating the effect of a magnetic field. Such a line may therefore be defined arbitrarily. In practice, it is usually defined as that magnetic induction per square centimeter in air, which exists in a magnetic field having an intensity of 1 dyne per unit pole. Thus in air the field intensity H and the flux density B have the same numerical value and are sometimes spoken of in the same units, that is, in lines per square centimeter or gausses. Such nomenclature leads to confusion, however, and it is better to think of field intensity only in terms of dynes per unit pole.

In Figure 28 we see that the magnetic field has greatest intensity nearest the poles. If we wish to create a field of greater intensity we can accomplish it by bending the magnet into the form of a horseshoe like that shown in Figure 32. Here each line emerging from the north pole returns to the south pole of the magnet through a much shorter distance than that represented by any one of the curved loops in Figure 28. If, with a unit pole or by other means, we should test the strength of the field between the two poles of a horseshoe magnet, we would find it more intense than that of a straight magnet of equal strength. We learn then that we not only shorten each line represented by a closed loop but, in so doing, create more lines. This gives us for a magnetic circuit an analogy to the electrical circuit. In the electrical circuit, if we have a conductor connected between the positive and negative poles of a battery and decrease the resistance by decreasing its length, we increase the current strength. In the case of the magnet, if we decrease the lengths of the paths from the north to the south pole by bending the magnet into the form of a horseshoe, we increase the number of lines of magnetic induction.

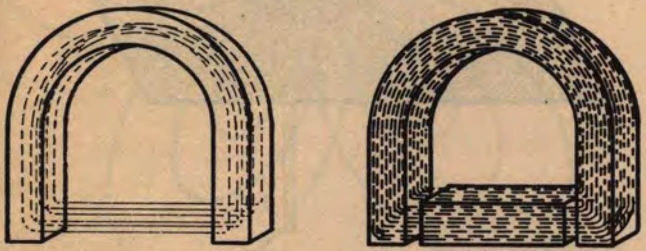


Figure 32

Again, if we insert between the poles of the horseshoe magnet in the space now filled with air, a piece of soft iron or other magnetic material, we greatly increase the number of lines of magnetic induction existing in the circuit formed by the magnet itself and the soft iron used for closing this circuit between the north and south poles. This is analogous to decreasing the resistance of an electrical circuit by substituting a conductor of lower resistance for one of higher resistance.

25. The Magnetic Circuit

As electric current is caused to flow in an electric circuit, so magnetic flux can be established in a magnetic circuit. Magnetic flux ϕ, or the total number of lines of induction existing in the circuit, then, is in some respects analogous to electric current.

The flux density B or the number of lines of induction per unit area may be written—

$$B = \frac{\phi}{A} \tag{13}$$

where A is the area taken at right angles to the direction of the flux and ϕ is the flux through and normal to this area.

It follows from the discussion of lines of magnetic induction being increased by the insertion of materials other than air in the magnetic field, that the flux density depends upon the materials of the completed magnetic circuit and the strength of the magnet, in the same sense that the current strength in any given cross-section of conductor depends upon the resistance of the closed electrical circuit and the electromotive force applied. We may then consider that there is a property of the magnetic circuit which is analogous to the resistance of an electrical circuit. This property is called **reluctance.** Likewise, there is a property of the magnet which is analogous to the electromotive force of a battery. This is called the **magnetomotive force** and is expressed in "gilberts". For the complete magnetic circuit, we may apply an equation identical in form to Ohm's Law which, in words, may be stated— **the flux for any given magnetic circuit is equal to the magnetomotive force of the magnet divided by the reluctance of the closed circuit.** Expressed mathematically, this may be written—

$$\phi = \frac{M}{R} \tag{14}$$

where the symbol for flux is ϕ, for magnetomotive force, M, and for reluctance, R. This may be compared to Ohm's Law as expressed by Equation (1),

$$I = \frac{E}{R}$$

In practice the above magnetic equation is seldom used in the form shown but from this relation we derive other equations dealing with flux density, field intensity and the magnetic properties of iron. These are treated along with the discussion of electromagnets, from which we shall learn more of the terms magnetomotive force and reluctance, as well as their respective units.

While we may see that in many respects the magnetic circuit is analogous to the electrical circuit, it is well to remember that the analogy is not complete since there are other respects in which the two circuits differ. The two more important of these to bear in mind are as follows:

(a) A magnetic circuit can never be entirely opened; a magnetic field must exist at all times in the vicinity of a magnet. For this reason the magnetic circuit would be more nearly analogous to the electrical circuit submerged in water. When the continuity of the metal conductors forming such an electrical circuit was broken, the circuit would be completed through the liquid across its gap. Though the current strength might be decreased in this way, the circuit could never be entirely opened; neither would the current be limited to the submerged metal conductors. There would be other flow surrounding the conductors but not of such great intensity as inside the metal conductors.

(b) Flux is not strictly analogous to current since current is rate of flow of electricity while the nature of flux is more nearly a state or condition of the medium in which it is established.

26. Electromagnets

If a straight vertical conductor carrying an electrical current pierces a cardboard as shown in Figure 33, there may be detected on the plane of the cardboard a magnetic field with lines of magnetic induction encircling the conductor. To illustrate further, if iron filings are sprinkled on the cardboard, they will form visible concentric circles as shown by Figure 34.

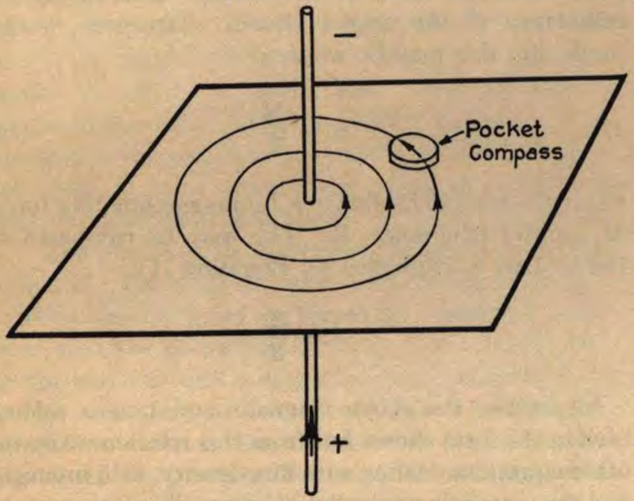


Fig. 33. Magnetic Field Around Current-Carrying Straight Conductor

Through such observations as these, we learn that **wherever an electrical current is flowing there is an established magnetic field, and the loops formed by the encircling lines are always in a plane perpendicular to the electrical conductor.**

If in either Figure 33 or 34 a compass is placed near the conductor, the needle will align itself tangent to some one of the many concentric circles. If the compass is moved slowly around the wire, the needle will revolve on its pivot and maintain its tangential relation. It will also be found that the direction of the lines with respect to the direction of current flow is that represented by the arrows in Figure 33.

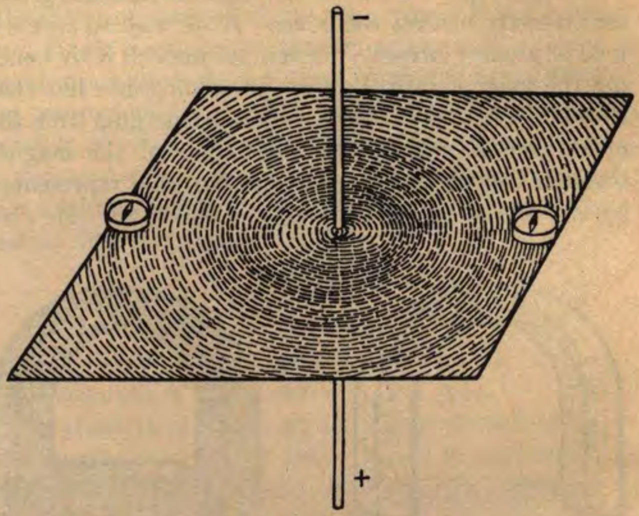


Figure 34

Though this magnetic effect is a positive one, under the conditions shown in the figures and even with a very strong current in the conductor, the magnetic field represented by the concentric circles is relatively weak. But if the electrical conductor is made to form a loop, the groups of lines forming concentric circles for every unit of the conductor's length can be imagined as arranging themselves as shown in Figure 35. The closed loops are no longer circular. They become more crowded in the space inside the loop of wire and less crowded in the space outside the loop of wire. Accordingly, the intensity of the magnetic field within the loop is increased. This may be more clearly seen by considering the single line which Figure 36 shows enclosed by imaginary boundaries both within and without the loop of wire. We may express the field intensity in terms of the cross-section of this imaginary bounding space. At the point p inside of the loop the intensity is such as to give one line for the area represented by the cross-section a, and at the point P outside of the loop the intensity is such as to give one line for an area represented by A.

If, instead of having an electrical circuit consisting of one loop of wire, we have a circuit consisting of several turns of wire, such as the winding on the spool shown in Figure 37, the intensity of the field is multiplied by the number of turns of wire. Thus, the value of the field intensity at any point for two turns would be twice that for a single loop; for three turns, three times that for a single loop; and for n turns, n times that for a single loop, providing the turns are sufficiently

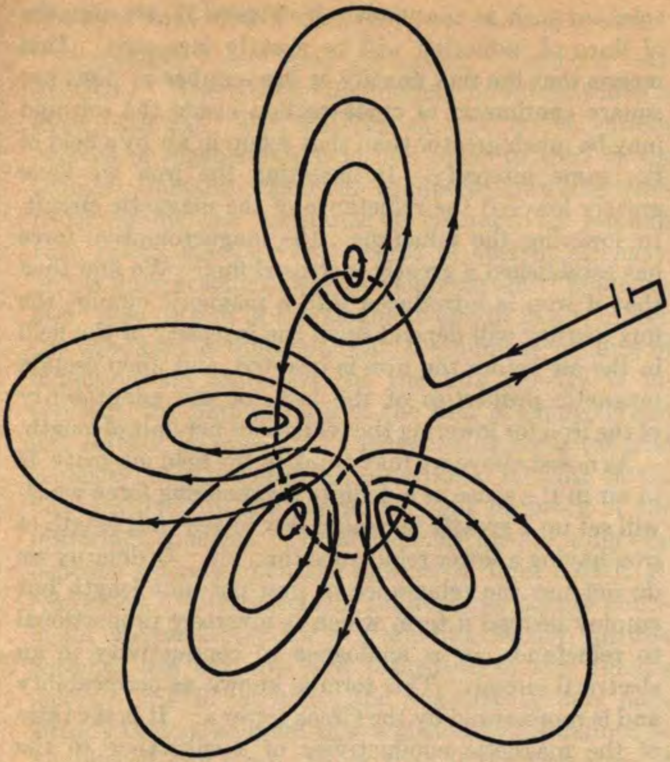


Fig. 35. Magnetic Field Around Current-Carrying Loop

close together so that the flux leakage between successive turns is negligible.

Comparing Figure 37 with Figure 28, we find that the current in the coil of wire creates a magnetic field similar to that of the bar magnet. In Figure 33 the relation between direction of current flow and direction of lines of induction was shown by arrows. We use this same relation in Figure 35 and going one step farther, we may determine the north and south poles of the magnet formed by the coil shown in Figure 37. A simple way to remember the relation for any electrical winding is illustrated by Figure 38. Here if we assume current flowing through a winding in the direction of "turn" for a right-hand screw, the lines leave the point of the screw which is the north pole and enter the slot which is the south pole.

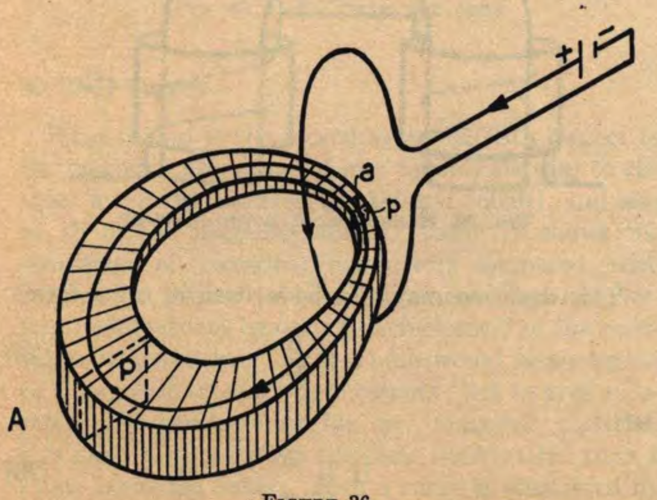


Figure 36

In Figure 32 the number of lines in the magnetic circuit established by the horseshoe magnet was greatly increased by the insertion of a piece of soft iron between the north and south poles. Likewise, if in Figure 37 the spool shown has a soft iron core, the number of lines will be greatly increased. Further, if the core of the winding is bent in the shape of a horseshoe as shown in Figure 39, we have the customary electromagnet which is capable of exerting considerable force.

27. Relation Between Current and Field Intensity

If we increase the current strength in the winding shown by Figure 37, we will find that the intensity of the magnetic field is increased proportionately. Thus, the value of H, or the magnetic field intensity in air, is directly proportional to the current flowing in the winding. We may accordingly establish a definite relation between field intensity and electrical current for any given set of conditions.

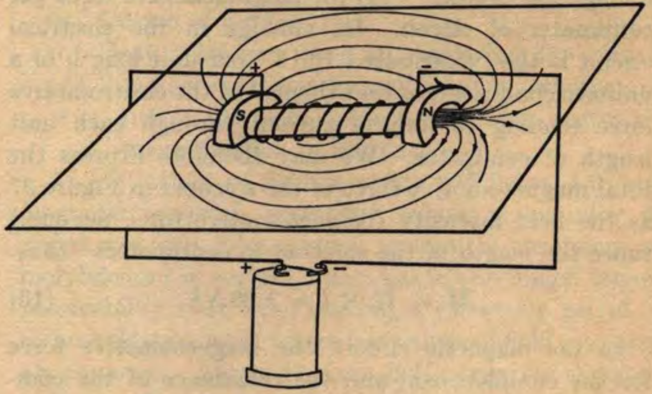


Fig. 37. Magnetic Field Around Air-Core Solenoid

A winding such as that shown in Figure 37 is called a "solenoid". If such a solenoid is very long as compared to its diameter, and is constructed with one turn of wire to each centimeter of length, and the current in the winding is one ampere, the field intensity in the air on the inside of the solenoid can be shown to be equal to .4 × 3.1416 or 1.26 dynes per unit pole. The field intensity inside any long air-core solenoid would then be expressed by the following equation:

$$H = \frac{1.26NI}{l} \qquad (15)$$

where N is the total number of turns of the winding, I is the current in amperes and l is the length of the solenoid in centimeters. This equation is apparent since one turn of wire per centimeter for a current of one ampere gives 1.26 dynes per unit pole, and the intensity is increased proportionally to the current and to the number of turns of wire per centimeter of length.

In electrical practice, the term "ampere-turn" is frequently used, which merely means the product of N and I in Equation (15).

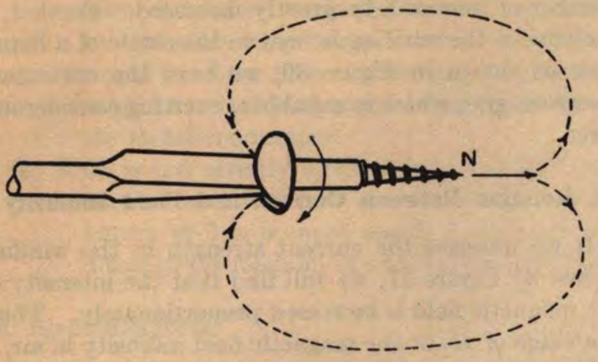


Figure 38

The field intensity H may be thought of as the force tending to produce magnetic flux in each unit length of a magnetic circuit. It is the **magnetomotive force per centimeter of circuit.** Its analogy in the electrical circuit is the "distributed EMF" per unit length of a uniform conductor, or that element of the electromotive force tending to force a current through each unit length of conductor. We may therefore express the total magnetomotive force of the solenoid in Figure 37 as the field intensity (magnetomotive force per cm.) times the length of the solenoid in centimeters—thus:

$$M = H \times l = 1.26NI \qquad (16)$$

In the magnetic circuit, the magnetomotive force for the complete coil and the reluctance of the complete circuit are not the most convenient quantities for practical calculations. The magnetic circuit, though analogous in many respects to the electrical circuit, does not take a definite form. The lines of induction may not be distributed equally throughout the cross-section of the circuit. There is always present the surrounding air which is an electrical insulator but is not a magnetic insulator. We, therefore, use another equation more frequently than Equation (14), which is likewise in the form of Ohm's Law, but is expressed in terms of quantities **per unit** of magnetic circuit rather than for the complete magnetic circuit.

28. Flux Density, Field Intensity and Permeability

In discussing field intensity we have thus far considered it only in connection with magnetic circuits in air. However, we have seen that if iron is inserted in a solenoid such as that shown by Figure 37, the number of lines of induction will be greatly increased. **This means that the flux density or the number of lines per square centimeter of cross-section** inside the solenoid may be much greater than that set up in air by a field of the same intensity. In inserting the iron we have greatly lowered the reluctance of the magnetic circuit. In lowering the reluctance, the magnetomotive force has established a greatly increased flux. We find then that if iron is introduced into a magnetic circuit, the flux density will depend upon the intensity of the field in the air before the iron is inserted, and upon certain magnetic properties of the iron, or the adaptability of the iron for lowering the reluctance per unit of length.

As noted above we may think of the field intensity H in air in the sense of a definite **magnetizing force** which will set up a greatly increased flux in any unit length of iron having a lower reluctance than air. Ordinarily we do not use the reluctance of iron per unit length but employ instead a term which is inversely proportional to reluctance, or is analogous to conductivity in an electrical circuit. This term is known as **permeability** and is represented by the Greek letter μ. It is the ratio of the magnetic conductivity of a substance to the magnetic conductivity of air. Using this ratio, we may express the flux per unit cross-section in the form of an equation as follows:

$$\frac{\phi}{A} = H \times \mu \qquad (17)$$

or

$$B = H \times \mu \qquad (18)$$

where B is the conventional symbol for flux density.

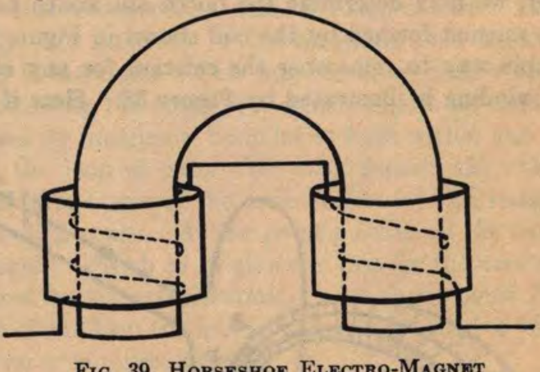


Fig. 39. Horseshoe Electro-Magnet

This equation may also be written in other forms:

$$\mu = \frac{B}{H} \qquad (19)$$

or

$$H = \frac{B}{\mu} \qquad (20)$$

29. Magnetic Properties of Iron

Permeability has been compared to electric conductivity. There is one distinction, however, which is most essential. The stability of iron under various degrees of magnetization is not equal to that of the ordinary metallic electrical conductor. In the electrical circuit the resistance or conductivity remains very nearly fixed for any degree of current strength, unless there is some change in temperature. While the same may be said of the magnetic circuit in air, in iron the condition is different. As the number of lines of induction are increased (or the flux density is increased), the permeability of the iron is changed, and any further increase in the magnetizing force (or field intensity) may not mean a proportional increase in the flux density. In simpler terms, that property of the iron which enables it to establish more lines of induction depends entirely upon the number of lines that it already has. After a certain number per square centimeter of cross-section, or a certain flux density, the iron becomes less effective and regardless of any further increase in field intensity, the flux density may have already become so great that additional lines cannot be established any more readily than if the core were of air. This condition is called the "saturation point" of the iron.

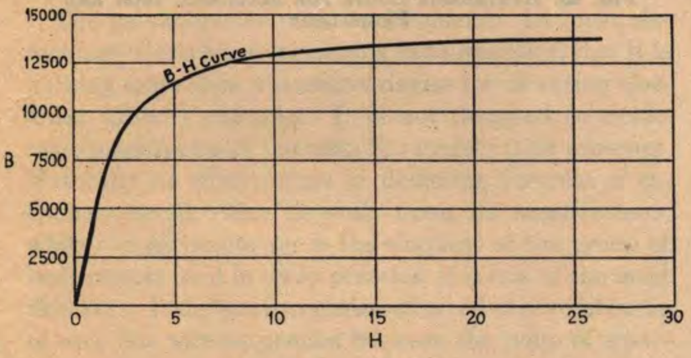


Fig. 40. B-H Curve for Iron

30. B-H Curves

What is said in the preceding article with respect to the magnetic properties of iron applies likewise to the other magnetic materials (nickel and cobalt), and also to all of the magnetic alloys. Table II shows the resistance of electrical conductors compared with copper. A similar table could be compiled for electrical conductivity by taking the reciprocal of the resistance values shown. Such a table would be analogous to a magnetic table for permeability; but to give accurately the permeability for any magnetic material, it is necessary to show a complete curve rather than a single tabulated value. Such a curve is illustrated by Figure 40 which is taken for a magnetic iron used by the Western Electric Company in the manufacture of certain relays and other telephone apparatus. This curve was determined after the iron had been annealed for three hours at a temperature of 900° C. Every magnetic material has some such curve. A magnetization curve will ordinarily depend upon many things, such as—

(a) Whether cast iron, wrought iron, steel or an alloy of these with other metals.
(b) Degree of purity.
(c) Heat treatment used in preparing the metal.
(d) Previous magnetic history; that is, whether or not it has been subject to a high degree of magnetization in the past.

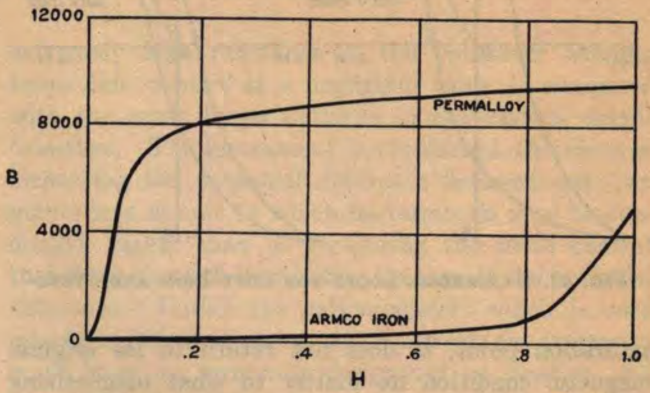


Fig. 41. B-H Curve for Permalloy

At low values of field intensity (H below 1.0) the magnetic material, permalloy, which is an alloy of nickel and iron (plus a small amount of chromium or molybdenum in certain cases) has a very much higher permeability than iron, making it extremely useful in communication work where low values of field intensity are common. Figure 41 gives B-H curves for a standard permalloy and a standard iron for low values of H; it will be noted that the magnetic flux for a given magnetizing force is very much greater in the permalloy than in the iron over the range covered.

31. Hysteresis

If a piece of iron is subjected to an increasing magnetizing force until the saturation point is reached and then the magnetizing force is decreased to zero and established in the opposite direction until the saturation point is again reached, and if the magnetizing force is again decreased to zero and again increased until the cycle is completed, the relations between flux density and field intensity for all parts of the cycle may be represented by a curve such as one of those shown by Figure 42. This is called the "hysteresis loop". Here it is seen that after the iron has once reached the

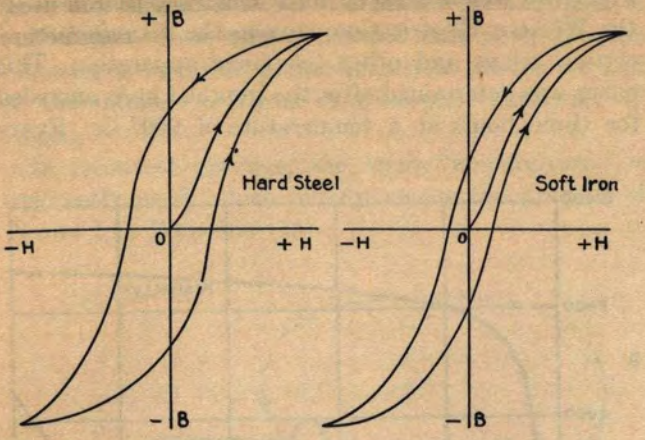


FIG. 42. HYSTERESIS LOOPS FOR SOFT IRON AND STEEL

saturation point, it does not return to its original magnetic condition no matter to what magnetizing forces it may be subjected. For example, an inspection of the hysteresis loop shows that iron will retain a certain degree of magnetization after the magnetizing influence has been reduced to zero. This is particularly true of hard steel and is the reason that all permanent magnets are made of hard steel or a material having similar characteristics. The two curves of Figure 42 illustrate the difference in the hysteresis loops of hard steel and soft iron. The fact that soft iron has a narrow hysteresis loop makes it adaptable for the cores of electromagnets. We may note here also that the hysteresis loop for permalloy is very much narrower than that for soft iron at low values of magnetizing force. This is illustrated in Figure 43 where the hysteresis loop for permalloy and iron are compared.

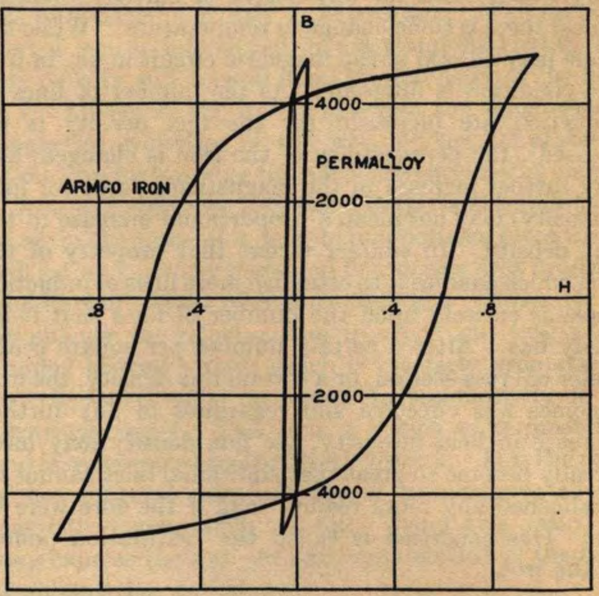


FIG. 43. HYSTERESIS LOOPS FOR MAGNETIC IRON AND PERMALLOY

CHAPTER IV

ELECTRICAL MEASUREMENTS IN DIRECT-CURRENT CIRCUITS

32. The Measuring Instruments

We have been discussing such electrical quantities as the volt, the ampere, the ohm and the watt, but little has been said about the electrical instruments that are used to measure these quantities. The more commonly used group of instruments includes the galvanometer, the voltmeter, the ammeter, the Wheatstone bridge (including a galvanometer) the megger, and the wattmeter. At this stage of our study it is important that we learn the fundamental principles of these measuring instruments and the distinction between instruments designed for different purposes, but it is not important that we study long descriptions of their construction or those details of design pertaining only to their manufacture. They are ordinarily sealed at the factory and are seldom repaired by the field maintenance man. Let us, therefore, concern ourselves with the intelligent and skillful use of them and only with those principles of their operation that are essential to this.

The galvanometer may be considered the most elementary of electrical measuring instruments in that it is nothing more than a sensitive device for detecting electrical (direct) currents. It is not designed to determine magnitudes of currents but merely their presence. Naturally its effectiveness in detecting currents of extremely small value depends upon its sensitiveness; while the galvanometer is the simplest of the group of instruments used in daily practice, it is one of the most delicate. It ordinarily consists of a coil of several turns of very fine wire suspended between the poles of a permanent horseshoe magnet and held in a neutral position by the torsion of fine suspension fibres, or other equally delicate means. The suspended coil carries a light needle which stands at the center of a fixed scale when the coil is in its neutral position with respect to the permanent magnet. A very small current through the suspended coil will set up a magnetic field that will tend to align itself with the field of the permanent magnet and thereby cause a deflection of the needle from its neutral position on the fixed scale.

The voltmeter (of the revolving coil type) is a galvanometer more ruggedly designed, having an extremely high resistance and with the scale so calibrated as to read the potential impressed on the terminals of the instrument. Of course the voltmeter deflection is caused by a very small current flowing through the high resistance winding, but in most simple circuits the extremely high resistance of the voltmeter winding keeps this current at a negligible value as compared with the much larger currents in the various circuit branches. The instrument is considered, therefore, as measuring the potential difference between any two points in a circuit to which its terminals may be connected, rather than as measuring the small current that flows through its winding because of the potential difference. Unlike the galvanometer, which is used merely to detect the presence of current, the voltmeter must have its terminals designated as positive and negative (unless it is a "zero center scale" type). We have already illustrated the use of this instrument in determining the E.M.F. of a battery or a drop in potential between two points in a series circuit.

The ammeter is likewise an application of the galvanometer principle, likewise usually more rugged in design, and likewise has a calibrated scale. But in this case the scale is calibrated to measure the value of the current that flows through its winding instead of the electromotive force across its terminals. We recall that in Figure 2 a flowmeter determined the gallons-of-water-per-minute being pumped through a water circuit. The ammeter is analogous to this flowmeter. It is inserted directly in the path of the current and the entire flow goes through the instrument (or through a calibrated shunt associated with the instrument). For the same reason that a water flowmeter should not be so constructed as to retard appreciably the flow of the water by causing a drop in head, the ammeter must, unlike the voltmeter, have a very low resistance. We may, therefore, think of the ammeter as a "flowmeter" designed with very low resistance so that it will not cause an appreciable readjustment of current or voltage values in any network when it is inserted to measure the current in any one branch.

Later we are to discuss the precautions to be taken in the use of instruments but just here it might be stated that wherever the ammeter is used there should be a consciousness that Ohm's Law is never failing in that it applies to every circuit branch, and that the current which will flow through the ammeter will be very large if an appreciable potential is connected across its terminals without other resistance in the circuit. As an illustration, if an ammeter has an internal resistance of .005 ohm and an electromotive force of one volt is connected to its terminals, the current through it in accordance with Ohm's Law will be 200 amperes. This may be considerably in excess of the maximum current value for which the instrument is designed. It is well to remember, therefore, that the ammeter is an instrument that will cause a short-circuit when connected across points in a circuit having a considerable difference in potential, while the voltmeter is on the other hand for most practical purposes an open circuit, and unless connected to points having potentials higher than its greatest scale reading, it cannot be damaged from excess current values. In the language of the electrician, **the ammeter must always be inserted and never connected across.**

Voltmeters and ammeters are manufactured for different ranges of voltage and current values and one instrument often has several scales. Instruments for measuring small values are prefixed with milli, meaning one-thousandth, or micro, meaning one-millionth. Thus, we have milliammeter, millivoltmeter, etc. It is obvious that **an instrument must not be used when the value of the voltage or current to be measured is likely to be greater than the maximum scale reading.**

If a voltmeter measures at any given instant the E.M.F. across any electrical circuit (either branch or mains) and an ammeter at the same instant measures the current in the same circuit (either branch or mains), the product of the two readings is, from the formula $P = EI$, equal to the power in watts supplied to the circuit. Meters are designed with both ammeter and voltmeter terminals to read this product, or the power in watts directly. These are called wattmeters.

There are two remaining instruments in the commonly used group. These are the Wheatstone bridge and the megger. The Wheatstone bridge is simply a network of resistances which can be used in connection with the galvanometer for measuring an unknown electrical resistance by an accurate comparison method. The megger is a combination of a magneto source of electromotive force and a sensitive meter, calibrated to read values of very high resistances connected across its terminals. A more detailed description and the practical use of these instruments is given in connection with the discussion of the various methods of measuring resistance.

33. Measurements of Resistance

There are numerous methods for measuring electrical resistance and the one which is most practical depends upon—

(a) the magnitude of the resistance to be measured;
(b) the conditions under which it is to be measured;
(c) the degree of accuracy required.

Probably the most difficult resistance measurements are those of extremely low values. Examples of these are: the internal resistance of an ammeter (or the resistance of an ammeter shunt); the resistance of an electrical connection such as the connection between cells of a storage battery; the resistance of an electrical bond, such as bonds used to prevent electrolysis and connected between railroad rails and water pipes or from one railroad rail to another.

Where very low resistances are to be measured accurately, it is usually a complicated laboratory process. Fortunately, we have but few such cases in our work, though there are cases where the presence of low resistance values is to be determined but not necessarily with a great degree of accuracy. For example, in the case of a connection between the cells of a storage battery, we may desire to know whether the resistance of the connection is greater than it should be. Were this to be accurately measured, the measurement would be a difficult one to make but it can usually be determined for practical purposes by some simple test such as touching the two sides of the connection with the terminals of a telephone receiver and listening for a click due to the potential drop caused by the resistance. It follows that we may confine our attention here to the practical methods used for measuring either those resistance values which are appreciable, such as the ones that are important in simple circuits, or those resistance values which are extremely high, such as the insulation resistance of cable or open wire conductors.

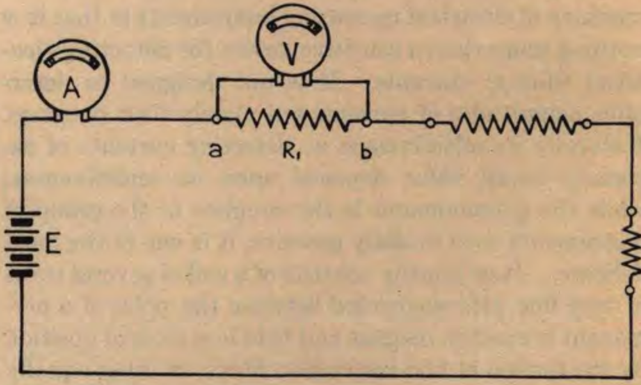


Fig. 44. Voltmeter-Ammeter Resistance Measurement

34. Voltmeter-Ammeter Method

Figure 44 shows a simple series circuit. Let us assume that it is desired to determine the value of the resistance R_1. We have learned that if a voltmeter is connected across the terminals *a* and *b* as shown, it will measure the potential drop across the resistance. But if, at the same instant this reading is taken, an ammeter is so inserted as to read the value of the current flowing through the resistance R_1, we will have not only an E.M.F. reading but a current reading as well and from the two, the value of the resistance may be calculated by Ohm's Law.

Example: In Figure 44, the voltmeter reading is 5 volts and the ammeter reading is .5 ampere; what is the value of resistance R_1?

Solution:

$$R_1 = \frac{V_1}{I_1} = \frac{5}{.5} = 10 \text{ ohms, ans.}$$

35. Drop in Potential Method

If in Figure 45 it is desired to determine the value of the resistance R_1, the "drop in potential method" can be used if a second resistance R_2 of known value is inserted in series and the voltage drops across both R_1 and R_2 are measured. Since the two resistances are in series, the same current is flowing through both and from Ohm's Law:

$$I = \frac{V_1}{R_1}, \quad \text{and also} \quad I = \frac{V_2}{R_2}$$

Therefore,

$$\frac{V_1}{R_1} = \frac{V_2}{R_2}$$

which may be written, either—

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

or

$$R_1 = R_2 \frac{V_1}{V_2} \qquad (21)$$

Example: If in Figure 45 the value of R_2 is 10 ohms and the drop across it is 12 volts, what is the value of R_1 which has a drop of 8 volts?

Solution:

$$R_1 = R_2 \frac{V_1}{V_2} = 10 \times \frac{8}{12} = 6.67 \text{ ohms, ans.}$$

36. Insulation Measurements

The application of the drop in potential method which has greatest importance in telephone and telegraph work is its special adaptation to insulation measurements.

If the series circuit in Figure 45 contains no resistance other than R_1 and R_2, it is not necessary to measure the drop across R_1 because it will be equal to the potential of the battery minus the drop across R_2. The formula for this special case may then be written—

$$R_1 = R_2 \frac{E - V_2}{V_2} \qquad (22)$$

where E is the E.M.F. of the battery.

If R_1 is very high in value such as a "leak" due to poor insulation, it can be measured using formula (22) but instead of using a second known resistance, the voltmeter itself may be inserted in series with the battery and R_1 as shown in Figure 46. The reading V_2 then applies to the drop across the **voltmeter's own resistance** which, as has been previously stated, is very high. But since the resistance being measured is very high, this gives greater accuracy than if a known resistance R_2 having a lower value were inserted and a drop of lower value measured across it. As a matter of fact, voltmeters used for measuring insulation are especially designed to have abnormally high internal resistance; the ones used in the standard testboard testing circuits have a resistance of 100,000 ohms.

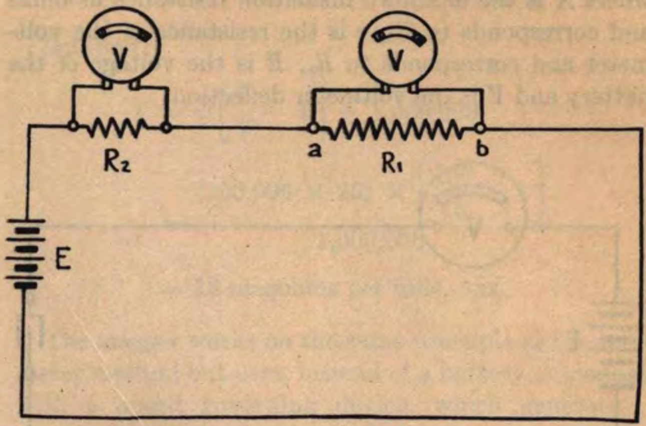


FIG. 45. DROP IN POTENTIAL RESISTANCE MEASUREMENT

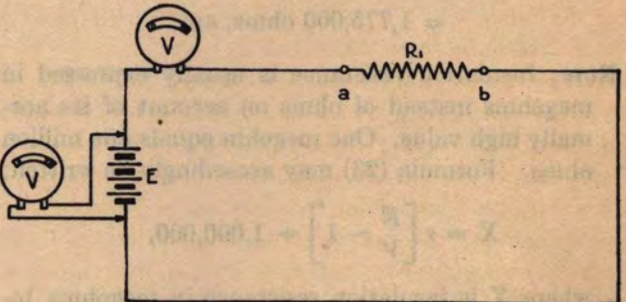


FIG. 46. INSULATION MEASUREMENT

Figure 47 shows the drop of potential method with series voltmeter for measuring the insulation of a condenser. Figure 48 shows a "leak" between two cable conductors and Figure 49 a "leak" between an open wire and ground, both being measured in the same manner.

For this application formula (22) is ordinarily written—

$$X = r \frac{E - V}{V}$$

or

$$X = r\left[\frac{E}{V} - 1\right] \qquad (23)$$

where X is the unknown insulation resistance in ohms and corresponds to R_1, r is the resistance of the voltmeter and corresponds to R_2, E is the voltage of the battery and V is the voltmeter deflection.

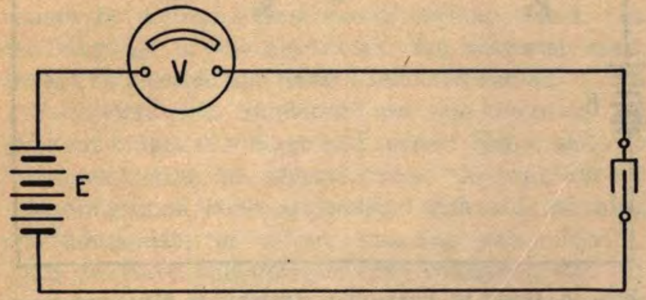


FIGURE 47

Example: The voltmeter shown in Figure 47 has a resistance of 100,000 ohms. If it reads 8 volts as shown and 150 volts when connected directly across the battery terminals, what is the insulation resistance of the condenser?

Solution:

$$X = r\left[\frac{E}{V} - 1\right]$$

$$= 100{,}000\left[\frac{150}{8} - 1\right]$$

$$= 1{,}775{,}000 \text{ ohms, ans.}$$

Note: Insulation resistance is usually expressed in megohms instead of ohms on account of its normally high value. One megohm equals one million ohms. Formula (23) may accordingly be written:

$$X = r\left[\frac{E}{V} - 1\right] \div 1{,}000{,}000,$$

where X is insulation resistance in megohms instead of ohms.

In the standard testboard circuits, dry cell batteries are ordinarily used for insulation testing batteries and

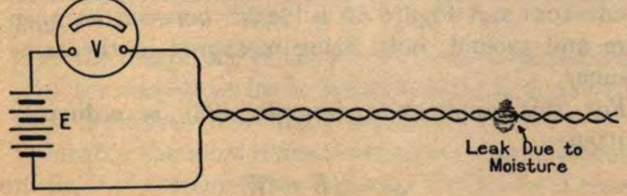


FIG. 48. METALLIC INSULATION TEST

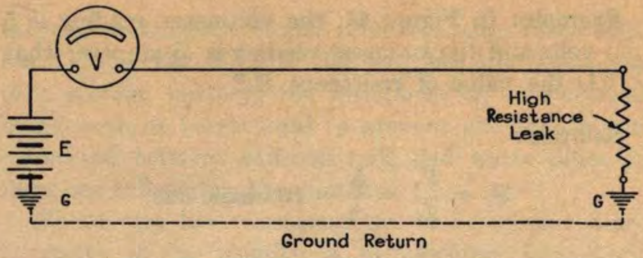


FIG. 49. TEST FOR INSULATION OF SINGLE WIRE

these are wired metallic; that is, they have neither the positive nor negative terminal grounded. In some cases, however, it is necessary to measure insulation across a pair of wires such as cable conductors using a

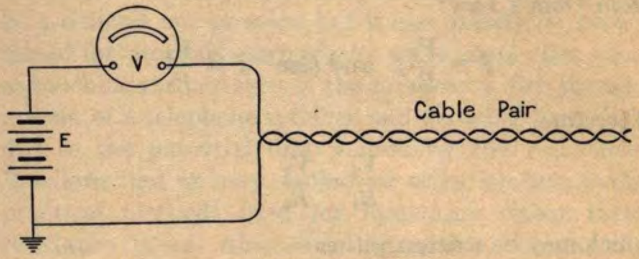


FIGURE 50

permanently grounded testing battery (such as a 120-volt telegraph battery tap). Figure 50 shows such a test, but here the "metallic" or "mutual" insulation is not distinct from the "wire to ground" insulation on account of one conductor being grounded. It is necessary in this case to take two readings, one with one conductor grounded and the other with the second conductor grounded. Figure 51 shows a reversing key wired in the testing circuit to facilitate this test. While neither of the two readings gives the mutual resistance, it may be calculated from these readings and readings for the single conductors to ground.

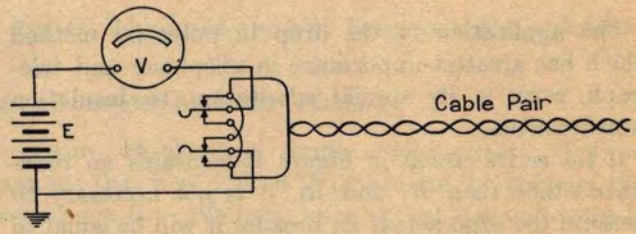


FIGURE 51

When determining the insulation resistance of cable or open wire pairs, the value is ordinarily expressed as the average resistance per mile rather than a value for the entire circuit. In calculating the resistance per mile value, it is assumed that each mile of wire (or circuit) has a concentrated leak and that these are all equal as shown in Figure 52. It is further assumed that the series resistance of the wire is negligible compared with the insulation resistance. Formula (23) when expressed for X equal to the resistance per mile instead of the entire circuit becomes—

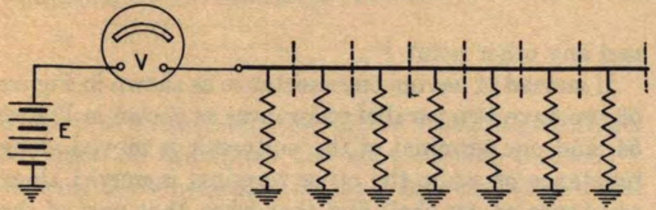


FIGURE 52

$$X = rl\left[\frac{E}{V} - 1\right] \text{ in ohms} \qquad (24)$$

or

$$X = rl\left[\frac{E}{V} - 1\right] \div 1{,}000{,}000 \text{ in megohms,}$$

where l is the length of the circuit in miles in both cases.

Example: Assume the wire shown in Figure 52 to be 20 miles long and the voltmeter to have a resistance of 100,000 ohms. What is the insulation of the wire to ground in megohms per mile if the battery E.M.F. is 150 and the voltmeter reading is 15?

Solution:

$$X = rl\left[\frac{E}{V} - 1\right] \div 1{,}000{,}000$$

$$= \frac{(100{,}000 \times 20) \times \left[\frac{150}{15} - 1\right]}{1{,}000{,}000}$$

$$= 18 \text{ megohms per mile, ans.}$$

The megger works on the same principle as the series meter method but uses, instead of a battery, a magneto with a speed governing device, which generates a constant E.M.F. It also includes a meter calibrated to read megohms directly, instead of volts. The generator potential is much higher than the battery potentials used for telephone testing, 400 volts being ordinarily used on the more common types. The internal resistance of the meter (and generator) are extremely high and the generated voltage cannot sustain any appreciable current, thereby making the instrument safe for practical work.

CHAPTER V

ELECTRICAL MEASUREMENTS IN DIRECT CURRENT CIRCUITS—(*Continued*)

37. Theory of the Wheatstone Bridge

The Wheatstone bridge has been described as a network of resistances that may be used in connection with a galvanometer to measure unknown resistance values. An analysis of its theory is the next step in order after the study of the potential drop method of measuring resistance.

In Figure 53, the voltmeter has one terminal permanently connected to a and the other terminal may be moved along the resistance ab. The voltmeter reading will be zero when both terminals are at a, and will gradually increase as the point P is moved toward b. We shall find that the potential drop measured between the points a and P is always proportional to that part of the resistance between a and P, or we may write:

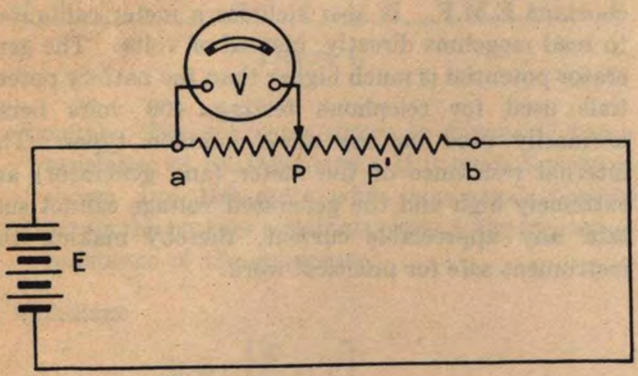


FIGURE 53

$$\frac{aP}{aP'} = \frac{V}{V'}$$

where V' is the potential drop measured between a and any other point P'.

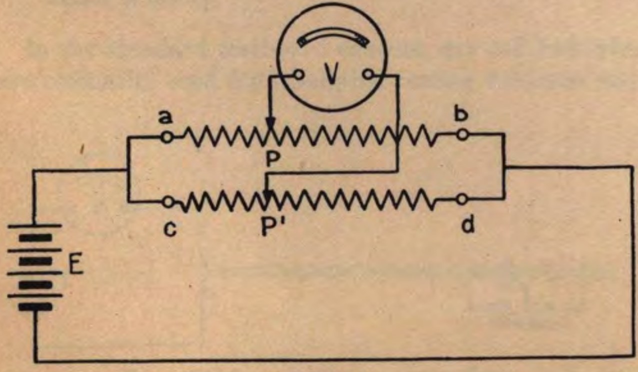


FIGURE 54

If instead of having one resistance as shown in Figure 53, we have two parallel resistances as shown in Figure 54, and one terminal of the voltmeter is moved along resistance ab while the other terminal is moved along resistance cd, we shall find that when that part of the resistance ab between the points a and P is proportional to that part of the resistance cd between the points c and P', the difference in potential between the points P and P' will be zero and there will be no reading of the voltmeter. Mathematically, this may be expressed:

$$\frac{aP}{cP'} = \frac{ab}{cd}$$

Likewise, we may develop a similar expression for the remaining part of the resistance:

$$\frac{Pb}{P'd} = \frac{ab}{cd}$$

From these two relations, we may write:

$$\frac{aP}{cP'} = \frac{Pb}{P'd} \tag{25}$$

This merely means that potential drop always distributes itself proportionally along one or more resistances. In Figure 55 let us assume that the resistances represented by the branch A, the branch B, and the branch R, are known, and that the resistance shown as the branch X is unknown. Inasmuch as the meter connected between the points P and P' is merely being used to determine that these two points have the same potential, a galvanometer can be employed instead of a voltmeter, and will be preferable in that it is more sensitive. If there is no deflection in the galvanometer

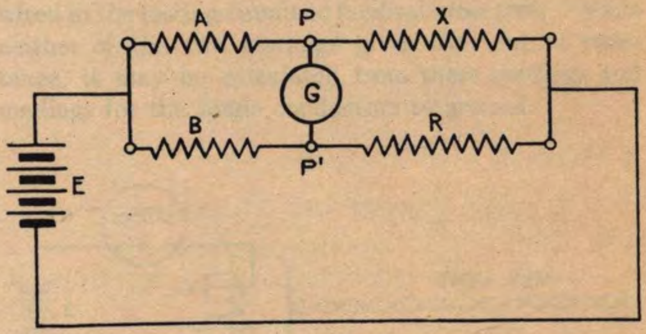


FIGURE 55

$R_1 = R_2 = R_3 = R_x$ $\frac{R_1}{R_2} = \frac{R_x}{R_3}$

needle, we may write the same relation as was given by Equation (25), namely:

$$\frac{A}{B} = \frac{X}{R} \quad \text{or} \quad \frac{A}{X} = \frac{B}{R}$$

This equation can be expressed:

$$X = \frac{A}{B}R \qquad (26)$$

which is the usual equation of the Wheatstone bridge.

Figure 56 illustrates the conventional method of showing the Wheatstone bridge. It is almost identical to the arrangements shown by Figure 55, but has the resistances connected in a diamond shaped diagram. S_1 is a switch for disconnecting the battery when not in use, and S_2 is a similar switch for disconnecting the galvanometer. Binding posts are shown for connecting the unknown resistance to be measured, which is usually designated as X. The resistances A and B are called the **ratio arms** of the bridge and the resistance R is variable so that for any unknown resistance X, the value of R may be adjusted to obtain a perfect balance, or to bring the galvanometer needle to the stationary or zero point on the scale. Though Figure 56 shows the resistance branch R as variable and the arms A and B as fixed, a balance could also be obtained by changing the ratio A/B in formula (26) instead of varying the value of R.

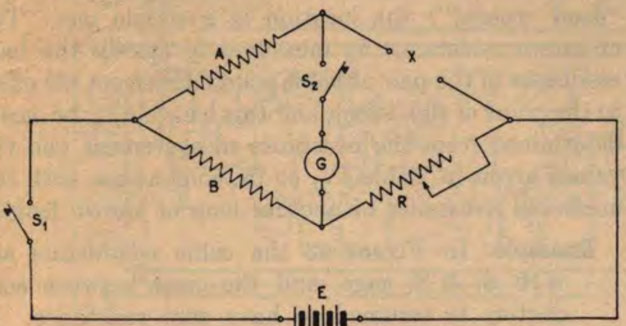


FIG. 56. STANDARD WHEATSTONE BRIDGE CONVENTION

In all forms of the Wheatstone bridge it is permissible to reverse the connections for the battery and the galvanometer in so far as these connections concern the theory of operation. Thus, in Figure 56 the galvanometer and dry cell could be interchanged without in any way affecting the operation of the bridge.

There are many commercial types of Wheatstone bridge testing instruments. There are four in particular that are used extensively in telephone and telegraph work. One is a small portable type bridge, which is also used sometimes at local test desks. The others are especially designed bridges for use in connection with toll testboards and are known as the "#12001 Bridge", the "Wheatstone Bridge per KS-3011", and the "Wheatstone Bridge per KS-5411". The dial and circuit arrangements of the three last named bridges are shown by Figures 58, 59, and 60 and the theory is shown by Figure 57. The portable bridge has both the battery and galvanometer mounted inside the case and is arranged for making simple resistance measurements, Varley loop tests, and Murray loop tests.

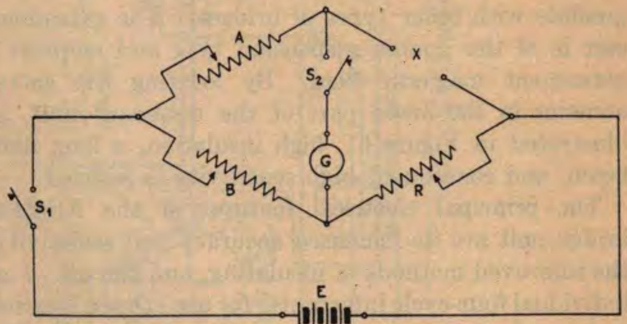


FIGURE 57

The #12001 bridge was designed for the #4 testboard testing circuit. The galvanometer is mounted in a separate case which in turn mounts inside the bridge case in such manner that it may be conveniently removed. All connections are brought out to binding posts so that various testing combinations can be secured with the particular key arrangement of the #4 testboard testing circuit. The galvanometer is equipped with resistance shunts and has a coil resistance of 288 ohms. Dials are used for the A and B arms and for the variable balancing arm, but no sliding contacts are exposed.

The Wheatstone bridge per KS-3011 is designed for use in both the #4 and #5 toll testboards and is of a type similar to the #12001 bridge but is somewhat more accurate. It employs a reflection type galvanometer having a lamp and scale instead of a needle, which permits the detection of smaller current values than is possible with the preceding type of bridges. The ratio arms are controlled by a single dial which gives the ratio A/B directly for nine values as follows:

$$1000,\ 100,\ 10,\ 1,\ \tfrac{1}{4},\ \tfrac{1}{9},\ \tfrac{1}{10},\ \tfrac{1}{100},\ \tfrac{1}{1000}$$

In addition, one position of the dial designated as M-1000 is for use in making open location measurements and Murray loop tests, as outlined in Article 40. The rheostat arm has a total resistance of 9999 ohms and is adjustable by means of four inverted dials in steps of one ohm. The resistances in the rheostat arm are accurate to $\frac{1}{10}$ of 1 per cent and in the ratio arms to $\frac{1}{20}$ of 1 per cent. Three additional dials are provided for use in connection with open location tests.

The Wheatstone bridge per KS-5411 is for use primarily in toll cable offices, but may be used for trouble location tests on open wire. It provides for certain improved methods of operation and greater accuracy in determining and locating faults than is possible with former types of Wheatstone bridge testing units.

In general, the operating principles of the KS-5411 bridge are the same as those for the KS-3011 bridge and other similar types. Each KS-5411 bridge is individual to the testboard position it occupies and cannot be associated with testing circuits in other positions, as is possible with other types of bridges. The galvanometer is of the double suspension type and employs a permanent magnetic field. By locating the galvanometer in the lower part of the testboard unit, as illustrated in Figure 61, high insulation, a long light beam, and consequent high sensitivity is realized.

The principal electrical features of the KS-5411 bridge unit are its increased accuracy and sensitivity, the improved methods of insulating, and the use of an individual four-cycle interrupter for use in open location and certain other tests.

Dial setting ratios, as shown below, are provided in the bridge circuit for use as required:

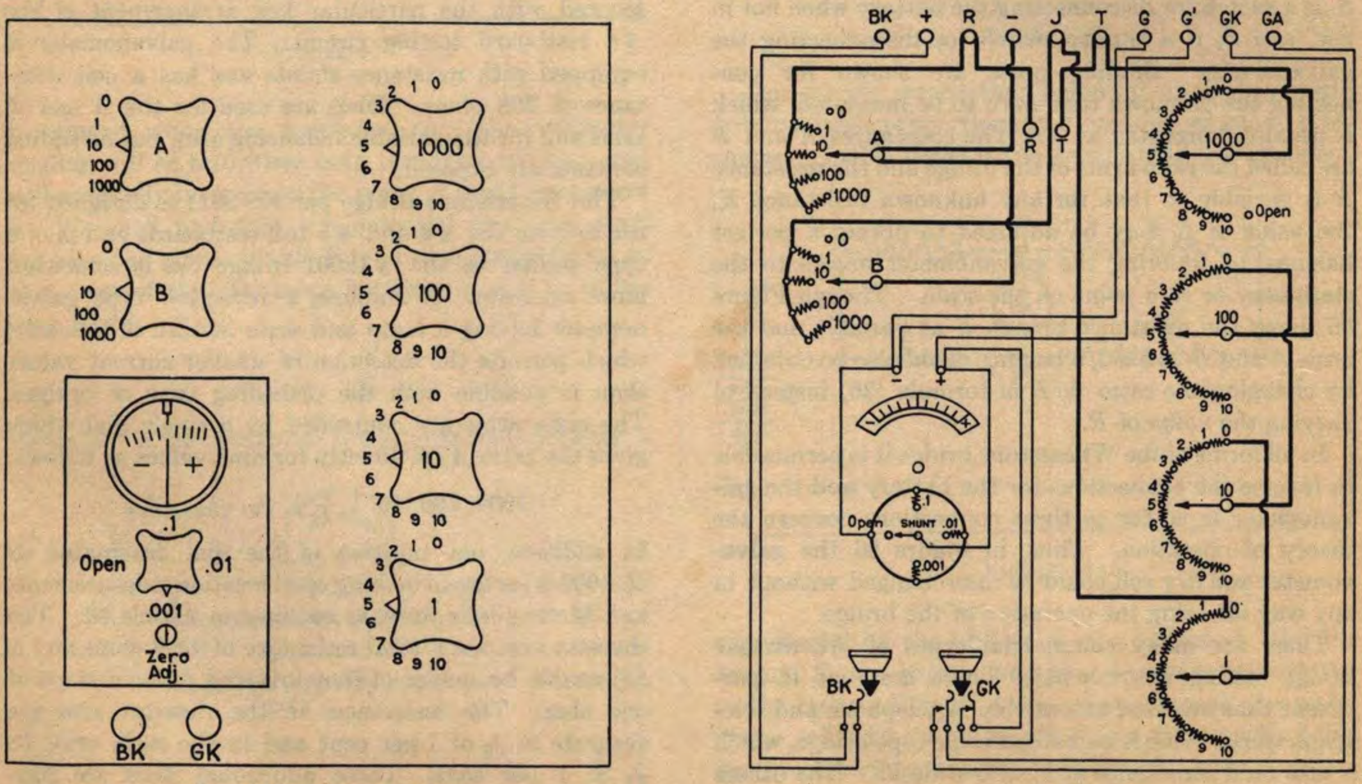
$$1000,\ 100,\ 10,\ 1,\ \tfrac{1}{4},\ \tfrac{1}{10},\ \tfrac{1}{100},\ \tfrac{1}{1000}$$

In addition, two positions of the dial designated as M-1000, and M-10,000 are provided for use in making Murray loop tests and open location tests.

38. Simple Loop Tests or Plain Resistance Measurements

In the telephone and telegraph plant, the Wheatstone bridge is used extensively in locating faults in both cable and open wire conductors. The simplest test of this kind is the location of a cross between two wires. Figure 62 shows the Wheatstone bridge connected to the office end of a cable pair which has its conductors crossed together some distance from the office. If the cross itself has zero resistance (i.e., if the wires are "dead crossed") the location is a simple one. The unknown resistance as measured is merely the loop resistance of the pair of cable conductors from the office to the point of the defect, and this length may be easily determined from the resistance measurement and the values given in Table IV, or by comparison with the measured resistance of another loop of known length.

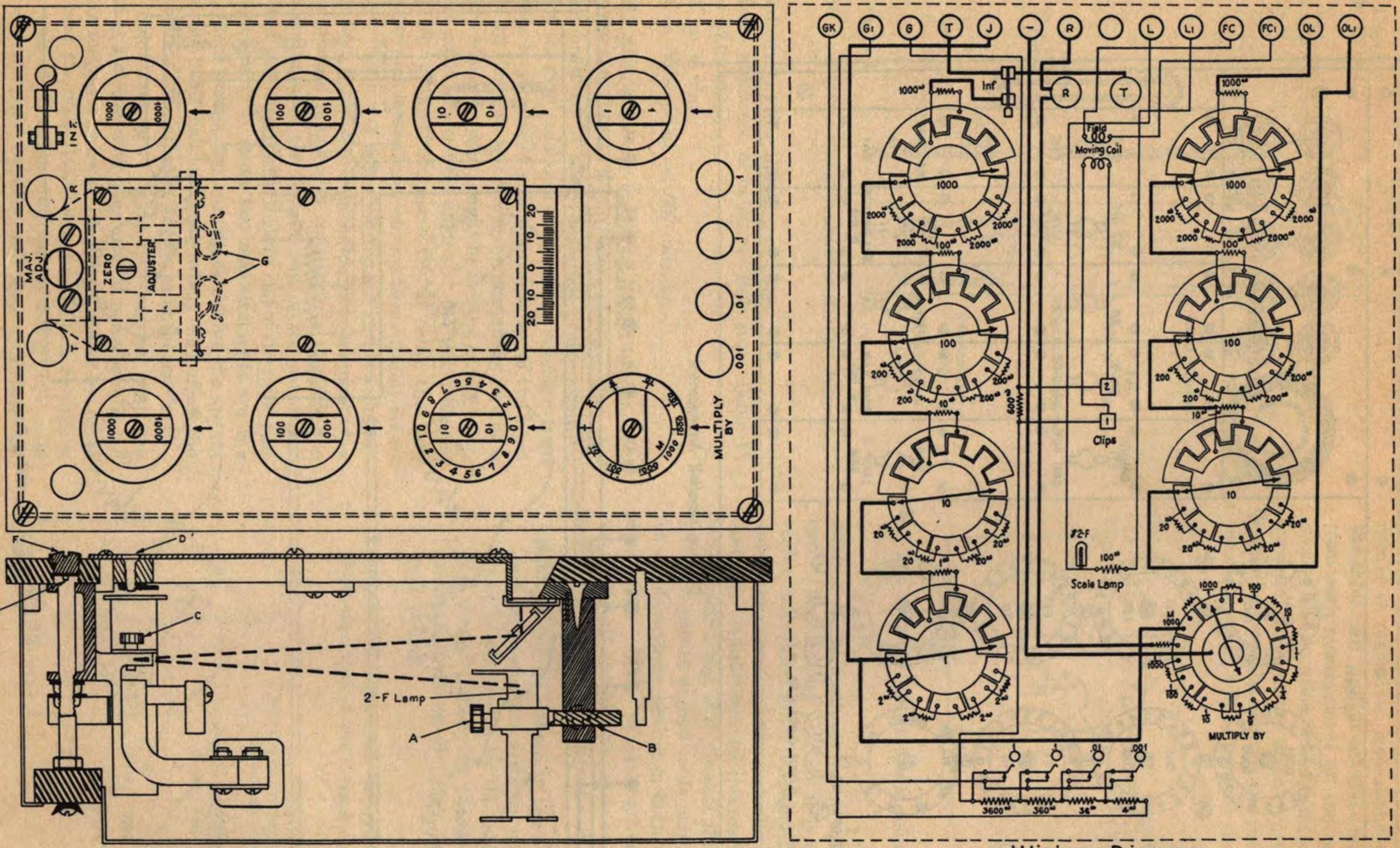
Example: In Figure 62 the cable conductors are #19 B. & S. gage, and the cross between conductors is assumed to have zero resistance. If the value of X, as measured by the Wheatstone bridge, is 55 ohms, how far is the cross from the telephone office?



Dial Arrangement

Wiring Diagram

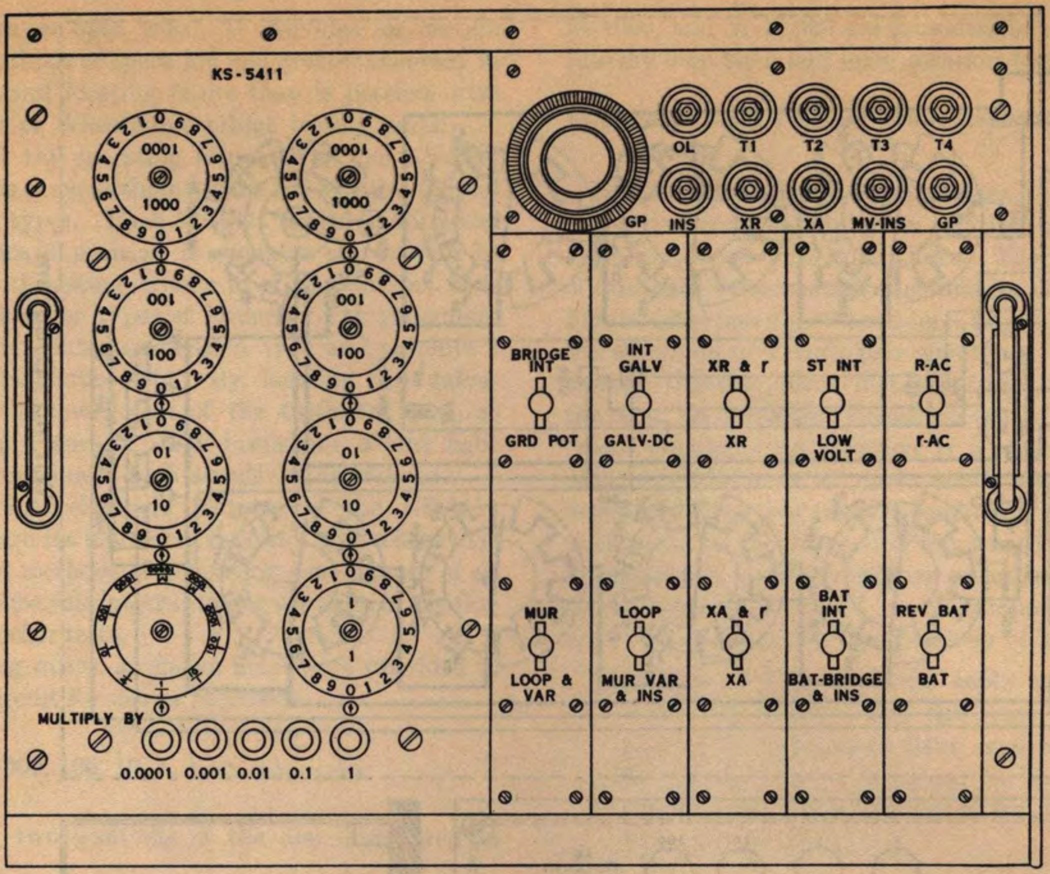
Fig. 58. Number 12001 Wheatstone Bridge



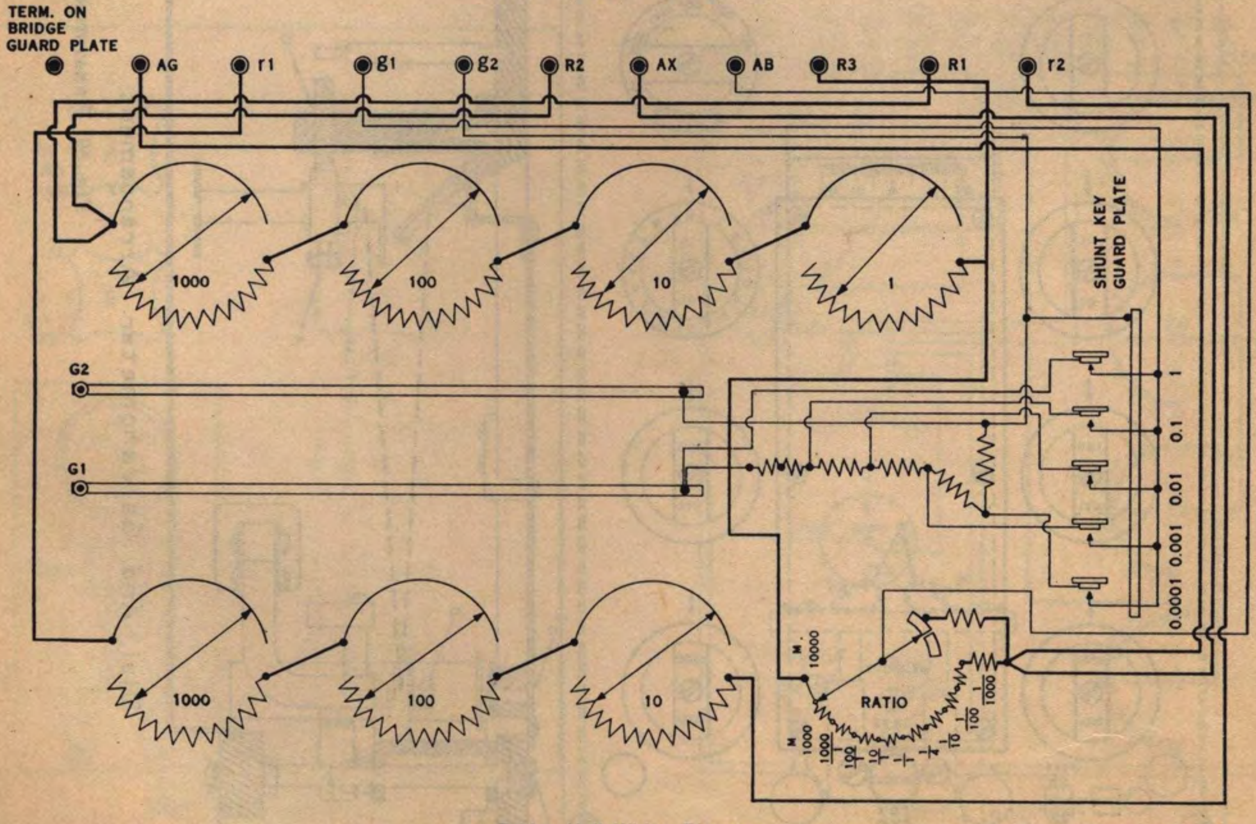
Dial And Galvanometer Arrangement

Wiring Diagram

FIG. 59. WHEATSTONE BRIDGE PER KS-3011



Dial and Keyshelf Arrangement



Bridge Unit Wiring Diagram

FIG. 60. WHEATSTONE BRIDGE PER KS-5411

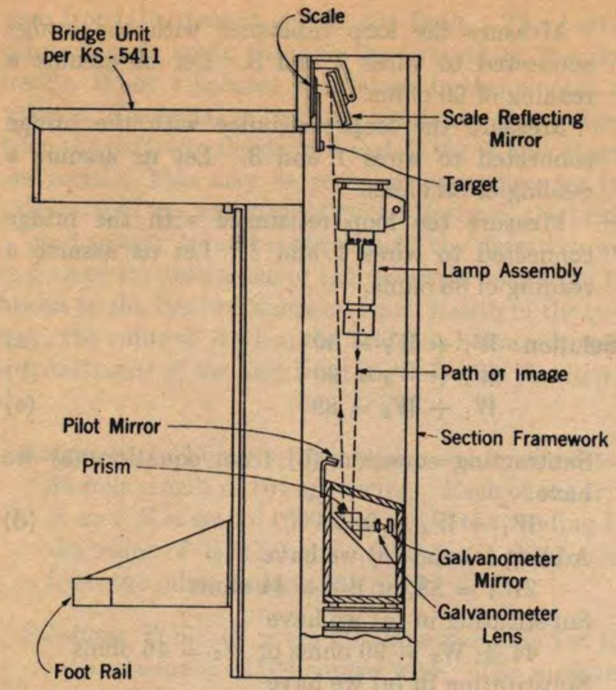


Fig. 61. Optical Arrangement of KS-5411 Bridge

Solution: Let d = distance in miles
Loop resistance of cable per mile from Table IV is 85.01 ohms
$X = 55$ ohms
$d = 55 \div 85.01 = .657$ mile, ans.

If the cross shown in Figure 62 should itself have a resistance value, which is quite often the case, the value of X as measured by the Wheatstone bridge would be equal to the loop resistance of the cable conductors from the office to the defect plus the resistance of the cross itself. In this case the defect, on account of having a definite resistance value, might be located at any intermediate point between the office and .657 mile from the office. It is, therefore, necessary in using the loop method to make two measurements to accurately determine the location of any cross when it is not definitely known that it has zero resistance. The simplest way to determine if it has zero resistance is to make one measurement with the distant end of the cable pair open, and another with the distant end of the cable pair short-circuited. **If these two measurements are the same, which means that opening or closing the distant end of the cable pair does not in any way affect the measurement, the cross is known to have zero resistance** (dead crossed). If the measurement with the distant end of the cable pair crossed is lower in value than the measurement with the distant end of the cable pair open, the cross itself has some definite resistance value, and the location, instead of being .657 mile away, is some point between .657 mile away and the office. One way to determine the exact location in this case is to make loop measurements from each end of the cable pair, and to calculate an imaginary location from each measurement on the assumption of a zero cross. The location, when calculated from the measurement made at the office end, will be too far away, and when calculated from the measurement made at the distant end, will be too near the office. The actual location is the mean, or point half way between the two. Of course, in practice it is oftentimes not convenient to transfer the Wheatstone bridge to the distant end of the circuit in order to make measurements from that end. A substitute for this method, which amounts to the same thing, is to connect the distant end of the defective pair to a good cable pair as shown in Figure 63. This permits testing in both directions from the same office. If the exact length of the good pair is not known, it can always be determined by making a measurement with the distant end crossed.

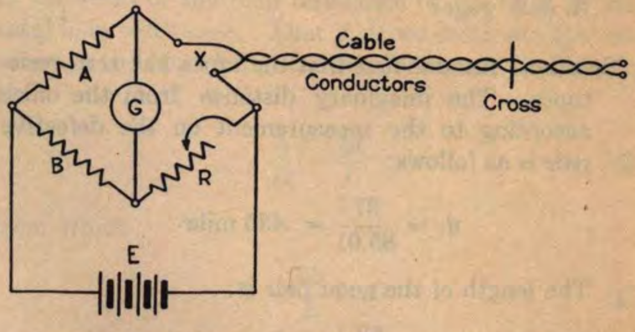


Fig. 62. Loop Resistance Measurement to Cross

Note: It will be learned in the next article that the quickest and most accurate method of locating a cross in practice is by the metallic Varley. But the theory underlying the foregoing should be thoroughly mastered before taking up the later type of test.

Example: In Figure 63 the good cable pair when short-circuited at the distant end has a loop resis-

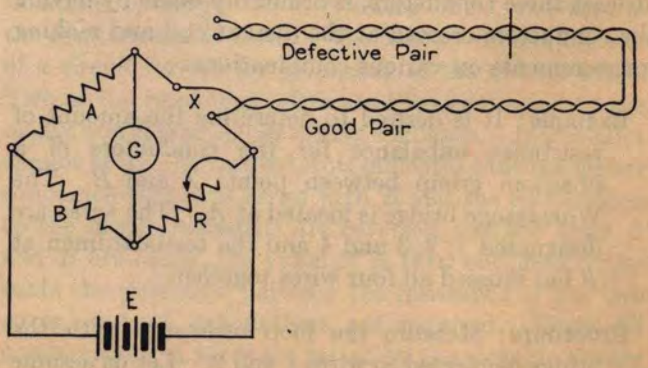


Figure 63

tance of 63 ohms. When connected to the defective pair as shown, the measurement from the office to the cross over the good pair and the distant end of the defective pair is 108 ohms. The measurement from the office to the cross on the defective pair is 37 ohms. What is the distance in miles from the office to the defect, and what is the resistance of the cross if the cable pairs are 19 B. & S. gage?

Solution: Assume first that the cross has zero resistance. The imaginary distance from the office according to the measurement on the defective pair is as follows:

$$d_1 = \frac{37}{85.01} = .435 \text{ mile}$$

The length of the good pair is:

$$l = \frac{63}{85.01} = .741 \text{ mile}$$

The imaginary distance from the distant end is:

$$l - d_2 = \frac{108}{85.01} - .741 = .529 \text{ mile}$$

Then the actual cross is at point half way between .435 mile from the near office and .529 mile from the distant office or .741–.529 = .212 mile from the near office. The actual location is therefore

$$\frac{.435 + .212}{2} = .323 \text{ mile, ans.}$$

The resistance of the cross caused an error in the single measurement location of $.435 - .323 = .112$ mile of cable pair. This expressed as resistance is $.112 \times 85.01 = 9.5$ ohms, ans.

Another application of the simple loop resistance measurement is to determine any inequality in the resistance of individual conductors, or as is commonly expressed, to locate "resistance unbalances" due to such causes as defective splices in cable pairs or defective sleeve joints in open wire. This test, requiring at least three conductors, is ordinarily made by having the conductors crossed at the distant end and making measurements on various combinations:

Example: It is desired to determine the amount of resistance unbalance for the conductors of a phantom group between points *A* and *B*. The Wheatstone bridge is located at *A*. The wires are designated 1, 2, 3 and 4 and the testboardman at *B* has crossed all four wires together.

Procedure: Measure the loop resistance with the bridge connected to wires 1 and 2. Let us assume a reading of 90 ohms.

Measure the loop resistance with the bridge connected to wires 2 and 3. Let us assume a reading of 90 ohms.

Measure the loop resistance with the bridge connected to wires 1 and 3. Let us assume a reading of 88 ohms.

Measure the loop resistance with the bridge connected to wires 1 and 4. Let us assume a reading of 88 ohms.

Solution: $W_1 + W_2 = 90$ (a)

$W_2 + W_3 = 90$ (b)

$W_1 + W_3 = 88$ (c)

Subtracting equation (b) from equation (a) we have:

$W_1 - W_3 = 0$ (d)

Adding (c) and (d) we have

$2W_1 = 88$, or $W_1 = 44$ ohms

Substituting in (a) we have

$44 + W_2 = 90$ ohms or $W_2 = 46$ ohms

Substituting in (c) we have

$44 + W_3 = 88$ ohms or $W_3 = 44$ ohms

And since $W_1 + W_4 = 88$, we likewise have

$44 + W_4 = 88$ or $W_4 = 44$ ohms

Thus we learn W_2 has a resistance unbalance of 2 ohms, ans.

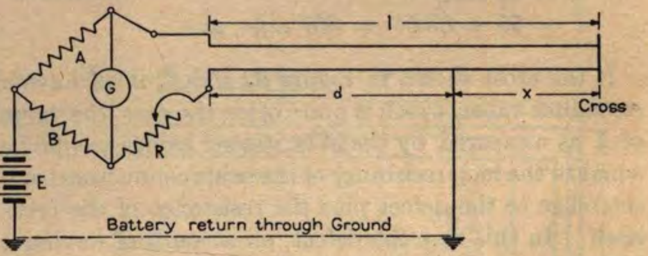


FIG. 64. GROUNDED VARLEY TEST

39. Varley Loop Tests

A Wheatstone bridge may be used to locate a defect due to a grounded open wire or cable conductor as well as a defect due to a cross between conductors. There are two recognized methods of making tests of this kind. One is known as the Varley loop test and is the more generally used; the other is known as the Murray loop test. Figure 64 shows the theory of the Varley loop test.

In comparing this figure with Figure 56, we can recognize a Wheatstone bridge circuit with the connections made in a little different way. The variable resistance *R* is in series with the resistance *d* of the defective wire from the office to the fault. The resistance *X* of Figure 56 becomes in Figure 64 the series resistance *l* of the good wire from the office to the distant end, plus the resistance *x* of the defective wire from the distant end to the fault. The battery connection is made through the ground to the fault itself. When a balance is obtained in this circuit, the value of R is equal to the loop resistance of the circuit from the defect to the distant end, if the A and B arms are equal. This may be seen by inspection, for it is evident that the adjustment of the R arm of the bridge is used merely to add resistance to the defective wire and since the resistance of the defective wire from the bridge to the fault balances an equal length of the good wire, the value of R when the bridge is balanced equals the resistance of the loop from the defect to the distant end.

Example: In Figure 64 the bridge is connected to a 30-mile circuit of 104 open wire. Each of the arms A and B is set at 1000 ohms. If the reading for the value of R is 22 ohms, how far is the ground from the office making the test?

Solution: Table IV gives 10 ohms per mile for the loop resistance of 104 copper wire. The measurement of 22 ohms represents the resistance of the loop from the defect to the distant end. This distance is therefore $22/10 = 2.2$ miles. If the circuit is 30 miles long, the defect is located $30 - 2.2$ or 27.8 miles from the measuring office, ans.

The above example assumes that the two wires of Figure 64 are alike, and that the loop resistance values per mile given in the table are correct under all conditions. Although the first assumption will usually be true in practice, unit resistance values may vary appreciably due to temperature differences. In either event, it is still possible to locate the fault, by making an ordinary loop resistance measurement on the pair, in addition to the Varley measurement.

Thus, referring again to Figure 64, it will be seen that when a Varley balance is obtained, with the bridge ratio arms equal—

$$R + d = l + x \tag{a}$$

or

$$d = (l + x) - R \tag{b}$$

This, of course, is true regardless of whether the good and the defective wires are of the same make-up.

Similarly, if the loop resistance L is measured, we have—

$$L = l + x + d \tag{c}$$

from which

$$d = L - (l + x) \tag{d}$$

Now, adding (*b*) and (*d*), we get

$$2d = L - R \tag{e}$$

In other words, **the loop resistance from the measuring end to the fault is equal to the loop resistance measurement minus the Varley measurement.** Since we do not know the unit resistance value of the two wires, we still do not know the distance to the fault. It is obvious, however, that if the wires are of uniform make-up throughout their whole length, the ratio of the distance to the fault to the total length of the line will be equal to the ratio of the loop resistance to the fault to the total loop resistance. That is, if we designate the distance to the fault k and the total length of the line, D, then—

$$\frac{k}{D} = \frac{2d}{L} \tag{f}$$

from which

$$k = \frac{2d}{L} \times D \tag{g}$$

or, applying (e) above—

$$k = \frac{L - R}{L} \times D \tag{h}$$

Example: Assume as in the above example that the total circuit length is 30 miles and that the Varley reading is 22 ohms with the ratio arms equal. If a loop resistance measurement gives 300 ohms, what is distance of the ground from the measuring end?

Solution:

$$k = \frac{300 - 22}{300} \times 30 = 27.8 \text{ miles, ans.}$$

A modification of the Varley test may be used for accurately measuring resistance unbalances, which is in some respects preferable to the method of combination loop measurements described in the foregoing article. It is called the metallic Varley, and is shown by Figure 65-A. In making this test, all wires are short-circuited at the distant end in the same manner as when making a series of loop tests for the various combinations of wires. At the testing office, one wire of the combination is used for the battery return, instead of a circuit formed by grounding at the distant office. Two of the remaining wires are then connected to the bridge and R is adjusted to give a balance. If a balance cannot at first be secured, this indicates that the higher resistance wire is in series with R and the connections to the bridge terminals are reversed. If the arms A and B are equal, the value of R then obtained represents the difference between the resistance of the two wires, and no calculations are required. When all combinations of wires are tested by the metallic Varley excepting the battery return wire, this wire may be interchanged with any one of the others and included in the tests.

A similar test requiring only three wires is commonly used in testboard work for locating crosses, particularly those having high resistance. As noted in the preceding article, the location of a cross having resistance by the use of loop resistance measurements involves certain difficulties. By using a good third wire of the same gage as that of the pair in trouble, and connecting the bridge for a metallic Varley measurement as shown in Figure 65-B, the resistance of the cross is removed from the "balanced" circuit of the bridge and placed in the battery circuit. Here it has no effect on the measurement, providing its resistance is not so high that the current supplied to the bridge is insufficient for its satisfactory operation. As may be seen from the diagram of connections, when the bridge is balanced with equal values in the ratio arms A and B, the resistance of the good third wire, plus the resistance of one wire of the crossed pair from the distant end to the fault, is equal to the resistance of one wire from the fault to the measuring end plus the resistance, R, in the rheostat arm of the bridge; or, we may write—

$$l + (l - d) = d + R$$

from which—

$$d = \frac{2l - R}{2}$$

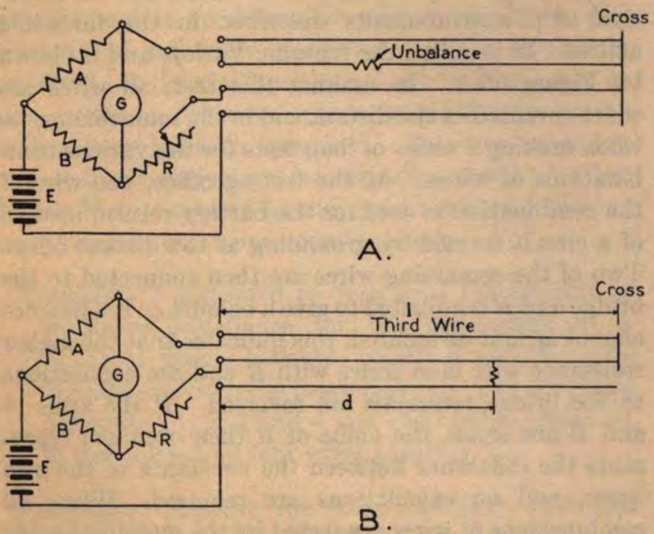
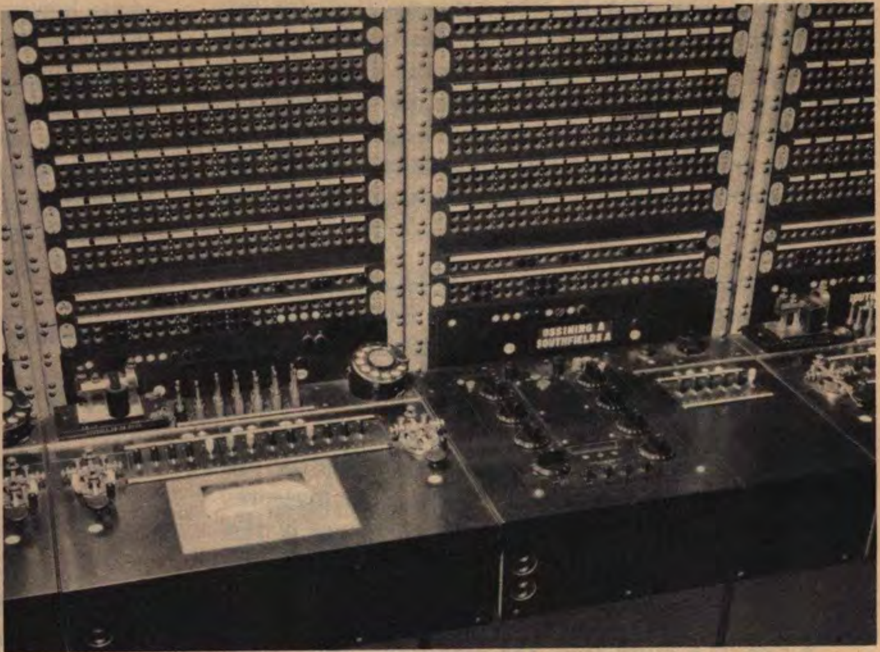


Fig. 65. Metallic Varley Tests

In locating a cross by this method in practice, it is only necessary to make a Varley measurement as described above and a loop resistance measurement on the pair consisting of the good third wire and one wire of the crossed pair, shorted together at the distant end. Then the loop resistance of the crossed pair from the measuring end to the fault may be obtained directly by subtracting the Varley reading from the loop resistance reading.



Testshelf of No. 5 Testboard Showing Voltmeter and Wheatstone Bridge Testing Arrangement

The Varley test may also be used for locating a cross between one wire of a circuit and some other wire, of different characteristics such as one wire of an iron circuit. The procedure here is to ground the wire of the second circuit, cross the first circuit at the distant end, connect the bridge to it and locate the ground by the Varley method described above, which is equivalent to locating the cross.

40. Murray Loop Tests

The theory of the Murray loop test is similar to that of the Varley. But instead of setting the arms A and B to have equal values and using the adjustable dials R to compensate for the difference in wire resistance between the good wire connection and the defective wire connection, the arm B is eliminated altogether and the variable resistance arm is connected in its place as shown in Figure 66. In this arrangement, the ratio of the reading R to the setting of the arm A is equal to the ratio of the resistance of the defective wire from the measuring office to the ground to the resistance of this same wire from the ground to the distant office plus the resistance of the good wire, or expressed mathematically—

$$\frac{R}{A} = \frac{l-d}{l+d}$$

This, of course, assumes that the defective and good wires have the same series resistance per mile, as would ordinarily be the case where for any given circuit being tested the defective wire's mate is used.

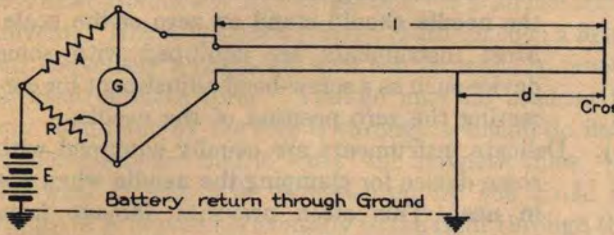


FIG. 66. MURRAY TEST

Example: In Figure 66, the arm A is set at 1000 ohms, and the bridge is balanced by varying the arm R. If the value of R is 634 ohms and the length of the circuit under test is 65 miles, what is the distance from the testing office to the fault?

Solution: The simple bridge relation gives

$$\frac{R}{A} = \frac{l-d}{l+d}$$

or,

$$\frac{634}{1000} = \frac{(65-d) \times \text{res. per mile}}{(65+d) \times \text{res. per mile}}$$

If the resistance per mile of each wire is the same, this factor will cancel and we have—

$$\frac{634}{1000} = \frac{65-d}{65+d}$$

which gives by cross multiplying

$$634\,(65+d) = 1000\,(65-d),$$

or

$$1634d = 23790$$

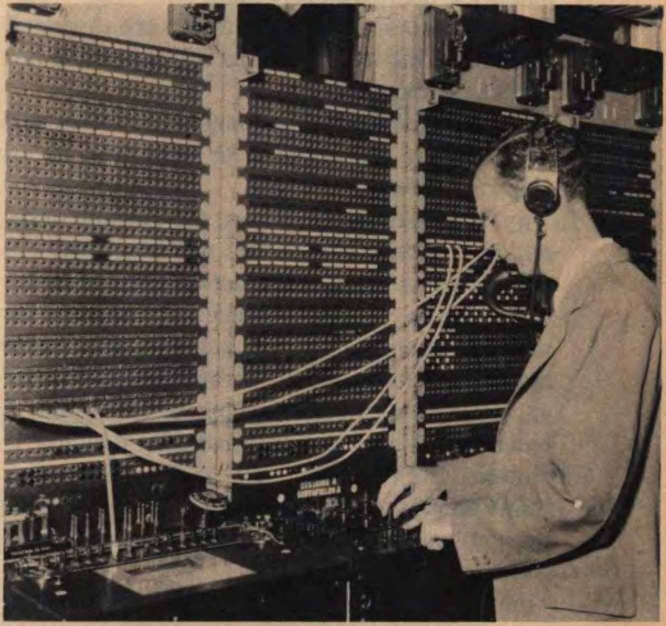
from which

$$d = 14.56 \text{ miles}$$

$$l - d = 50.44 \text{ miles, ans.}$$

There are a number of other standard tests made with the Wheatstone bridge and with these as well as with the tests that have been described, the procedure in practice is somewhat more involved than the simple theory might indicate. There are in nearly all practical tests various complicating factors such as temperature variations, effect of loading coils, short lengths of cable, irregular facilities, etc., which must all be considered if accurate locations are to be made.

For instance, in the majority of toll cables, parts of each section are aerial and other parts are underground. There is usually a considerable temperature difference between the two types of facilities, as a result of which the resistance of the wires in the two types of facilities is different. It is therefore necessary to apply correction factors to the measurements taken in order to accurately locate a fault. The details of how these various factors are taken care of in practice present a rather complete study in themselves, however, and their consideration is necessarily beyond the scope of this book. The intent here has been only to treat a few of the outstanding testing methods in a more or less theoretical way, with a view to establishing the general principles upon which all testing work is based.



No. 5 PRIMARY TESTBOARD

41. Precautions to be Taken in the Use of Measuring Instruments

The intelligent use of the electrical measuring instruments described in this chapter and in Chapter IV depends upon skill and care, as well as upon an understanding of the theory of each test made. There are numerous precautions to be taken, some of which are to be learned only through experience, but a few cardinal ones are listed here and may be studied accordingly. In the use of all testing instruments there is one important motive,—the most accurate results possible should be secured without damaging the instruments.

a. **Precautions should be taken against dropping or jarring** electrical measuring instruments, particularly galvanometers, voltmeters, ammeters, and wattmeters. Instruments of this class have revolving coils, either suspended in a delicate manner or equipped with jewelled bearings. Jarring may permanently damage the instruments or impair their accuracy.

b. Electrical measuring instruments should be **kept free from dampness.**

c. **Instruments should never be connected to circuits where the values to be measured are likely to be greater than the highest scale reading,** and the low resistance coils of a Wheatstone bridge should not have E.M.F.'s impressed across them sufficiently high to cause currents greater than the carrying capacity of these coils. In general, for ordinary testing, the *A* and *B* arms should not be set upon low values if the voltage of the testing battery is comparatively high.

d. **Milliammeters and millivoltmeters are designed for measuring millivolts and milliamperes, not volts and amperes.**

e. **Ammeters must always be inserted in series** and never across any branch or any part of an electrical circuit.

f. In any Wheatstone bridge test, **the galvanometer and the battery key should not be closed excepting when the tester is actually endeavoring to obtain a bridge balance.** If the galvanometer is equipped with a shunt, **the lowest resistance shunt should be bridged across the galvanometer when beginning to obtain a balance.** When an approximate balance is obtained in this way, the next lowest value shunt should be bridged, and thus by degrees the galvanometer coil may be connected into the circuit.

g. In making Wheatstone bridge measurements, **precautions should be taken against extraneous sources of E.M.F. such as ringing current, cords with battery, telegraph legs, etc.** being connected to the circuit at the distant end or at some intermediate point while a measurement is being made.

h. For accuracy when reading scales of electrical instruments **the eye should be directly over the needle,** that is, the line of vision should be perpendicular to the scale. Some instruments are equipped with small mirrors beneath the needle in order to guard against reading the scale at an angle. When the image of the needle in the mirror is directly beneath the needle, the eye is perpendicular to the scale. An error caused by the eye not being perpendicular to the scale is called error due to parallax.

i. When an indicating instrument is not connected, the **needle should stand on zero of the scale.** Most instruments are equipped with some device such as a screw-head adjustment for correcting the zero position of the needle.

j. Delicate instruments are usually equipped with some device for **clamping the needle when not in use.** This often prevents damage from jarring. Instruments not equipped with a clamping device may have their coils "dampened" by short-circuiting their terminals. Care must be taken that the short-circuit is removed before using the instrument.

k. Errors are often encountered in Wheatstone bridge measurements on long cable and open wire circuits due to foreign potentials caused by induction, ground potentials, etc. To correct for these, it is often necessary to reverse the polarity of the testing battery and make a second measurement. The average of the two measurements may be recorded as the correct one.

l. In making Wheatstone bridge measurements, precautions should be taken that the circuit under test is absolutely cleared of all bridged or other apparatus not permanently associated with the circuit and essential for giving simple continuity.

m. **Beware of loose connections.** Make sure that all connections to binding posts or elsewhere have zero resistance. Do not use high resistance wires for leads.

n. **Make a mental estimate of the value you expect to read** from your knowledge of the conditions. This will often prevent mistakes due to errors that are obvious, and will usually prevent the improper use of the instruments.

CHAPTER VI

THE DIRECT-CURRENT DYNAMO-ELECTRIC MACHINE

42. Induced Electromotive Force

Chapter III describes how lines of magnetic induction exist around any wire in which there is an electrical current. Not only does a current establish such a field, but conversely a magnetic field can be made to create an electromotive force. Voltage may be induced in any conductor by moving it through a magnetic field in such a manner that it "cuts" the magnetic lines. If the wire indicated in cross-section by the circle in Figure 67 is moved horizontally to the right through the magnetic lines having a direction vertically downward, it may be considered that the wire displaces or "stretches" the lines, which may be thought of as possessing a certain elasticity. This finally causes them to wrap themselves around the conductor, as shown. Referring to Figure 38 in Chapter III and applying this figure conversely to our new conditions, we find that a magnetic field which loops around a conductor in a clockwise direction, gives rise to a current flowing **into** the conductor as seen in cross-section. This is illustrated in Figure 67-D and E.

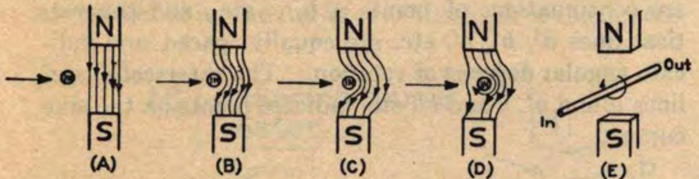


FIG. 67. WIRE MOVING THROUGH MAGNETIC FIELD

This rule, stated in another way, is called the **right-hand rule** for remembering the induced E.M.F. relation. It is illustrated in Figure 68. The forefinger of the right hand represents the direction of the lines of magnetic induction (flux—north to south); the thumb, when pointed perpendicular to the forefinger, represents the direction in which the conductor moves; and the second finger, when perpendicular to both the forefinger and the thumb, gives the direction of the induced E.M.F., or the direction of current flow. If a galvanometer is connected to the conductor, as in Figure 69, it will be found that the effect is more noticeable when the conductor is moved swiftly. From these and other similar experiments we learn that the law for induced E.M.F. may be stated as follows:

When any conductor is made to cut lines of magnetic induction there will be an E.M.F. induced in it, and the direction of the E.M.F., the direction of the flux, and the direction of the motion of the conductor have a perpendicular relation as shown by the right-hand rule. The amount of induced E.M.F. depends upon the rate of cutting magnetic lines, or the number of lines cut per second. In the established system of electrical and magnetic units, an E.M.F. of one volt is induced when a conductor cuts 100,000,000 lines per second.

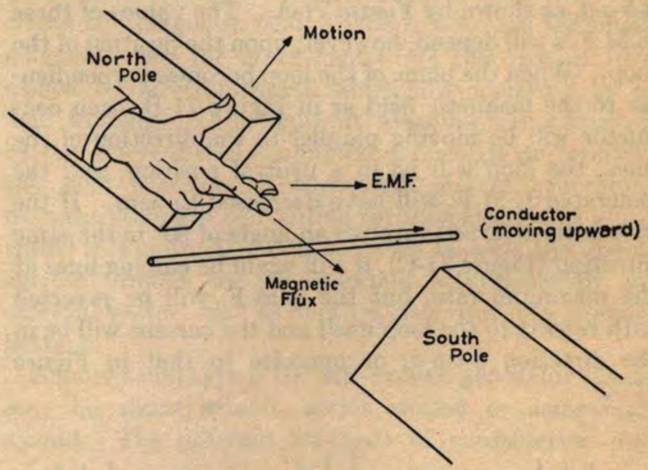


FIG. 68. RIGHT-HAND RULE

43. E.M.F. Induced in a Revolving Loop

Instead of a single conductor cutting lines of magnetic induction, we may have a loop of wire revolving in the

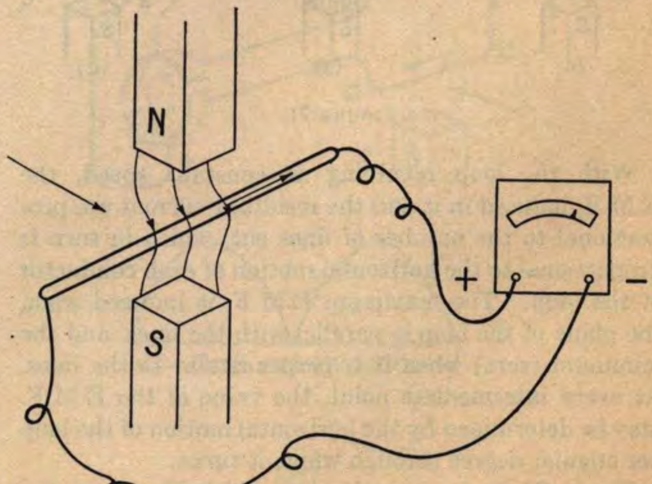


FIGURE 69

magnetic field between the poles of a magnet, as shown in Figure 70. In this case, the conductor nearest the south pole moves to the left while the conductor nearest the north pole moves to the right, and the E.M.F. induced has a different direction in the two conductors.

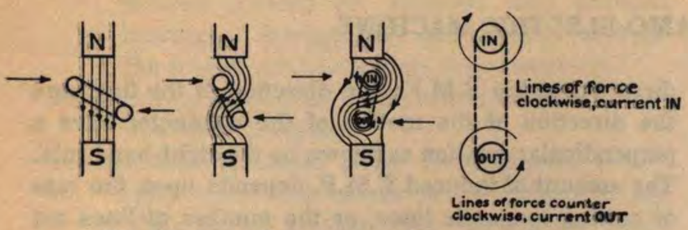


FIG. 70. LOOP ROTATING IN MAGNETIC FIELD

But, because the loop is complete, these E.M.F.'s will aid in causing a continuous current in the direction *a-b-c-d*, as shown by Figure 71-A. The values of these E.M.F.'s will depend, however, upon the position of the loop. When the plane of the loop becomes perpendicular to the magnetic field as in Figure 71-B, each conductor will be moving parallel to the direction of the lines, the loop will be in a neutral position, and the generated E.M.F. will have decreased to zero. If the loop is then turned through an angle of 90° in the same direction (Figure 71-C), it will again be cutting lines at the maximum rate, but the E.M.F. will be reversed with respect to the loop itself and the current will be in the direction *d-c-b-a*, or opposite to that in Figure 71-A.

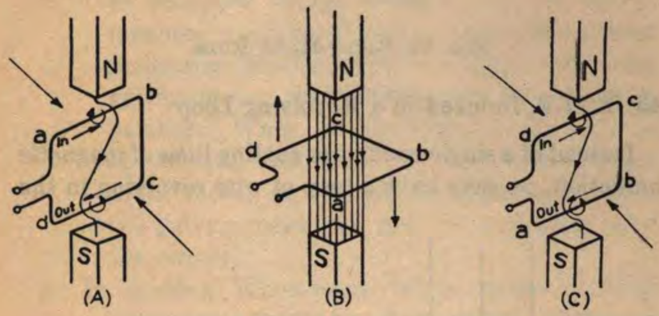


FIGURE 71

With the loop revolving at constant speed, the E.M.F. induced in it and the resultant current are proportional to the number of lines cut, which in turn is proportional to the **horizontal** motion of each conductor of the loop. The maximum E.M.F. is induced when the plane of the loop is parallel with the lines, and the minimum (zero) when it is perpendicular to the lines. At every intermediate point, the value of the E.M.F. may be determined by the horizontal motion of the loop per angular degree through which it turns.

Figure 72 shows a mechanism which illustrates the way in which this current varies. The wheel *d* is rotating at a constant speed, causing the attached pin *a* to slide in the slot *o*, moving the bar *b* (with the pencil *e* attached) vertically between the guides *gg*. When the horizontal component of the motion of the pin *a* is a maximum, that is, when the motion is in an entirely horizontal direction, the pencil *e* is at either its highest or lowest position, depending upon whether the motion of *a* is from left to right or right to left. When the horizontal motion of *a* is zero, *e* is midway between its extreme high and low points. If *f* represents a strip of paper which is being moved horizontally to the right at a constant speed while the wheel *d* is also rotated at a constant speed, the pencil *e* will draw a curve as shown. This curve will indicate a positive maximum (or highest point) when the horizontal motion of *a* to the right is a maximum; and will indicate center or zero points when the horizontal motion of *a* is zero. If the pin in this mechanism represents one conductor of a loop of wire revolving in a vertical magnetic field, the position of the pencil *e* with respect to the mid-point of its travel represents the E.M.F. induced in the conductor. This analogy is apparent since the induced E.M.F. in each loop is proportional to the horizontal motion of the loop. The curve not only represents maximum and zero points but shows all intermediate values of the induced E.M.F. as well.

Such a curve is called a **sine wave.** It is the **fundamental** wave form in alternating-current circuits of all kinds. A sine wave may be actually plotted by the method shown in Figure 73, where the horizontal lines are continuations of points *a*, *b*, *c*, etc., and the vertical lines *a′*, *b′*, *c′*, etc. are equally spaced and indicate **angular degrees of rotation.** The intersections of lines *a* and *a′*, *b* and *b′*, etc. indicate points on the sine curve.

44. Principle of the Direct-Current Generator

The revolving loop or **armature** shown in Figure 71

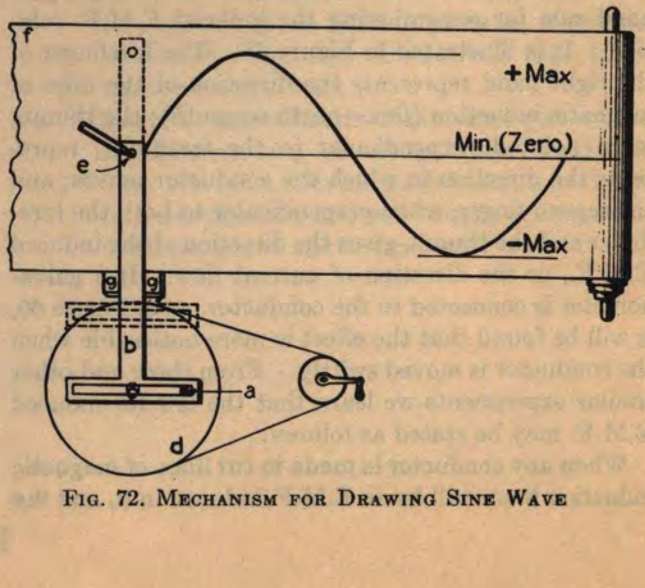


FIG. 72. MECHANISM FOR DRAWING SINE WAVE

may be connected to slip-rings, as shown in Figure 74-A. In this case the resulting E.M.F. between the two terminals or **brushes** will reverse in direction as the loop revolves, giving rise to an **alternating** E.M.F., one **cycle** of which is plotted in the figure. If it is desired to produce a unidirectional E.M.F., it is necessary to devise some means for reversing the connections to the loop at the same time that the current in the loop reverses. This is done by means of the **commutator** shown in Figure 74-B. This commutator effects the reversing of the connections to the armature leads just as the E.M.F. or current is reversed, changing the negative half-cycle to a positive pulsation. The resultant E.M.F. then consists of two positive pulsations per revolution of the loop, as shown.

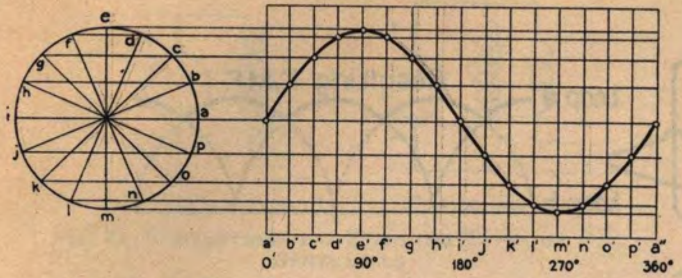


Fig. 73. Graphical Construction of Sine Wave

Generators may be constructed with more than one loop, as in Figure 75 in which two loops and four commutator segments are shown. The resultant E.M.F. is represented by the full lines at the right of the figure.

Comparing Figure 74-B with Figure 75, it may be seen that an increase in the number of loops causes a smaller fluctuation in the armature E.M.F. An armature wound with many turns therefore produces a practically continuous non-pulsating E.M.F., causing a **direct** current.

A standard generator armature consists of a large number of loops or turns which may be wound in several ways, depending upon the number of poles and the speed and voltage desired. The actual winding, however, consists of one continuous conductor, from which taps are brought out and connected to commutator segments, instead of a large number of separate loops.

In Figures 71, 74 and 75, we have assumed that the generator is equipped with permanent magnets which create the magnetic field. This is the case for small magnetos, but for other generators this field is furnished by electromagnets which are energized by a **field winding.** Direct-current machines are classified by the different means adopted to energize or "excite" this field winding. A **separately excited generator,** with the standard convention for indicating it, is illustrated in Figure 76. It is so called because the direct current through the field winding is furnished by an external source, such as another generator or a storage battery.

A more usual type is the **self-excited generator** which may be **shunt wound, series wound** or **compound wound.** The different methods of construction are

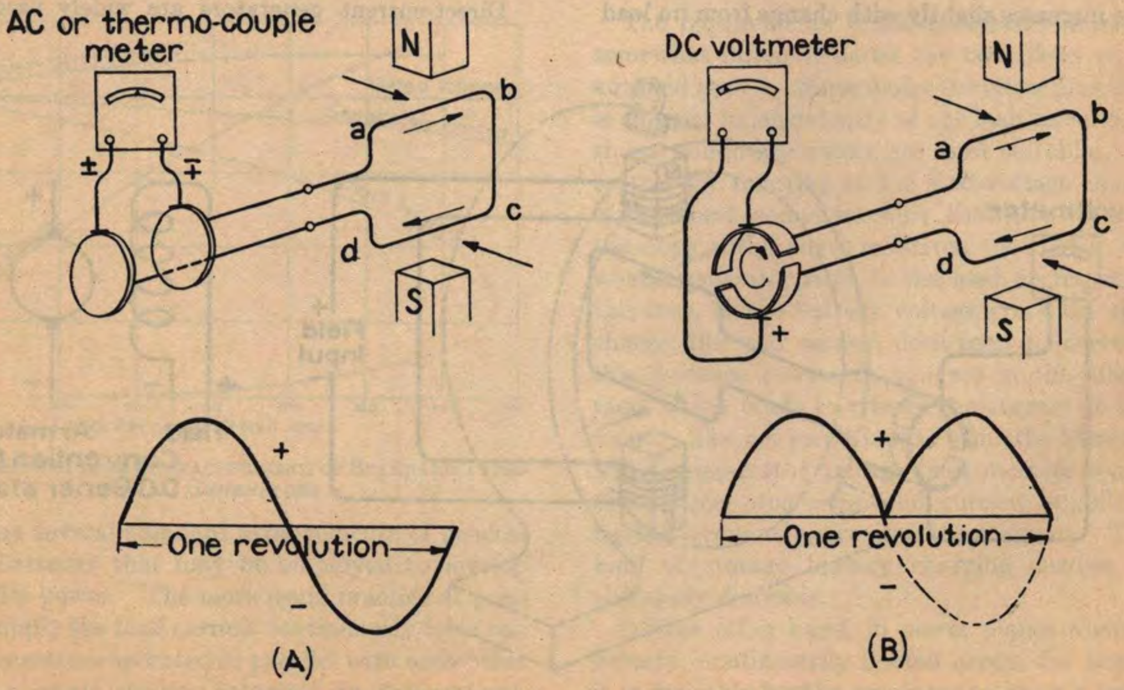


Fig. 74. Slip-rings and Commutator

shown schematically in Figure 77. As the E.M.F. induced in the armature is proportional to the magnetic flux, which in turn is proportional to the current in the field windings, a variation in the field current will cause a change in the armature E.M.F. With the shunt wound generator, an increase in load current causes a decrease in field current, as may be seen from a study of parallel resistances, and consequently causes a decrease in armature E.M.F. On the other hand, in the case of the series wound generator, the armature E.M.F. increases with the load current. The compound wound generator is designed to neutralize this change in armature E.M.F. by balancing the series effect against the shunt effect. An **over-compounded** generator is constructed with the series effect predominant so that the voltage increases slightly with change from no load to full load. Figure 78 shows curves representing armature voltage plotted against load for these various types of generators.

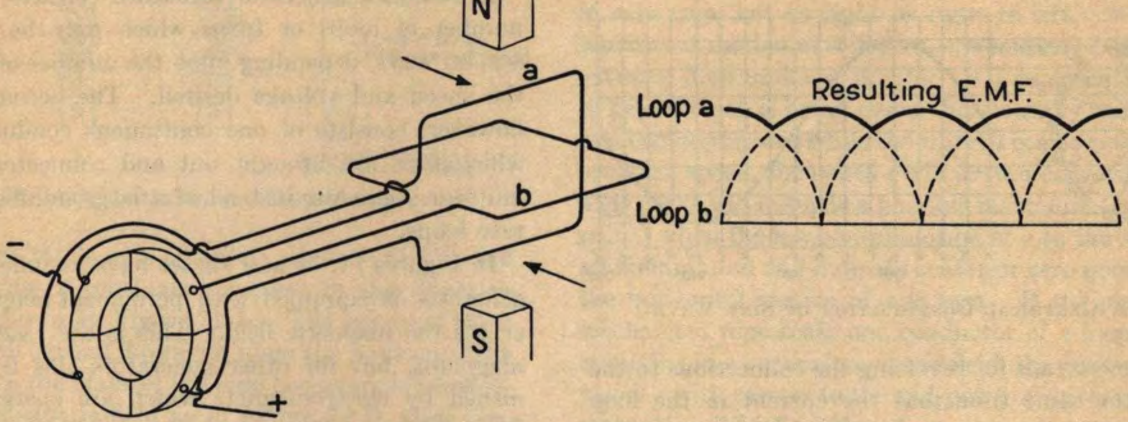


Fig. 75. Effect of Additional Loops

Generators may be further classified by the number of poles, a four-pole machine being represented by Figure 79. In every case there are the same number of brushes as poles, alternate brushes being connected together, as shown, to form the armature terminals. The voltage with four poles will be double that with two poles if the same armature winding and the same machine speed are used.

45. D.C. Generators for Supplying Central Office Power

Direct-current generators are widely used in tele-

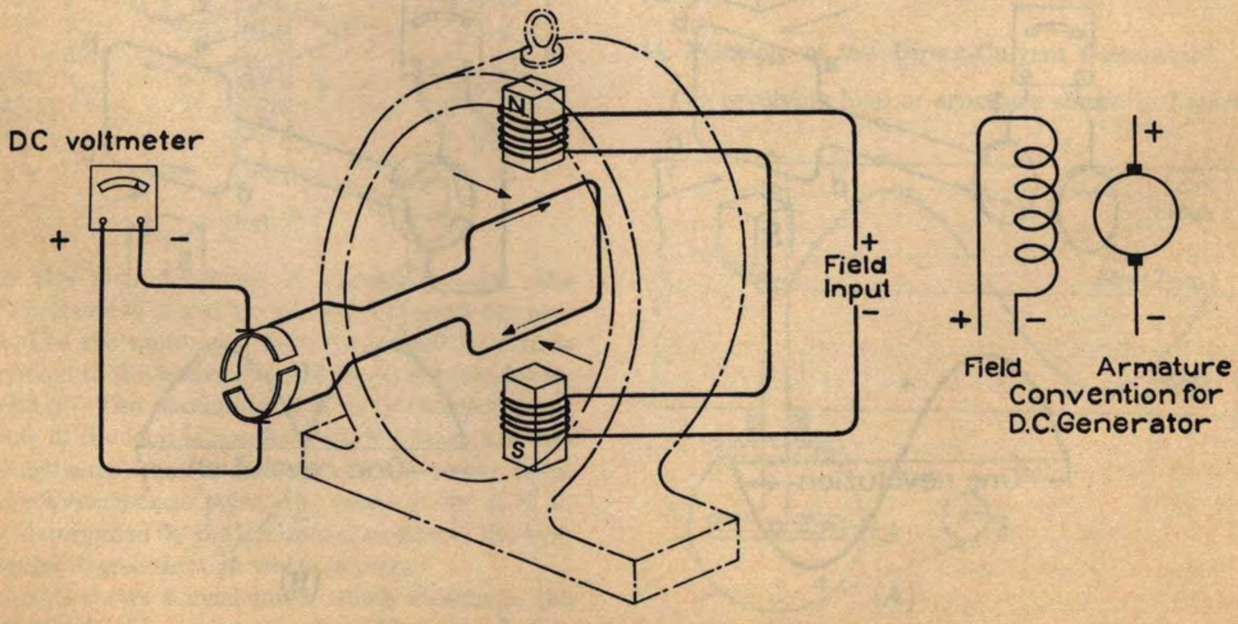


Fig. 76. Separately Excited D.C. Generator

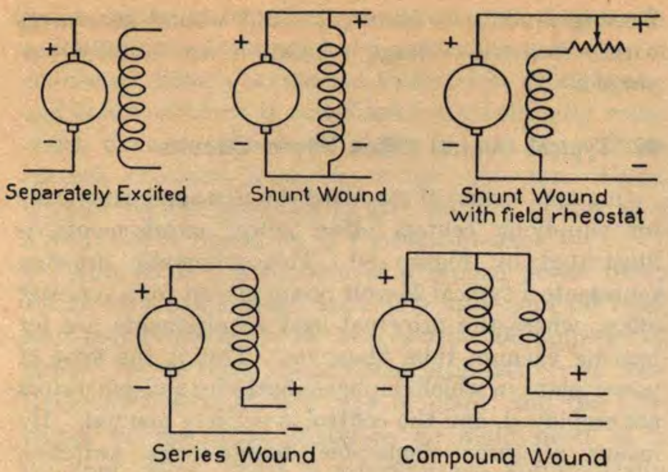


FIG. 77. CONVENTIONS FOR STANDARD TYPES OF D.C. GENERATORS

phone and telegraph work for supplying the several voltages required to operate the central offices. These include 24 and 48 volts used for "talking battery" and for operating vacuum tube filaments, relays, etc.; and also several higher voltages, ranging up to a maximum of 152 volts, for vacuum tube plate supply and operation of telegraph circuits. The motors which drive the generators are ordinarily supplied with power from commercial power lines and to guard against the possible failure of this supply, storage batteries are always provided in central offices. These batteries are kept charged by the central office generators so that they can take over the load temporarily in case of failure of the primary power supply. Being always connected to the load, the storage batteries also act as filters to reduce noise caused by the generators.

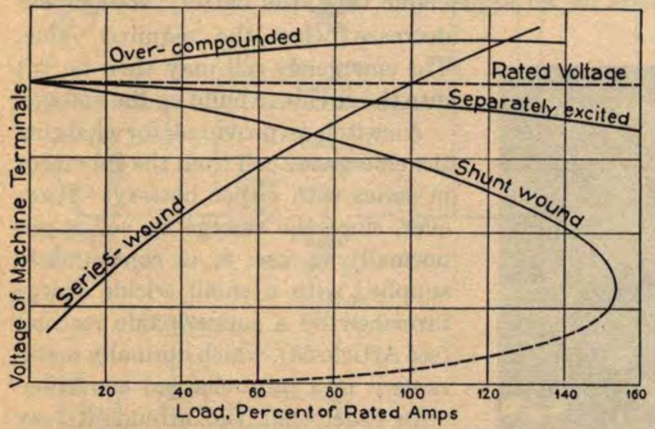


FIG. 78. LOAD-VOLTAGE CHARACTERISTICS OF STANDARD TYPES OF D.C. GENERATORS

There are several standard arrangements of generators and batteries that may be employed to develop central office power. The more usual practice at present is to supply the load current continuously from one or more generators operated in parallel with each other and with a single storage battery. In this arrangement, the storage battery is "floated", or connected continuously across the main bus-bars. The normal generator voltage is then maintained at a value sufficiently high to take carę of the load requirements and to supply a small "trickle" charge to the battery, thus keeping it fully charged. Another standard practice is to employ duplicate storage batteries and two or more generators. Under this plan, one battery may be charged while the other battery is either supplying the load by itself, or is floated across another generator which is supplying the load. Both of these methods are considered more fully in the next article.

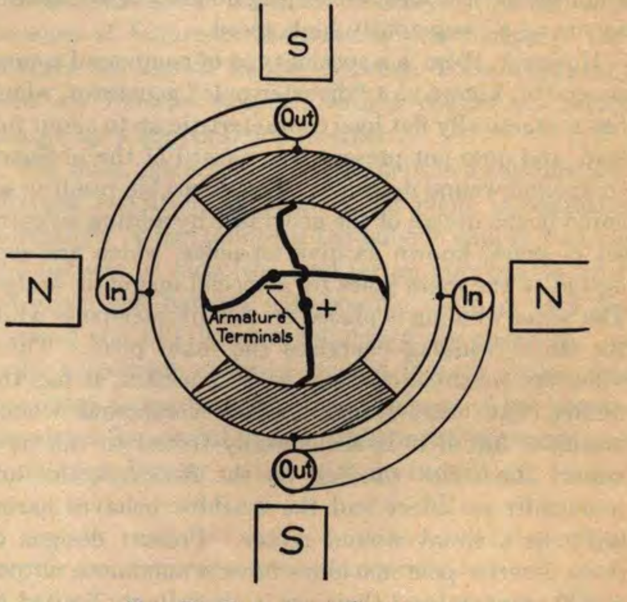


FIG. 79. FOUR-POLE GENERATOR

The requirements which generators must meet are somewhat different under the two plans of operation outlined above. Since under the latter plan the battery is charged independently of the load circuits, standard shunt wound generators are most suitable. This may be seen by referring to the load-voltage characteristic of the shunt wound machine, shown in Figure 78. As the slope of this curve indicates, the E.M.F. of a shunt wound generator rises as the load decreases. And in this case, as the battery voltage gradually rises under charge, the load current does tend to decrease. But this decrease causes an increase in the machine voltage, which tends to restore the current to its former value. The net result is that while the battery voltage and the generator voltage both increase somewhat as the charge progresses, the current supplied to the battery remains approximately constant. This is the kind of storage battery charging current which is ordinarily desirable.

On the other hand, in power plants where a single battery, continuously floated across the line, is used, it is desirable for the generator to have a load-voltage characteristic as nearly flat as possible. Because of its drooping characteristic, the shunt wound generator is therefore not suitable unless its voltage is constantly controlled by manual or automatic means.

The required flat characteristic could be obtained from an ordinary compound wound generator of proper design; but such a machine is not safe to use because in case of failure of the outside power, the floating battery would run the generator as a motor if the reverse current circuit-breaker failed to operate. In this situation, the reversed current in the series winding would cause the generator to operate like a series motor and because it would be carrying no load, it would tend to run at a dangerously high speed.

However, there is a special type of compound wound generator, known as a "diverter-pole" generator, which has a practically flat load characteristic up to about full load, and does not present this hazard of the ordinary compound wound machine. This desirable result is secured in the design of the generator by adding an extra set of poles, known as diverter-poles, which are connected to the main poles by a special magnetic bridge. The series winding is placed on the diverter-poles while the shunt winding energizes the main poles. Then, when the machine operates as a generator, it has the desired flat characteristic of the compound wound machine; but if it is accidentally forced to run as a motor, the series winding on the diverter-poles has practically no effect and the machine behaves harmlessly as a shunt wound motor. Present designs of these diverter-pole machines have a maximum output of 200 amperes, and their use is accordingly limited to offices where the total current requirements are relatively small. At larger offices where the continuous floating practice is followed, shunt wound generators with automatic voltage regulation are usually employed.

46. Typical Central Office Power Circuits

One application of standard shunt wound generators for supplying central office power requirements is illustrated by Figure 80. This schematic drawing represents a typical 24-volt power circuit for a repeater office, where the principal load requirements are for heating vacuum tube filaments. This is the type of power plant in which duplicate batteries and generators are employed, and the control is entirely manual. By means of three single-pole double-throw switches, either generator may be used to charge either battery while the other battery is carrying the load; or either machine may be connected to the load with one battery floated, while the other battery is being charged by the other machine. A filter, consisting of a "choke coil" and three "electrolytic condensers" connected in parallel to ground, is inserted in the output circuit to the filament supply panel. This smooths out small variations in current which might have an adverse affect on the sensitive apparatus supplied from this panel.

The circuit also includes an emergency storage battery cell which is connected to two single-pole double-throw switches in such a way that it can be connected in series with either of the main batteries. This cell is provided to take care of emergency conditions where the outside power supply fails and the generators are therefore inoperable. In such a case, the load must be carried by the batteries alone and if the failure persists for an appreciable time, the battery voltage will decrease below the required value. The emergency cell may then be cut into the circuit to build up the voltage.

A switch is provided for charging the emergency cell from the generator in series with either battery. However, since the emergency cell is not normally in use, it is continuously supplied with a small trickle charge furnished by a copper-oxide rectifier (see Article 53), which normally maintains it in a fully charged condition.

In order that the attendant may observe the operation of the circuit at all times, an ammeter is inserted in each generator lead, and another is inserted in the main output lead to the fuse panels. On the power panel also, is a voltmeter connected to a circular switch so arranged that it can read the voltage of either gen-

TYPICAL REPEATER STATION POWER PLANT

erator, either main battery, or either main battery in series with the emergency cell. Another voltmeter is connected directly across the load circuit at all times, and this voltmeter is paralleled by a voltmeter relay which gives an automatic alarm in case the voltage exceeds specified limits in either direction. Alarm circuits are also provided to give warning in case of a blown fuse or operation of a circuit-breaker.

Figure 81 is a schematic of a typical power plant where only one storage battery is used, and the total load requirements are in the order of 500 amperes or more. As we have already seen, the battery is continuously floated in this type of plant, and the generator voltage must therefore be maintained at a constant value. This is accomplished automatically by means of motor driven field rheostats associated with the shunt wound generators, as indicated in the figure. A voltage relay (designated Gen. Reg. Voltage Relay in the drawing) is bridged directly across the main battery. As long as the battery voltage remains at its proper value, this relay is not operated; but if the battery voltage becomes too high, or too low, one or the other of the two relay contacts is closed. This causes either relay L or relay R to operate, as the case may be, and the operation of either of these relays causes the motor driven field rheostat to move in the direction which will restore the generator voltage to its normal value. To avoid the possibility of overloading the generator, an ammeter relay is inserted in series with the line. When the generator is fully loaded, a contact of this relay closes causing relay A to operate and open the voltage relay circuit. This prevents any further attempt on the part of the voltage relay to increase the generator output.

Like the circuit previously discussed, this circuit is equipped with emergency cells which are automatically cut into the circuit in series with the main battery by means of another voltage relay bridged across the line. As before, these cells come into operation only when the storage battery is required to carry the load alone because of failure of the outside power supply. Although not shown in the drawing, these emergency cells are likewise supplied with a continuous trickle charge by a copper-oxide rectifier.

The main battery is, of course, kept in a continuously charged condition as long as the plant is operating normally. When failure of the outside supply requires the battery to carry the load for an appreciable time, however, the battery will become more or less discharged and will therefore require special charging. In order to provide charging current in such a case, it is necessary to increase the output voltage of the generator above its normal value. But since the generator is connected directly to the load, an increase in its out

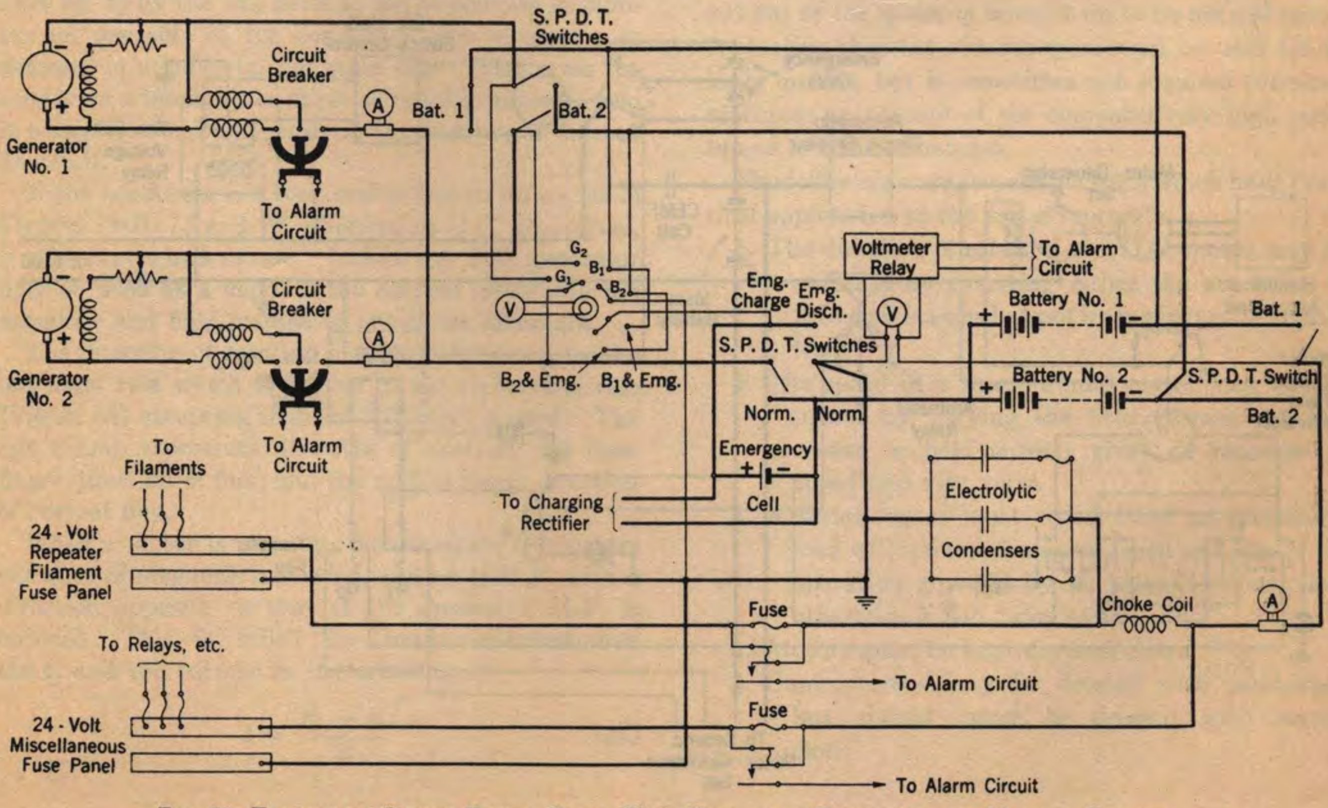
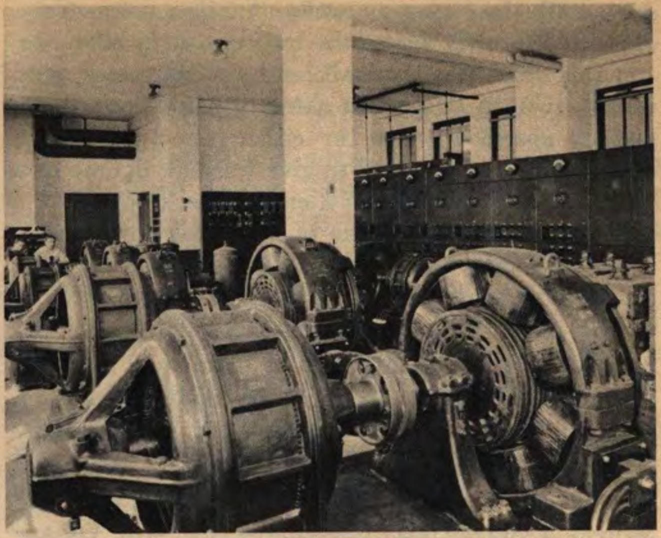


FIG. 80. TELEPHONE OFFICE POWER PLANT WITH DUPLICATE BATTERIES AND MANUAL CONTROL

put voltage would also increase the load voltage. To avoid this, the circuit includes a "counter-E.M.F. cell" which is automatically inserted in series with the load circuit when the output voltage of the generator is increased above its normal value.

The C.E.M.F. cell has the property, when current flows through it, of setting up a voltage opposing the voltage which is driving the current. The counter voltage is approximately 2 volts per cell and is developed without any appreciable loss of energy. Physically, the C.E.M.F. cell consists of two plates of pure nickel immersed in a caustic soda solution. As in the case of storage batteries, which are discussed in Article 50 following, the size of the nickel plates depends upon the amount of current which the cell is required to handle. The cells are usually mounted along with the storage battery cells.

Figure 81 shows only one generator but, as indicated at the bottom of the drawing, additional generators may be included. To insure continuity of operation, a practical power plant always includes at least two generators, and as many more may be added as are necessary to handle the maximum load. The second generator is equipped with a motor driven field rheostat like the first generator. When the first generator becomes fully loaded, this is put into operation by throwing the transfer key shown on the drawing. Additional generators, when required, are connected across the main leads to the battery, but are manually controlled.



Dial Central Office Power Plant

This power plant may be arranged so that the motor-generator sets will start automatically upon restoration of the outside power supply after failure. By including additional relay circuits, this general type of plant may also be arranged so that needed generators will be

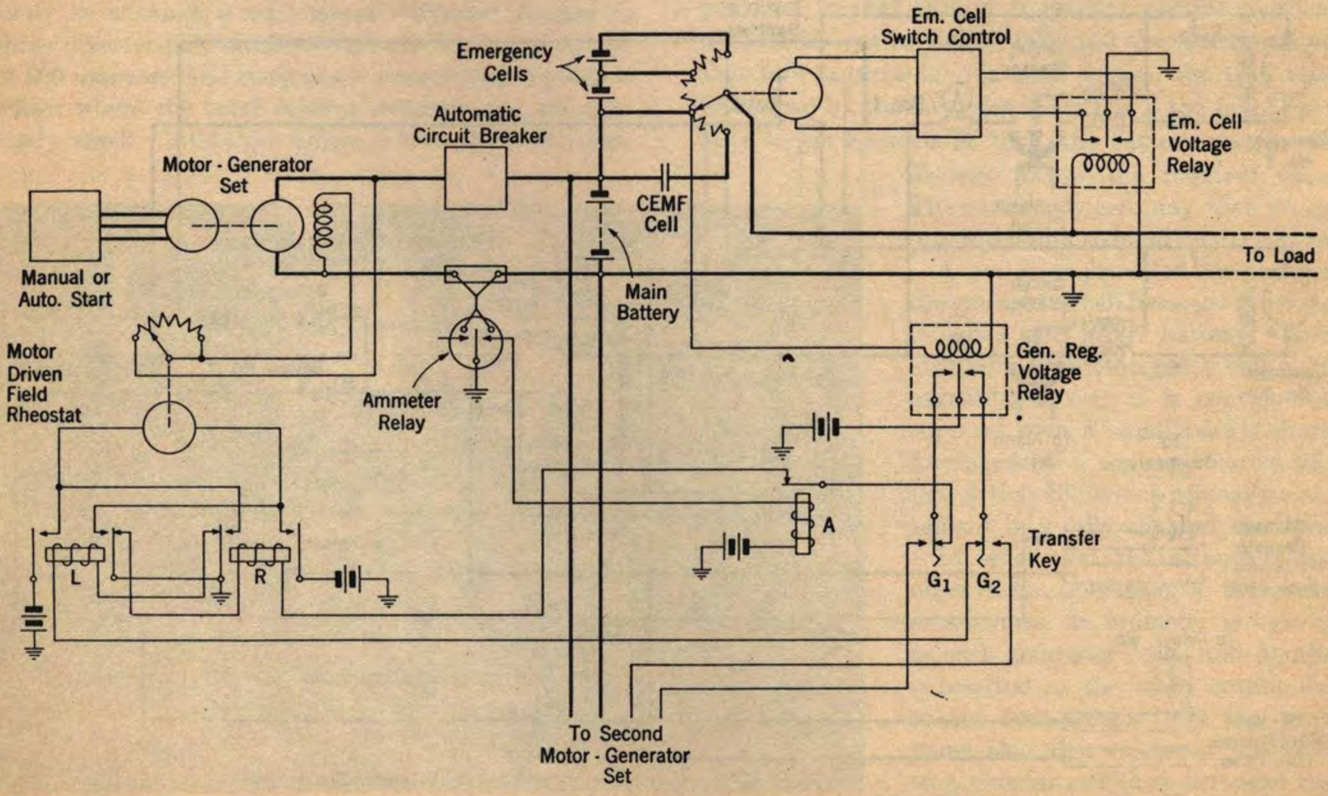
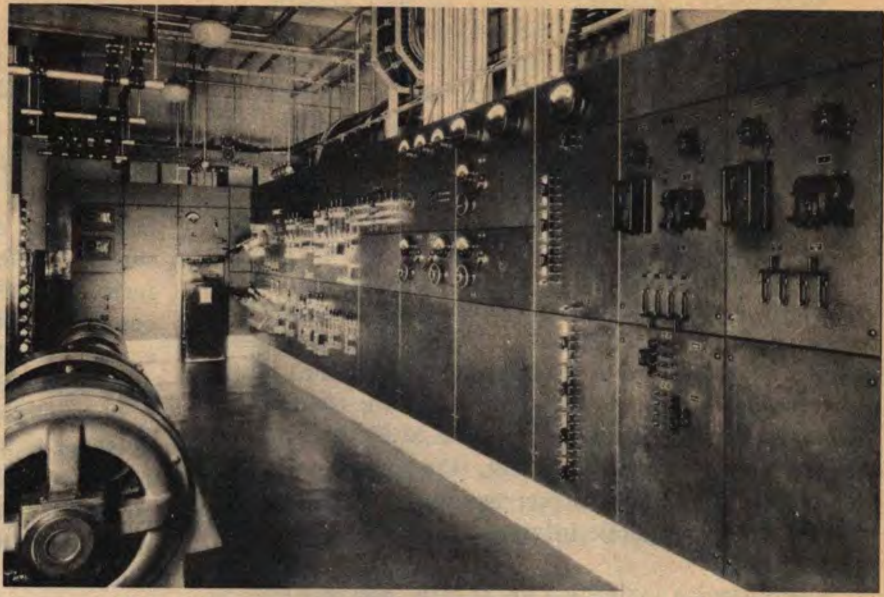


Fig. 81. Telephone Office Power Plant With Single Floating Battery and Automatic Control

automatically started and connected to the line as the load increases, and automatically disconnected and stopped as the load decreases.



Power Switchboard of Large Telephone Central Office

47. Direct-Current Motors

In the telephone plant, most of the electric motors used to drive charging generators, ringing machines and other minor units such as polishing machines and fans, operate on alternating current as supplied by the regular power distribution systems. However, direct-current motors are occasionally used. There are many classes of such motors (series, shunt, compound, multipolar) and each has different characteristics of power and speed. It is impracticable to discuss particular types in this book, and only a brief explanation of the fundamental working principle will be given.

When a conductor carrying an electric current is placed in a magnetic field at right angles to the lines of magnetic induction, there is a reaction between the circular field about the conductor and the field in which it has been placed. This reaction causes the lines set up by the two fields to aid or increase in number on one side of the conductor and to oppose or decrease in number on the other side. This gives the conductor a tendency to move across the magnetic field in a direction which depends on the direction of current flow in it.

If the conductor is a loop and is free to rotate, as in Figures 74-B, 75 and 76, illustrating D.C. generators, it will revolve as a motor. In fact **any D.C. generator may be used as a motor if the current flows into the armature and field instead of out of the armature.**

The direction of rotation may be determined by the **left-hand rule** which is similar to the right-hand rule (Figure 68) excepting that the left hand is used. The left thumb represents direction of motion; the forefinger direction of flux; and the middle finger direction of current flow.

When a motor is running, the armature conductors cut lines of magnetic induction, and an E.M.F. with a direction opposite to that of the applied E.M.F. is induced. This is called the **counter-electromotive force,** and the current in the armature is—

$$I = \frac{E_i - E_c}{R} \tag{27}$$

where E_i is the impressed E.M.F., E_c is the counter-E.M.F., and R is the armature resistance.

Since there is low counter-E.M.F. until the motor has reached about its normal speed, it will draw a very large current at starting unless this is prevented by a **starting rheostat.** This is a variable resistance placed in series with the motor's armature which is gradually cut out as the motor is brought up to its normal speed. A starting rheostat of some type must be used for all large motors, but is sometimes not required for small machines on account of the comparatively high resistances of their armatures.

The following are a few simple rules which have practical application to the use of motors:

1. The direction of rotation of a D.C. motor may be reversed by reversing either the armature or field connections but **not** by reversing the supply leads.
2. The speed of a shunt wound motor may be adjusted by varying the field current. A **decrease** in field current gives an **increase** in speed and vice versa.
3. A series motor must either have an increasing load with increase in speed, such as a fan, or its operation guarded by an attended controller; otherwise it will "run away".
4. Motors must be kept dry and clean.
5. Commutators may be dressed with sandpaper but should never be dressed with emery cloth.

CHAPTER VII

OTHER SOURCES OF DIRECT ELECTROMOTIVE FORCE

48. Types of D.C. Energy Sources

For an electrical circuit to become energized, some source of electromotive force must be connected to it either by direct connection or through inductive relations. In the case of a direct current, the circuit must be energized by the actual connection of the conductors to the terminals of the source of E.M.F.; but in the case of an alternating current, the circuit may be energized either by such connection or by inductive effects due to magnetic interlinkages or capacity relations.

If any device maintains an E.M.F. and sustains a current of electricity in a circuit, energy is supplied to the circuit. But the law for conservation of energy states that energy cannot be created or destroyed. Any source of E.M.F. may then be defined as a device for supplying electrical energy by converting it from some other form. The battery converts chemical energy into electrical energy, the generator converts mechanical energy into electrical energy, and the thermocouple changes heat to electrical energy. A rectifier is in one sense a source of direct E.M.F. but it converts alternating-current energy into direct-current energy, changing it from one electrical form to the other rather than from some other form to the electrical.

Figure 82 shows the circuit conventions for sources of direct E.M.F. that are common in electrical work. In the operation of the telephone plant we are interested principally in the battery, the generator and the rectifier. The theory of the generator is covered in Chapter VI. We shall at this time consider the various types of batteries and the general battery requirements of telephone service, and make some mention of rectifiers and other interesting though perhaps less important sources of direct E.M.F.

49. Primary Batteries

Chemical batteries are divided into two classes,

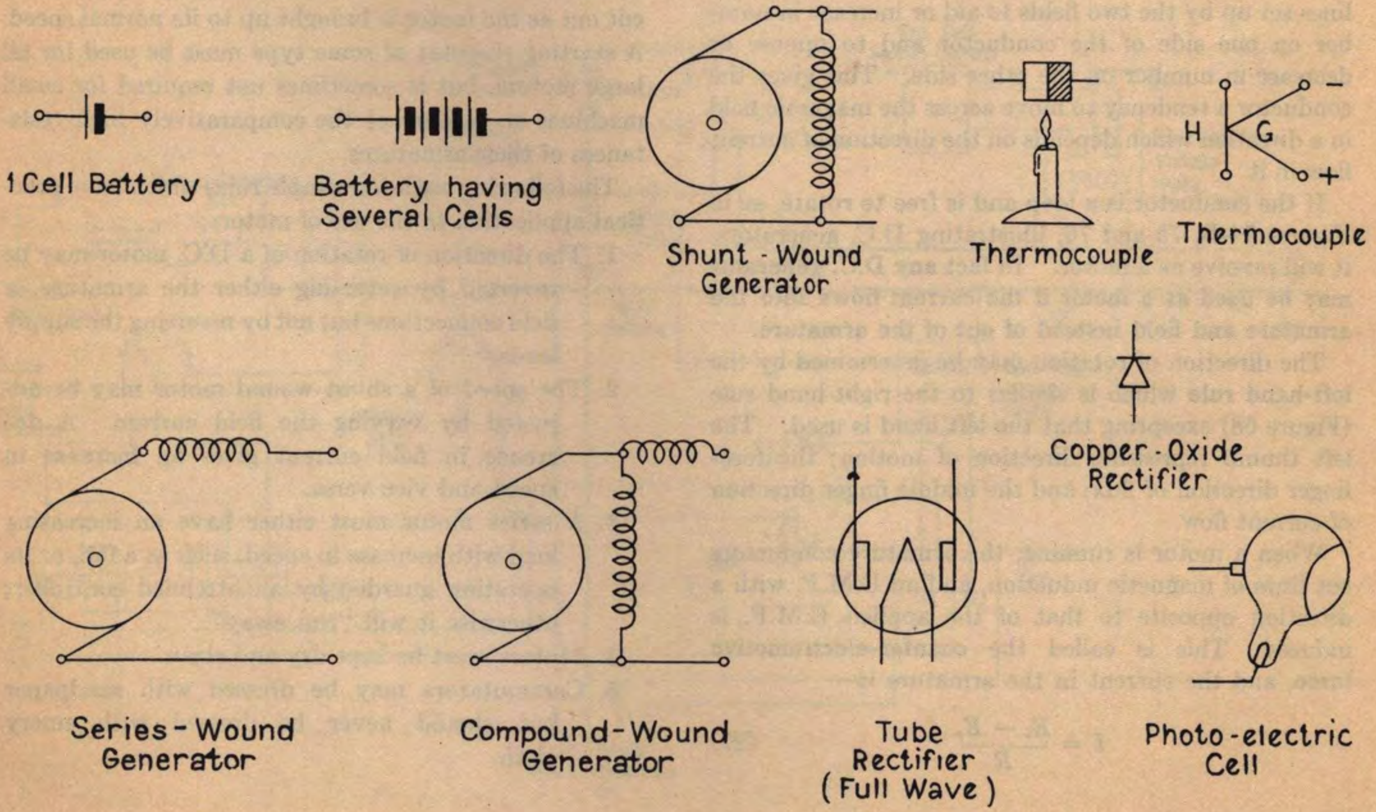


Fig. 82. Standard Conventions for Sources of Direct E.M.F.

primary and secondary. A primary battery is one that generates an E.M.F. by virtue of certain chemicals coming in contact with submerged metals or other substances which constitute the positive and negative terminals. A secondary battery stores electrical energy but does not directly generate an E.M.F. unless a current is first passed through the battery in a direction opposite to that in which it will flow when supplying energy to an external circuit.

The unit of a battery is the cell, consisting of a single couple of submerged positive and negative poles or plates. As illustrated in Figure 83, cells may be connected in parallel or in series, depending upon the value of the E.M.F. desired and the value of current to be sustained. If they are connected in series, the E.M.F.'s are added, making the total E.M.F. of the battery the sum of the E.M.F.'s of the individual cells. If they are connected in parallel, the E.M.F. of the battery is that of a single cell, but the current supplied to the circuit is divided between the several cells.

Parallel

Series

Fig. 83. Cells in Series and Parallel

A battery may consist of groups of cells connected in parallel and these in turn connected in series, or vice versa. Figure 84 shows two methods of connecting six cells where the E.M.F. desired is that of only three cells and a single string is not sufficient to sustain the current required. Theoretically, the two methods give the same results, but in the case of dry cells, method "B" has some advantage from the standpoint of deterioration of the battery due to the uneven electrical characteristics of the individual cells.

The various types of primary batteries may be divided into two general groups called "wet" cells and "dry" cells. There are numerous kinds of wet batteries, the more common of which are as follows:

a. The **Daniell cell** which consists of a zinc plate in a solution of zinc sulphate and a copper plate in a solution of copper sulphate (blue vitriol). In earlier forms of this cell the two solutions were separated by a porous cup which contained one solution and was submerged in the other. One of the later and more commonly used types, called the "gravity cell", dispenses with the porous cup on account of the two solutions having different specific gravities. The copper sulphate, being heavier than the zinc sulphate, is placed in the bottom of the jar with a copper plate, and the zinc sulphate in the top of the jar with a zinc plate (or "crow's foot").

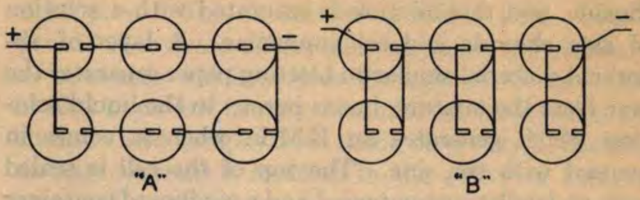


Figure 84

b. The **sal ammoniac cell,** which consists of a zinc negative rod or plate and a carbon positive plate in a solution of sal ammoniac (ammonium chloride).

c. The **Lalande cell,** which consists of a zinc negative cylinder in a solution of caustic soda and a perforated sheet iron cylinder in which is embodied black copper oxide. The two are separated by cylindrical insulators.

About the only **wet cell** used to any considerable extent in the telephone plant is a special form of Lalande cell, known as the "air-cell battery". It consists essentially of a negative zinc plate and a porous carbon rod immersed in a caustic soda solution. The chemical action of the cell is such that hydrogen is liberated at the positive carbon electrode, which combines with oxygen from the air breathed in by the porous carbon to form water. It is necessary to keep the top of the carbon electrode clean and to locate the battery in a well ventilated cabinet or room, as each cell must absorb some 45 cubic inches of air per hour for proper operation at full load. The air cell has a nominal voltage of 1.25 and a capacity of 600 ampere-hours with a maximum current drain of .66 ampere. Its principal use in practice is for supplying current for operators' transmitters in magneto offices and for operating certain types of interrupters.

The **dry cell** is a special form of chemical battery, so constructed that the chemicals used in its action are sealed. It is most convenient for shipping and general use. There are two important and general classes of service for which dry cells are designed. They may be constructed for heavy current duty, such as for flashlights, at a sacrifice of life; or they may be intended for connection to a high resistance and a correspondingly low current output. In the latter case, the batteries do not require replacement for a much longer period, particularly if the service is required only at intervals and the battery is allowed to "rest" on open circuit.

The Blue Bell dry cell is representative of the "long-life" type. Its construction is illustrated in Figure 85. The negative terminal consists of a zinc container in which is centered a bar of carbon as a positive terminal. The carbon is surrounded by a porous medium consisting principally of ground carbon and manganese dioxide, and this mixture is saturated with a solution of zinc chloride and sal ammoniac. A layer of absorbent material similar to blotting paper separates the zinc from the mixture, but is porous to the liquid solution which generates an E.M.F. when it comes in contact with the zinc. The top of the cell is sealed with an insulating compound and a cardboard container acts as an insulating cover for the zinc. Spring connectors, which are securely fastened to the zinc and carbon electrodes, form suitable terminals. When new, this dry cell gives a voltage of about 1½ volts, which decreases with age, and has an internal resistance of .2 to .3 ohm, which increases with age. For average use, its capacity may be roughly estimated at 20 to 30 ampere-hours but this will vary considerably depending upon conditions. For example, the capacity when connected to a high resistance circuit may be several times the capacity when connected to a low resistance circuit. Intermittent use is also an important factor.

Dry cells are commonly used in the telephone plant for service where connections to central office storage batteries are not feasible, or cannot be used because the storage battery is grounded. In addition to transmitter batteries for magneto subscribers' stations, such uses may include battery supply for telegraph sounders on subscribers' premises, Wheatstone bridge testing battery for toll testboards, plate and grid batteries for vacuum tube circuits, and testing batteries for portable testing sets. For many of the above purposes, the current requirements are comparatively low while the voltage needed may be considerable. To meet these conditions, it is the usual practice to employ small or miniature cells which are connected in series and assembled in sealed "battery blocks" in the manufacturing process. Standard battery blocks of this type are available having nominal maximum voltages of 3, 4½, 22½, and 45 volts. The higher voltage blocks usually have intermediate taps giving various voltage values below the maximum.

As noted above, the life of a dry cell or a battery block depends upon the kind of service in which it is used. Standard maintenance provisions call for replacement if batteries fail to meet the following tests:

a. When the current drain is negligible, as in vacuum tube grid batteries, a voltage of at least 1.33 volts per cell should be obtained when the battery is tested with a voltmeter having a resistance of 1000 ohms per volt of full scale deflection.

b. When the current drain is steady and fairly large, as for vacuum tube plate supply, the voltage should be at least 1.13 volts per cell when tested under load with a voltmeter having a resistance of 60 to 100 ohms per volt.

c. When the current drain is fairly large but variable, the voltage should measure at least .9 volt per cell when tested 10 seconds after the application of an artificial load of 5 ohms per cell for large cells and 10 ohms per cell for small cells, with a voltmeter having a resistance as in (b) above.

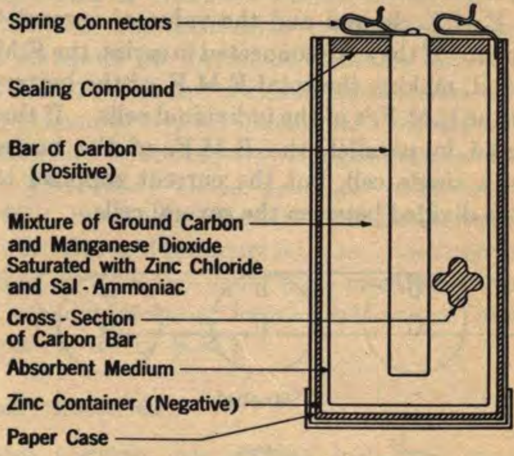


FIG. 85. BLUE BELL DRY CELL

50. Storage Batteries

A chemical battery that is capable of storing electrical energy delivered to it from some other source, and delivering this energy to an electrical circuit at some later time, is called a storage battery. Other names commonly used are "accumulator" and "secondary battery". The two general types of storage batteries are the lead-acid and the Edison (iron-potassium hydroxide-nickel). On account of its low internal resistance and more constant terminal voltage, the lead-acid type more nearly meets the exacting requirements of the telephone central office. (These requirements are discussed in Article 51 following.)

When the lead-acid cell is in a fully charged condition, the active constituents are a positive plate of lead peroxide (PbO_2) and a negative plate of spongy lead (Pb) in a dilute solution of sulphuric acid ($H_2SO_4 + H_2O$). When the battery is discharging, the current, passing from the positive to the negative plate through the external circuit, must return from the negative to the positive plate through the dilute acid (electrolyte). In doing so, it breaks the electrolyte into its component parts resulting in first, the spongy lead of the negative plate combining with the positively charged component (SO_4) of the electrolyte, forming lead sulphate ($PbSO_4$) and losing its negative charge; second,

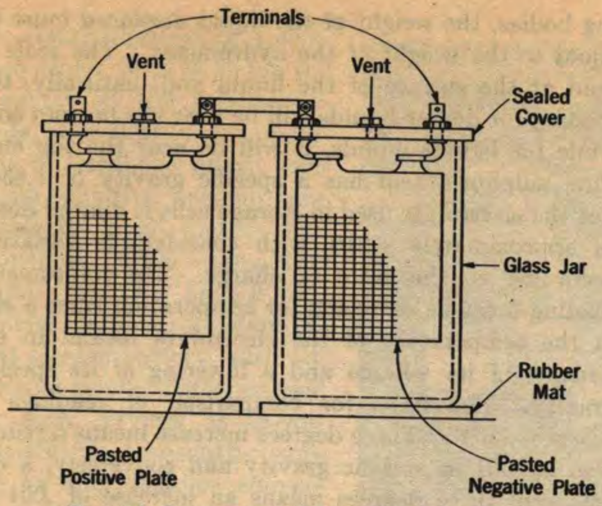


FIG. 86. ENCLOSED TYPE STORAGE BATTERY

the oxygen of the lead peroxide of the positive plate combining with a part of the hydrogen liberated from the electrolyte, forming water, and converting the positive plate to pure lead; and third, a similar breaking up of the sulphuric acid at the positive plate, forming more water and converting some of the lead of the positive plate into lead sulphate by the same chemical action that takes place at the negative plate.

When the storage battery is charging, this chemical action is reversed. The charging current, in passing through the electrolyte in the opposite direction to that of the discharge current, breaks down some of the water of the electrolyte into hydrogen and oxygen. The oxygen travels against the current to the positive plate where it combines with the lead sulphate of that plate to form lead peroxide. The sulphate (SO_4) released by this action combines with hydrogen to form sulphuric acid. At the same time, hydrogen, travelling with the current to the negative plate, combines with the lead sulphate of that plate to form sulphuric acid. This leaves pure metallic or sponge lead on the negative plate, and the two plates and the electrolyte are thus gradually restored to their original charged condition.

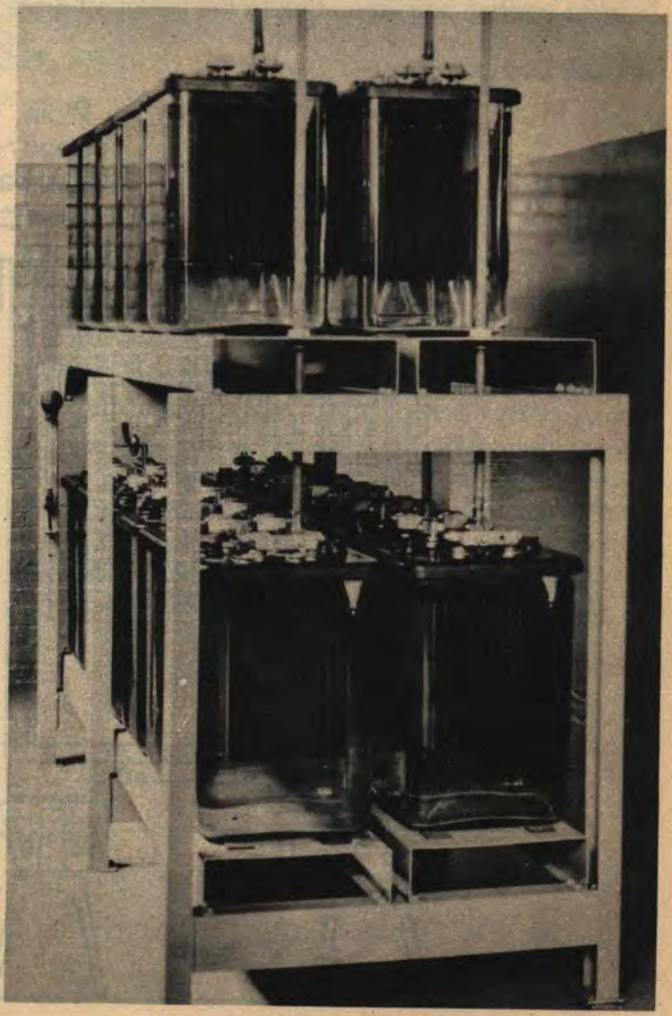
The following chemical equation may be used to explain the action of discharge when reading from left to right and the action of charge when reading from right to left:

$$PbO_2 + Pb + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O \quad (28)$$

Storage batteries are built in a wide variety of sizes to meet the various load requirements. The capacity of a cell naturally depends on the total area of plate surface which is exposed to the electrolyte. The smallest cell consists of a single pair of plates having a total area of only a few square inches, while the largest cells may have more than 100 plates, each with an area of more than three square feet.

In modern central office practice, the plates of the smaller storage cells (up to a maximum ampere-hour capacity at an 8-hour discharge rate in the order of 1000) are mounted in glass jars. These are enclosed at the top with a cover of glass or acid-resisting compound which is sealed to the glass jar to form an acid-tight joint. The covers are provided with vents to permit the release of gas and the plates are connected to terminals which project through the cover. Cells of this type are usually mounted on iron racks, and since no acid escapes from them, they may be installed at any convenient location in the power or terminal room. Larger cells are assembled in lead-lined wooden tanks. These cells are open at the top and must therefore be installed in a separate well-ventilated room.

The general arrangement of the two main types of cells is illustrated in Figures 86 and 87. As these drawings indicate, different methods are employed for impressing the active material (lead peroxide and sponge lead) on the plates. In all cases, the basic structure of the plate is a cast antimony-lead grid.



ENCLOSED TYPE STORAGE BATTERY

The method of applying the active material is purely a mechanical problem and has no effect on the electrical behavior of the cells. The plates are kept separated by wooden or rubber separators, and are supported in the manner indicated in the drawings.

In the practical operation of a storage battery, we must be able to determine the state of charge or discharge at any time. It is not convenient to do this by chemical analysis, but in the foregoing explanation of the cycle of charge and discharge, there are two changes taking place that may be easily determined. One is the change in the electrical charge held by the plates, resulting in a change in the E.M.F. of each cell. The other is the increase on discharge, and the decrease on charge, of the amount of water contained in the electrolyte, which increase or decrease, as the case may be, changes the specific gravity of the electrolyte. This latter condition gives the better index to the cell's operation and is the one ordinarily used.

Figure 88 shows a hydrometer designed for determining the specific gravity of the electrolyte. A weight at the bottom makes the hydrometer float in an upright position and, according to the law of all floating bodies, the weight of the liquid displaced must be equal to the weight of the hydrometer. The scale is read at the surface of the liquid and, naturally, the reading for denser liquids will be near the bottom end, while for lighter liquids, it will be near the top end. Pure sulphuric acid has a specific gravity of 1.8342 but the electrolyte used in storage cells is diluted down to approximately 1.210, with considerable variation according to the state of charge. The hydrometer reading must be corrected for temperature since a rise in the temperature of the electrolyte means an expansion of its volume and a lowering of its specific gravity. The basis for comparison of readings is taken at 70°F. Three degrees increase means a reduction of .001 in specific gravity and conversely, a decrease of three degrees means an increase of .001 in specific gravity.

51. Power Plant Requirements in Telephone Offices

The telephone central office power plant must be not only absolutely reliable at all times but must meet other exacting requirements. Modern practice has led to

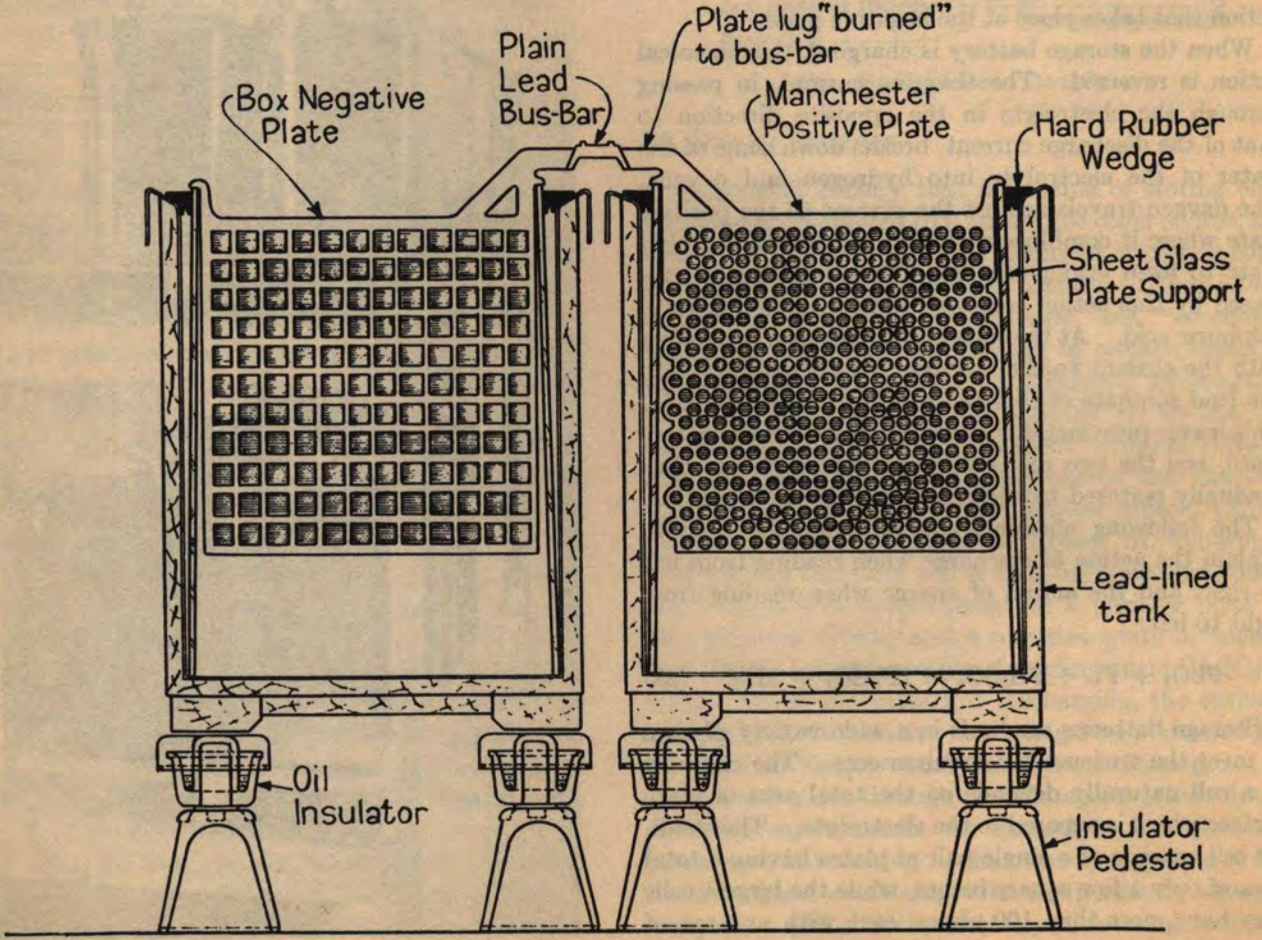


Fig. 87. Open Tank Type Storage Battery

OPEN TANK TYPE STORAGE BATTERY

the standardization of a common source of E.M.F. for the majority of the talking circuits, as well as for the operation of telephone relays, telegraph sounders, vacuum tube filaments, small motors, and numerous other apparatus units. We thus have a very general use of the standard 24-volt storage battery, with additional smaller batteries used for such services as 48-volt subscriber's transmitter supply on long distance connections, 120-volt supply, both positive and negative, for telegraph repeater operation, and other voltages, for telephone repeater operation. The common battery results in a number of plant economies, but, on the other hand, imposes certain exacting electrical requirements. Probably the most essential of these requirements is **low internal resistance.**

In our study of simple electrical circuits, we have considered a single source of E.M.F. for each individual circuit. But we have learned that any number of resistances may be connected in parallel, as shown by Figure 89, and that the current in any single resistance is independent of that in any other resistance provided all resistance branches are connected directly to the terminals of the battery as indicated. This follows naturally from the application of Ohm's Law to a single resistance branch, since the E.M.F. impressed on any single branch is the E.M.F. of the source and, theoretically, is independent of current flowing through other branches. This assumes, however, that the battery is a perfect source of E.M.F. without internal resistance.

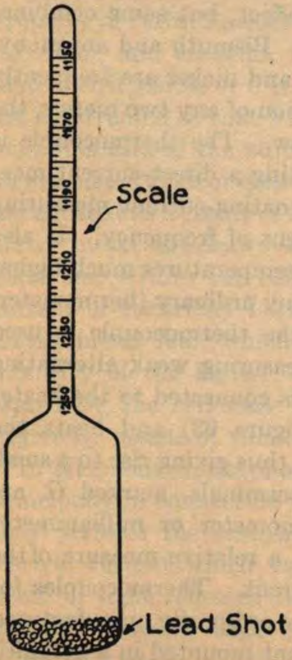


FIG. 88. HYDROMETER

Figure 90 represents the central office storage battery connected to bus-bars at the fuse panel. The central office circuits are cabled to this fuse panel and receive their battery supply through taps to the small panel busses. Thus hundreds of circuits of varying resistance are connected in parallel to a common battery, and we have in practice a circuit arrangement identical to that shown in theory by Figure 89, excepting that as indicated in Figure 90, fuses for protection against excessive currents due to short-circuit or overload are used, and the positive terminal of the battery is connected to ground. This ground connection stabilizes the potential of all circuits in the central office by short-circuiting their capacities to ground. It also simplifies the central office wiring and affords circuit protection, but it cannot in any way affect the total current supplied by the battery or the current in any individual circuit that may be connected to the bus-bars.

Returning to Figure 89, in which the current in any

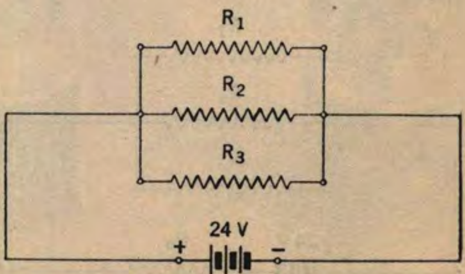


FIGURE 89

one resistance branch was seen to be independent of that in any other (provided the source of E.M.F. is a perfect one), let us assume, on the contrary, that the battery has an internal resistance R_0 and that the circuit is actually that shown by Figure 91. Due to the resistance R_0, the current in one branch is no longer independent of that in other branches. Let us assign values as follows:

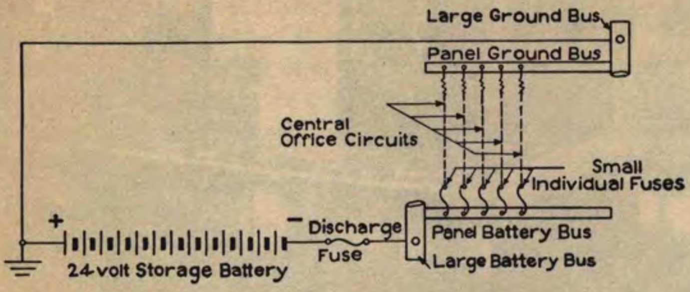


FIG. 90. STORAGE BATTERY LOAD CONNECTIONS

$R_0 = 2$ ohms

$R_1 = 5$ ohms

$R_2 = 4$ ohms

$R_3 = 3$ ohms

$V = 24$ volts

If we solve this network, we shall find that the current through R_1 is 1.87 amperes. If we should suddenly open resistances R_2 and R_3, however, it would immediately change to 3.43 amperes. Applying the same principle to Figure 90, **unless the central office source of E.M.F. has negligible resistance, including both the internal resistance of the battery and that of the supply leads from the battery to the bus-bars where individual circuit leads are connected, there will be ever-changing current values in the individual circuits. This will result in noise and crosstalk in all talking circuits and unreliable operation of various other telephone apparatus.** From this it follows that common battery operation for any number of circuits may be substituted for local or individual batteries only when the common source of E.M.F. has negligible internal resistance.

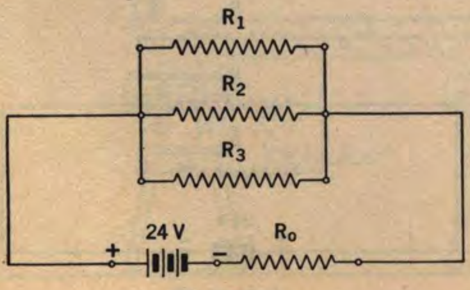


FIGURE 91

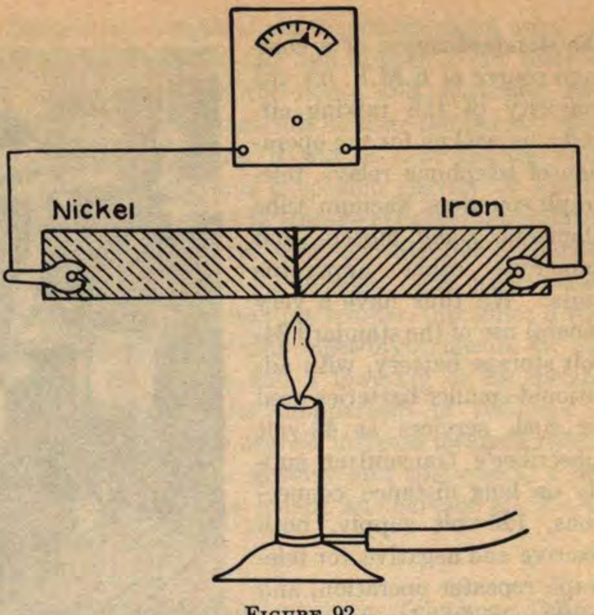


FIGURE 92

52. Thermo- and Photo-Electric Effects

The thermocouple is probably the simplest source of electromotive force but it has little practical use as a source of energy supply. Nevertheless, because it is a direct means of establishing an electrical current from heat, its principle of operation is important. It consists of two dissimilar metals in contact, with heat applied to their junction. The different characteristics of the two metals result in a difference of potential between them when heated and if a galvanometer is connected as shown in Figure 92, current can be detected. Almost every combination of dissimilar metals will give the thermocouple effect, but some combinations are better than others. Bismuth and antimony, iron and constantin, copper and nickel are frequently used. For a single combination of any two metals, the E.M.F. generated is very low. The thermocouple is used extensively for converting a direct-current measuring instrument to an alternating-current measuring instrument that is independent of frequency. It also permits the measurement of temperatures much higher than can be measured with any ordinary thermometer.

In the telephone plant, the thermocouple is used primarily as a device for measuring weak alternating currents. The A.C. circuit is connected to the heater terminals (marked *H* in Figure 93) and heats the junction of dissimilar metals, thus giving rise to a small direct current. The D.C. terminals, marked *G*, are connected to a D.C. galvanometer or milliammeter which gives by its deflection a relative measure of the input A.C. or "heating" current. Thermocouples for laboratory and general use are ordinarily manufactured with the glass-enclosed element mounted in a cylindrical metal container equipped with either ordinary terminals or a vacuum tube base for use in standard sockets. For general use, there are three standard resistance values for the heater element, viz. 5 ohms, 40 ohms, and 600 ohms.

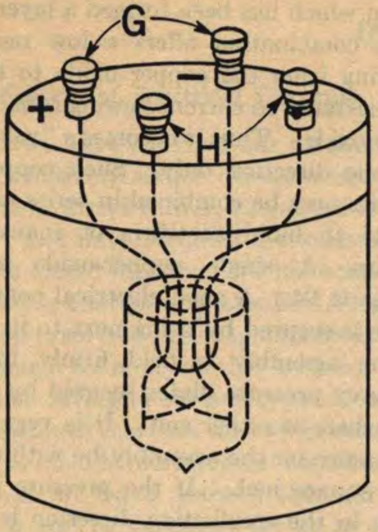


Fig. 93. Standard Thermo-couple

Like the thermocouple, the photo-electric cell is not important as a source of electrical energy. Its ability to convert the energy of light into electrical energy is extremely useful, however, in connection with telephotography, television, and various systems for controlling relays or other electro-magnetic devices by means of light.

The action of the photo-electric cell depends upon the property of certain metals, notably sodium, potassium, rubidium, and caesium, to emit electrons when irradiated with visible or ultra-violet light. Practical cells are constructed so that a beam of light may fall upon a very thin film of the pure metal which is contained in an evacuated glass or quartz bulb. The electrons which are emitted as a result of the light falling on the photoactive metal are drawn away to a positively charged plate also within the tube, thus establishing a small current of electricity between this plate and the irradiated metal film, which varies in strength with the intensity of the light. The very weak current generated by the cell may be amplified to any desired degree by means of vacuum tube amplifiers.

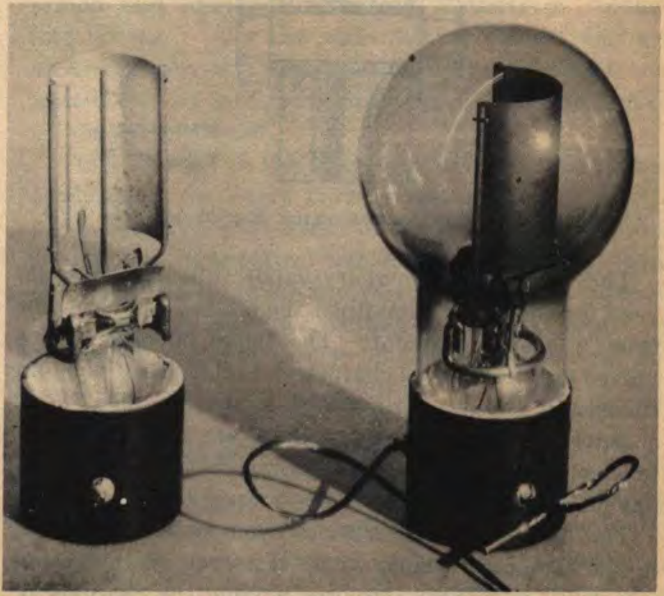
In telephone work, photo-electric cells are now used principally in connection with telephotography. Here they perform the essential function of producing an electric current which varies with the intensity of a beam of light reflected from the picture being transmitted. A much larger field of use for these cells is in sound motion picture projection where they translate the "sound-track" on the edge of the film into sound. They are also employed extensively for operating relays under light control in various industrial applications.

53. Rectifiers

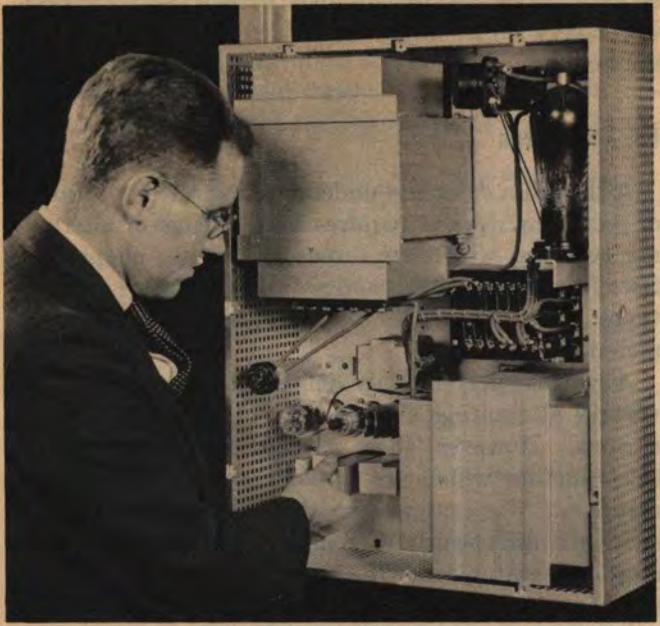
Although a complete understanding of the operation of rectifying devices requires a knowledge of alternating currents, which are discussed in later chapters, a few of the essential characteristics of the more common types of rectifiers may be mentioned here for completeness.

A rectifier is commonly defined as a device for converting alternating electric current to direct electric current. However, there are devices which perform this function which are not normally referred to as rectifiers. For example, an alternating-current motor driving a direct-current generator is referred to as a motor-generator set. If the motor and generator of such a set are combined in one housing with a single rotor, the machine is referred to as a rotary converter. In either case, however, electrical energy is first converted to mechanical energy and this in turn is converted to a different type of electrical energy. Similarly in the thermocouple described in the preceding section, A.C. electrical energy is converted to heat and this in turn generates D.C. energy. Accordingly, rectifiers may be somewhat more precisely defined as devices for converting A.C. energy to D.C. energy directly or without an intervening step.

All rectifying devices depend for their operation upon the characteristic of permitting electric current to flow through them freely in one direction only. They include a variety of vacuum and gas filled tubes such



Photoelectric Cell



Mercury-Vapor Tube Rectifier

as the older mercury arc tube, the newer mercury-vapor tube, and the Tungar tubes, as well as nearly all other types of vacuum tubes when properly connected. In addition, there is the copper-oxide type of rectifier.

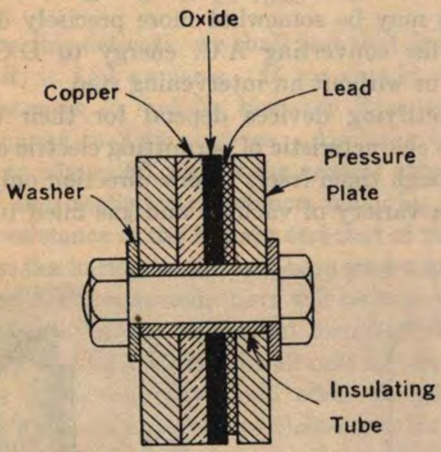
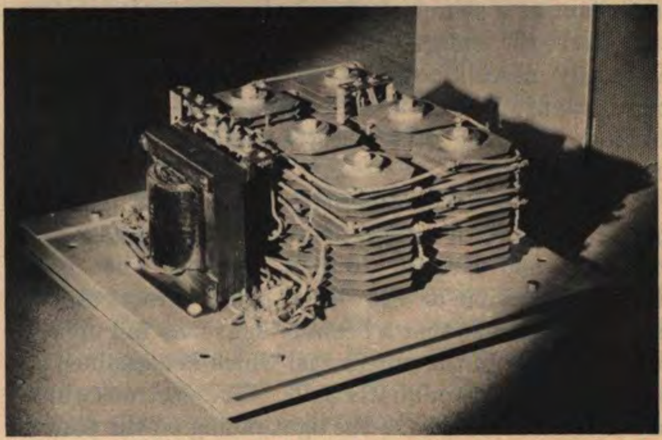


Fig. 94. Copper-oxide Rectifier

The Tungar and mercury-vapor tube rectifiers depend for their operation upon the emission of electrons from a heated filament. The basic phenomena involved are the same as characterize all types of vacuum tubes and these are discussed more fully in a later chapter. Both types of rectifiers are used quite extensively for charging small storage batteries and similar purposes.

The copper-oxide rectifier is even more widely used in the telephone plant, where it serves an increasing variety of purposes. Its uses include the charging of small storage batteries and emergency cells, the furnishing of a direct source of power for small repeater installations, etc. In addition, as we shall see in a later chapter, it has extensive applications in many carrier circuits.

The copper-oxide rectifier element consists of a copper disc upon which has been formed a layer of copper oxide. This combination offers a low resistance to current flowing from the copper oxide to the copper but a high resistance to current flowing from the copper to the copper oxide. Thus it becomes a "valve" to pass current in one direction only. Such copper copper-oxide elements may be combined in series and parallel arrangements to build rectifiers of many different characteristics. A single copper-oxide element is shown in Figure 94. A good electrical contact to the copper oxide is secured by using next to it a soft lead washer. The assembly is held firmly together by means of heavy pressure plates secured by a bolt and nut with washers at either end. It is very important that the pressure on the assembly be within 500–2000 pounds per square inch. If the pressure is low, the current flow in the conducting direction is not maximum and if the pressure is high, the resistance in the reverse direction breaks down, permanently injuring the element.



Copper-Oxide Rectifier

Copper-oxide rectifiers suffer a rapid decrease in the amount of current they will pass in the first three or four months of use. This deterioration is called aging. The decrease in initial output does not usually amount to more than 25%, however, and this is anticipated in initial design. Plating the lead washers with tin and graphiting the oxide surfaces reduces the aging somewhat. The amount of aging a rectifier undergoes is also a function of temperature. For this reason current drains in excess of the rated output should be avoided as excess current will raise the temperature, increase the aging and may destroy the rectifying action of the discs.

CHAPTER VIII

INDUCTANCE AND CAPACITY

54. Classification of Electrical Currents

Thus far we have confined our attention largely to circuits of relatively simple characteristics. We have had a source of direct E.M.F. connected to one or more resistances, and have assumed a resultant steady current in each closed branch. We have noted, however, the alternating character of the E.M.F. generated by a closed loop revolving in a magnetic field; but we have not attempted to analyze the behavior of such an E.M.F. when acting in various types of circuits.

It is desirable at this time that we broaden our studies somewhat to include more general conditions and while nothing that we have learned thus far will be invalidated, it will be necessary for us to study certain additional properties of electrical circuits and their effect on the current set up in them by impressed E.M.F.'s.

Broadly speaking all electrical currents may be classified into five groups as follows:

a. The current that results from a constant direct source of E.M.F. connected to a resistance network (i.e., the condition assumed in the earlier chapters for the calculation of direct-current networks through the application of Ohm's and Kirchoff's Laws).

b. The current immediately after opening or closing a circuit, varying its resistance, or in some way interrupting the steady direct current for a short period of time during which the current values readjust themselves before again becoming fixed or steady.

c. Current where the source of E.M.F. is an alternating one, having the simplest, most common and most convenient wave form, viz. the sine wave.

d. Current where the source of E.M.F. is an alternating one having a definite wave shape other than the sine wave.

e. Alternating current immediately after opening or closing the circuit, or immediately after effecting some other change in circuit conditions.

We can further classify the currents in the foregoing: *a*, *c*, and *d* are those relating to **steady state** currents, while *b* and *e* refer to temporary currents, sometimes called **transients.** In practice we are mostly interested in steady state currents in so far as the actual determination of current values is concerned, but under certain conditions the effects of transients are important. Certainly, in a telephone connection, we are concerned with any "clicks" or "scratches" that may be heard in a telephone receiver due to the opening or closing of circuits which are electrically connected to the telephone system. For example, when sending telegraph signals over a telegraph circuit superposed on a telephone circuit, there should be no appreciable "telegraph thump" in the telephone circuit. The successful operation of both telephone and telegraph circuits introduces certain important considerations having to do with changes in current values.

In fact, we deal with all five of the circuit conditions mentioned above in the telephone plant. Let us consider a long distance line wire not only composited for telegraph service but having a carrier current telegraph channel superposed as well. The resulting current in the wire can best be studied by scrutinizing the behavior of its separate components. When analyzed, the current due to the composited telegraph connection alone is an illustration of two of the classifications, namely *a* and *b*. At the instant of "make" or "break" of the key, conditions are as described by *b*. When the key is closed, i.e., when signals are not being sent, conditions are as described by *a*. For the carrier channel, we likewise have condition *c* for a part of the closed key period and condition *e* for the instants of "make" and "break". For the main talking circuit, we have an application of *d* when a vowel sound is being transmitted, and an application of *e* when a consonant sound is being transmitted.

Thus we find in the telephone plant no scarcity of applications for every current classification. It happens, however, that some of these are by no means simple and for practical telephone work we may limit our study to a thorough analysis of steady state currents only, and to concepts, rather than calculations, of transients in either direct- or alternating-current circuits.

55. Changes in Direct-Current Values

We may analyze classification *b* (changes in direct-current values) since this will lead us to certain of the new circuit properties that we wish to examine. In Figure 95, with the switch open we have a circuit with infinite resistance and zero current; with the switch closed we have, by Ohm's Law, a current—

$$I = \frac{E}{R} = \frac{10}{5} = 2 \text{ amperes.}$$

In spite of the apparent promptness with which electricity responds to the operation of any controlling device, we cannot conceive of the current changing from zero to two amperes without going through the range of every intermediate value between zero and two amperes; neither can we conceive of the current building up in the circuit in zero time to the value given by the application of Ohm's Law. If such were the case, the current would have every value from 0 to 2 amperes at the instant of closing the circuit. Reverting to our water analogy with the circulating mechanism in Figure 2, when a valve is shut we know there is no flow of water in a long pipe line and when the valve is opened we know that, due to the inertia of the water, a definite time is required for the flow to become a maximum. A current in an electrical circuit cannot be established instantaneously any more than the water flow can be established instantaneously.

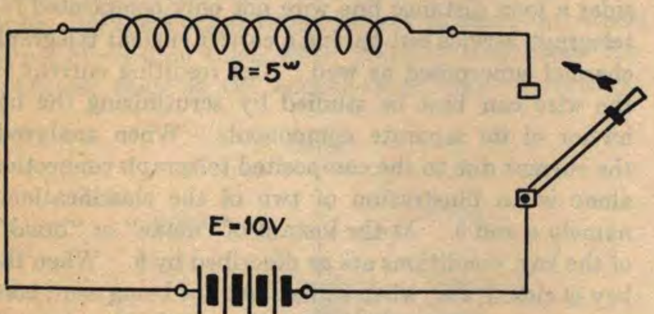


FIG. 95. SIMPLE INDUCTIVE CIRCUIT

Again, if in Figure 95 we suddenly open the switch in a dark room while there is a current of two amperes in the circuit, we shall observe a spark at the contacts of the switch. Though the electrical current is reducing in value, it continues to flow for an instant after the switch points are no longer in contact, forcing itself through the air, and thereby forming an "electrical arc" which gives the illumination.

We thus have two conditions where the current in a brief interval of time assumes all intermediate values between two amperes and zero, and we may compare these with other less abrupt changes in a circuit, such as those due to a varying transmitter resistance. It may be said that an electrical circuit "reacts" to such current changes. But this reaction cannot be explained by our previous understanding of either resistance or E.M.F. The circuit has other properties which are latent when the current is a steady unidirectional one but which are immediately brought into play when the current attempts to change its value. There are two such additional properties, namely, "**inductance**" and "**capacity**". **Inductance tends to give the circuit something that is analogous to inertia in a mechanical device, and capacity something analogous to elasticity.**

56. Inductance

When an E.M.F. is connected to a circuit, the conditions are somewhat analogous to those obtaining when a locomotive starts a train. The locomotive exerts considerable force which, in the circuit, corresponds to the impressed E.M.F. A part of this force is used in overcoming resisting forces such as the friction of the moving wheels, the grade of the track, and others that apply to the train as a definite resistance to its motion at all times. The second part of the force is used in setting the train in motion, i.e., accelerating the heavy inert body. As soon as the train is accelerated to full speed, the entire force applied is available for overcoming the resistance alone. Likewise in the electrical circuit, for any given E.M.F., the current does not instantaneously establish itself to that value which represents the effect of the full voltage overcoming the resistance.

We have learned that there is a magnetic field about every current-carrying conductor, and when a conductor is wound into a coil or is in the presence of iron, the magnetic field is intensified. The magnetic field cannot be established instantaneously any more than the train can be instantly changed from its state of rest to that of full speed. What actually happens in the case of the electrical circuit is that the E.M.F. endeavors to start a current; the current in turn must establish a magnetic field; this field reacts upon the circuit in a manner similar to that in which the counter-E.M.F. generated by a motor opposes the applied voltage, and for an instant a part of the E.M.F. that is connected to the circuit must be used in overcoming these reactions. The current, therefore, increases gradually and as it does so, the magnetic field becomes more nearly established and the reaction becomes less pronounced, until finally the entire E.M.F. is applied to overcoming the resistance of the circuit alone, thereby sustaining the established current at a value determined by Ohm's Law.

This may be more clearly understood by referring to the circuit shown in Figure 96 and following the change in current that is taking place immediately after the switch has been closed. When the switch S is closed, the E.M.F. E endeavors to establish a current in the circuit equal in value to E/R, or two amperes. But the current, as has been stated, must go through every intermediate value from zero to two amperes. By directing our attention to only one turn of the coil, for example, T_1, we can imagine the current building up and in consequence establishing lines of magnetic induction around this single turn which will, however, cut every other turn of the coil. This action will set up in the other turns an induced E.M.F. tending to establish a current in the opposite direction in much the same way as we learned a back E.M.F. was set up in the electric motor. And as in the case of the motor, the two currents are in one and the same circuit and the induced current is opposed to the current established by virtue of the battery E.M.F.

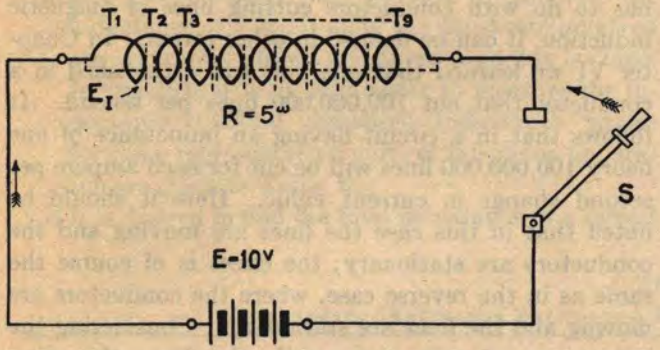


FIGURE 96

Figure 97 represents graphically the current in this circuit. With the switch open, the current is zero. When it is closed (or when sufficiently near the contacts for the E.M.F. to break down the insulation of the narrow separation of air, since the current starts to flow before actual contact is made), the 10-volt battery will attempt to establish a current of two amperes in accordance with Ohm's Law. But the current cannot be completely established until after an interval of time represented by t_2; and at the start, it cannot be increasing at a rate greater than that which would induce a back E.M.F. of 10 volts, because if it did so, the induced E.M.F. would be equal to the applied E.M.F. and since they oppose each other, there would be no current whatsoever. As would be expected, however, the maximum rate of increase of the current occurs at the instant the switch is closed.

Now let us consider the conditions at some intermediate time between the closing of the switch and t_2. If, from the value represented by point P, the current increased at a rate that continued without changing, the line PM would represent the trend of current values that would follow. But with the current increasing at this rate, the lines of magnetic induction are cutting other turns of wire and inducing an E.M.F. which we might represent in Figure 96 as a second battery E_1, and which must be of the value necessary to establish a current equal to two amperes minus the current which has been already established at the point P. This follows from the earlier explanation regarding the directional property of an induced E.M.F. If the battery voltage E acted alone, the current value would be E/R or two amperes. Since the actual current flowing is less than two amperes, the difference between the actual current and two amperes may be regarded as due to a current flowing in a direction opposite to that of the two amperes set up by the battery. This current is established by the induced E.M.F. and we may designate it as an **induced current** to distinguish it from the two-ampere current which the supply voltage tends to set up. The actual current in the circuit at any instant, then, is the numerical difference between the two-ampere battery current and the induced current.

If we now assume for the sake of reasoning that the induced voltage E_1 remains unchanged, the resulting induced current will oppose the battery current, and the net amount of current flow will remain at the value P. We know, however, that the current which will eventually flow is two amperes, and furthermore, if the current becomes constant at a value P, no lines of magnetic induction are in motion; hence, there is no induced voltage and consequently no induced current. But with no induced current, the battery will set up two amperes; therefore our assumption that the induced voltage E_1 remains constant, keeping the current down to a value such as that represented by the line PN is false. On the other hand, it is clear that the induced voltage E_1 cannot become zero until the current becomes two amperes, though it does continue to decrease in value, since we know that a current is always accompanied by a magnetic field which must change if the current changes, and the result of such a change is an induced voltage. From this we conclude that there must be a compromise trend for the curve of current as it establishes itself, somewhere between the two extremes. This compromise is that shown by the curve PQ which is tangent to but bending away from PM. The current is neither maintaining the same rate of change as it approaches the value fixed by Ohm's Law nor does it cease entirely its increase in value before

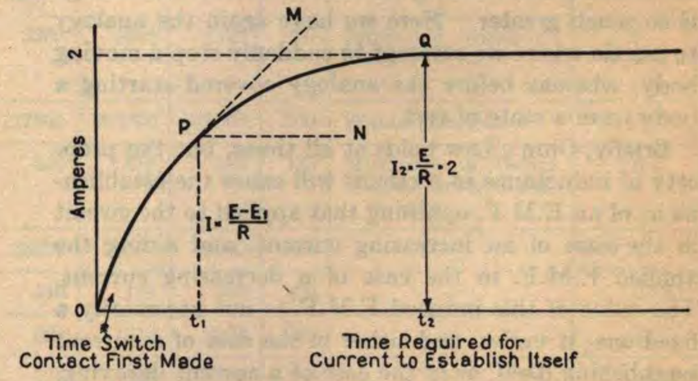


FIG. 97. BUILD-UP OF CURRENT IN INDUCTIVE CIRCUIT

it reaches two amperes. This is true because although the induced E.M.F. that would stop the change in current is gradually becoming less in value, the IR drop is becoming greater, and the sum of these two must always equal the impressed voltage in accordance with Kirchoff's second law. Thus we see from the curve in Figure 97 the "choking" effect of an inductively wound coil to increases in current value.

The case of a decreasing current value, and the E.M.F. induced at the time of opening a circuit, is of course another application of the same theory, but the effects are different in their practical aspects. Because this E.M.F. is induced as a result of a decreasing current instead of an increasing one, it aids rather than opposes the existing E.M.F. Moreover, the current change is a very rapid one because the opening of the switch tends to change the resistance of the circuit from a definite value to infinity with great suddenness. As a result, the induced E.M.F. may become much greater than the applied E.M.F. besides being additive to it, whereas in the closed circuit it can never be greater than the applied E.M.F. This total E.M.F. of the opening circuit tends to force an arc across the switch contacts, which is much more evident than the arc at the time of closing the switch because the voltage is so much greater. Here we have again the analogy to inertia where we attempt to suddenly stop a moving body, whereas before the analogy covered starting a body from a state of rest.

Briefly, Ohm's Law holds at all times, but the property of inductance in a circuit will cause the establishment of an E.M.F. opposing that applied to the circuit in the case of an increasing current, and aiding the applied E.M.F. in the case of a decreasing current. The value of this induced E.M.F. is not necessarily a fixed one; it varies, and either in the case of a current establishing itself, or in the case of a current decaying, eventually becomes zero. The magnitude or influence of the induced E.M.F. as a reactive effect is determined by two factors:

a. The first is a property of the circuit having to do with the number of inductive turns, whether or not each coil has a magnetic core and if magnetic, the permeability of the iron, etc.

b. The second is the rate of change of current. This employs the property of the circuit as a tool or facility for creating the induced E.M.F.

The **property of the circuit** which we have called **inductance** is represented by the symbol L and is measured in a unit called the **henry.** The rate of change in current, though a varying quantity, would naturally be measured in amperes per second or I/t. (In this case I/t represents the rate of change of current which if maintained constant, would permit the current to rise from a value 0 to a value I in a time interval t.)

The unit value of the henry is defined as the inductance of a circuit that will cause an induced E.M.F. of one volt to be set up in the circuit when the current is changing at the rate of one ampere per second. From this we may write—

$$E_1 = \frac{LI}{t} \tag{29}$$

where E_1 is the chosen symbol for induced E.M.F. and L represents inductance in henrys.

Since L depends upon a property of the circuit which has to do with conductors cutting lines of magnetic induction, it can be defined in other terms. In Chapter VI we learned that one volt was established in a conductor that cut 100,000,000 lines per second. It follows that in a circuit having an inductance of one henry 100,000,000 lines will be cut for each ampere per second change in current value. Here it should be noted that in this case the lines are moving and the conductors are stationary; the effect is of course the same as in the reverse case, where the conductors are moving and the lines are stationary. Considering the inductance of any given coil, the lines threading through the coil, as they build up or decrease, will cut each turn, or we may write—

$$E_1 = \frac{\phi N}{100{,}000{,}000 \times t} \tag{30}$$

where ϕ is the flux through the coil, N is the number of turns and t is the number of seconds required for the flux to cut the turns. But, from Equation (29), $E_1 = \frac{LI}{t}$; therefore, $\frac{LI}{t}$ can be substituted for E_1 in Equation (30) and we have—

$$\frac{LI}{t} = \frac{\phi N}{100{,}000{,}000 \times t} \tag{31}$$

or, with the t cancelled on both sides of the equation—

$$LI = \frac{\phi N}{100{,}000{,}000} \tag{32}$$

But in Equation (14) we learned that $\phi = M/R$ where M is magnetomotive force and R is reluctance. Also, in Equation (16) we found that for a solenoid, $M = 1.26NI$. Therefore—

$$\phi = \frac{M}{R} = \frac{1.26NI}{R} \tag{33}$$

which may be substituted in Equation (32) giving—

$$LI = \frac{1.26NI}{R} \times \frac{N}{100{,}000{,}000}$$

$$L = \frac{1.26N^2}{R \times 100{,}000{,}000} \tag{34}$$

The reluctance for any entire coil is determined by the dimensions of the coil and the permeability of the iron core. We may substitute in Equation (34) an expression for reluctance that may be derived from Equations (14), (16) and (17); namely, $R = \frac{l}{\mu A}$ where μ is the permeability, l is the length of the core in centimeters and A is the area of the core in square centimeters. Thus, we have finally—

$$L = \frac{1.26N^2\mu A}{100{,}000{,}000 \times l}\ . \qquad (35)$$

Note: This equation may be used to calculate the inductance of a coil if all of the constants involved are accurately known and there is no flux leakage. In practice, it is usually easier to measure the inductance. Actual measured inductance values for some representative units of telephone apparatus are given in Table V.

If it is desired **to find the total inductance of a circuit having several coils in series, the inductances should be added in the same way that resistances in series are added. Similarly, parallel inductances are calculated by the same formulas as are parallel resistances.** For example, see Equation (4) and substitute L, L_1, and L_2 for R, R_1 and R_2, respectively, etc.

This property of a circuit which creates an E.M.F. from a change of current values when the reaction effects are wholly within the circuit itself is called self-inductance to distinguish it from the relation permitting electromagnetic induction between coils or conductors of separate circuits. This latter property of the two circuits taken jointly is called mutual inductance. It is discussed in a later chapter.

57. Capacity

There remains that property of the circuit that we have called "capacity", which gives it something

TABLE V

Approximate Inductance Values for Windings of Various Electrical Apparatus

APPARATUS		NO. WINDINGS	DC RESISTANCE	IMPEDANCE					INDUCTANCE (HENRYS) (SEE NOTE 2)
Name	Code No.			AC Resistance (See Note 1)	Reactance (See Note 1)	Impedance	Freq.	Connections	
Relays, AC Type	172-B	2	Inductive 540 Non-inductive 2000 Comb. 406	3260	5650	6520	900	Inductive winding only	1.0
Relays, AC Type	196-A	2	1600; 1600	117500	203000	235000	900	Windings in Series	36.0
Relays, AC Type	218-B	2	117; 117	450	678	810	135	Windings in Series Armature held stationary	.8
Relays, AC Type	J-1	1	1090	38000	39400	55000	900	—	7.0
Receivers	144	—	83	140	164	250	800	—	.0325
Receivers	525	—	276	620	1910	2000	800	—	.38
Receivers	528	—	56	106	237	260	800	—	.0475
Receivers	557-B	—	30	46	110	120	800	—	.022
Retardation Coils	5-U	2	(1-2) 500	—	—	—	16	Single Winding	3.0 to 4.0
			(2-3) 500				16	Series Aiding	12.0 to 15.0
Retardation Coils	5-AA 77-A	2	74 ea.	—	270	—	16	Two windings as connected for 1 wire	2.7
Retardation Coils	12-A	1	165	—	5024	—	800	—	1.0
Retardation Coils	44-D	2	83 ea.	2480	39565	39580	900	Windings in Series	7.0
Retardation Coils	47-B	1	150	160	1700	1710	900	—	.3
Retardation Coils	57-B	2	175 ea.	1620	22610	22700	900	Windings in Parallel	4.0
Retardation Coils	82-H	1 (tapped)	(1-8) 25.2	47	1640	1640	1800	Entire winding	.145
Retardation Coils	182-B	1 (tapped)	(1-8) (30.0)	56	1640	1640	1800	Entire winding	.145

Note: (1) Impedance and impedance components are discussed in Chapter XVI. A.C. Resistance or the resistance component of impedance is often widely different from the resistance to direct-current flow.

(2) Inductance values vary greatly depending upon conditions under which apparatus is operated, age of iron, degree of saturation, etc. This table gives only representative and approximate values.

analogous to elasticity. While a storage battery stores electricity as another form of energy, in a smaller way a **condenser** stores electricity in its natural state.

As a container, a condenser is hardly analogous to a vessel that may be filled with water, but more nearly to a closed tank filled with compressed air. The quantity of air, since air is elastic, depends upon the pressure as well as the size or capacity of the tank. If a condenser is connected to a direct source of E.M.F. through a switch as shown by Figure 98, and the switch is suddenly closed, there will be a rush of current in the circuit. This will charge the condenser to a potential equal to that of the battery, but the current will decrease rapidly and become zero when the condenser is fully charged.

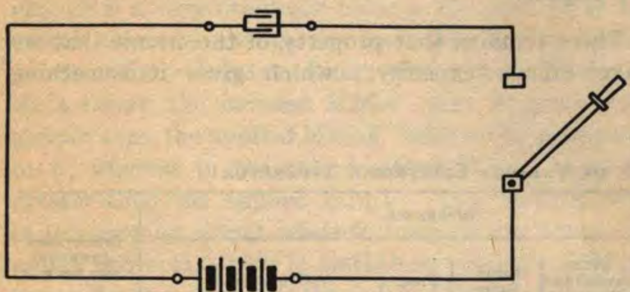


FIG. 98. SIMPLE CAPACITIVE CIRCUIT

The insulated conductors of every circuit have to a greater or less degree this property of capacity. A certain quantity of electricity, representing a certain quantity of energy, is accordingly delivered to a circuit before the actual transfer or transmission of energy from a sending device to a receiving device takes place. The capacity of two parallel open wires, or a pair of cable conductors of any considerable length, is appreciable in practice.

The quantity of electricity stored by a condenser depends upon the condenser's capacity and the electromotive force impressed across its terminals. The following equation expresses the exact relation:

$$Q = EC \qquad (36)$$

where Q is the quantity of electricity in coulombs, E is the impressed E.M.F. in volts, and C is the capacity of the condenser in **farads.** The farad is a very large unit and is seldom used in practice. The microfarad (from "micro", meaning one one-millionth) is the practical unit more commonly used; and with C expressed in these units, Equation (36) becomes—

$$Q = \frac{EC}{1{,}000{,}000} \qquad (37)$$

Figure 99 illustrates a condenser in its simplest form together with one convention used for a condenser connected to a battery. Two wires are connected to two parallel metal plates having a definite separation as shown. This is called an "air condenser" because air is the "dielectric" medium between the plates. The capacity of such a condenser is directly proportional to the area of the plates, and inversely proportional to their separation. At the instant a battery is connected to its terminals, there is a rush of electricity which charges the plates to the potential of the battery, but as the plates become fully charged, the current in the connecting conductors becomes zero. Were we to insert a sensitive high resistance galvanometer in series with the battery, we would observe an instantaneous "kick" of the needle when the connection is made, but the needle would return and come to rest at zero. If the capacity of the condenser were increased, the kick would become more noticeable. If now the battery were disconnected and the condenser short-circuited through the galvanometer, there would be a kick of the needle in the opposite direction. This would result from the quantity of electricity, which had been stored in the condenser, establishing an instantaneous current in the opposite direction and discharging the condenser through the winding of the galvanometer.

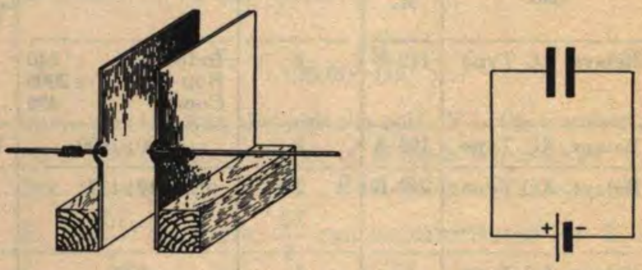


FIG. 99. ELEMENTARY CONDENSER AND CONVENTION

In addition to the size of its plates and their separation, the capacity of a condenser depends upon the insulating medium between the plates. For example, if mica is inserted between the plates of an air condenser its capacity is increased about five times. The insulators, in addition to being classified in the order of their insulating properties as given in Table III, may be classified in the order of their "dielectric powers", or "specific inductive capacities", i.e., their ability to increase the capacity of a condenser over that of an air condenser. Such a classification is given in brief in Table VI.

The equation for the capacity value of a two-plate condenser is—

$$C = K\frac{A}{d} \qquad (38)$$

where C is capacity in microfarads, K is the constant taken from Table VI, A is inside area of one plate in square centimeters, and d is separation of plates in centimeters. There are similar equations for calculating the capacity per unit length of parallel open wire conductors or cable conductors. These may be found in various electrical handbooks, but for telephone and telegraph work, tables giving measured values, which vary for each class of open wire or cable pairs, are preferable and are usually available.

TABLE VI

DIELECTRIC POWER OF VARIOUS INSULATING MATERIALS

Values are only approximate and are given for value of K in Equation (38) rather than compared to air as unity.

SUBSTANCE	K IN EQUATION (38)
Glass—Very dense flint	$.9 \div 10^6$ approx.
Mica	$(.3 \text{ to } .7) \div 10^6$ approx.
Glass, ordinary	$.3 \div 10^6$ approx.
Shellac	$.3 \div 10^6$ approx.
Gutta-Percha	$(.2 \text{ to } .4) \div 10^6$ approx.
India Rubber	$.2 \div 10^6$ approx.
Paraffin paper	$(.2 \text{ to } .3) \div 10^6$ approx.
Air (at atmospheric pressure)	$.0885 \div 10^6$ standard

An inspection of Equation (38) will show that if two identical condensers are connected in parallel as shown by Figure 100, the effect is that of doubling the plate area of a single condenser, and therefore doubling the capacity. On the other hand, if two identical condensers are connected in series as shown by Figure 101, the middle or common plates have a neutral potential and the effect is that of doubling the thickness of the dielectric of a single condenser, which cuts the capacity in half. It follows that capacities in parallel and series act inversely to resistances or inductances in parallel and series. This may be stated in a single rule covering all conditions—

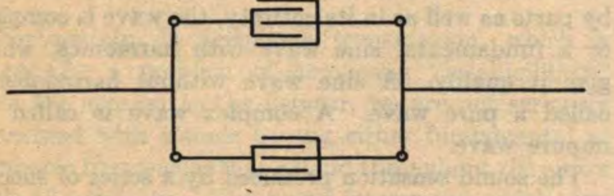


FIGURE 100

Capacities in parallel should be added to find the total capacity in the same way that resistances in series should be added to find the total resistance; and the reciprocal of the sum of the reciprocals must be taken to find the total capacity of capacities in series in the same way that the reciprocal of the sum of the reciprocals must be taken to find the total resistance of resistances in parallel.

This rule may be expressed by two simple equations: For several parallel capacities—

$$C = C_1 + C_2 + C_3 \text{ etc.} \qquad (39)$$

For several series capacities—

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \text{ etc.} \qquad (40)$$

Or for only **two** series capacities, a third equation may be written as follows:

$$C = \frac{C_1 \times C_2}{C_1 + C_2}. \qquad (41)$$

Note: Equation (39) may be compared with Equation (4) and Equation (41) may be compared with Equation (8).

FIGURE 101

58. Effects of Inductance and Capacity in Direct-Current Circuits

The circuit reactions coming from the presence of inductance and capacity offer their most common applications in alternating-current circuits where we deal with their effects singly or jointly as "reactance", a quantity measured in ohms just as resistance is measured in ohms. Direct-current applications in telephone and telegraph work are nevertheless common. Figure 102 shows one way to apply the property of capacity to neutralize the detrimental effects of the self-inductance that is always present where there is a relay winding. Here the key contacts are bridged with a condenser which prevents excessive arcing when the circuit is opened because the sustained current is charging the condenser instead of forcing an arc. In practice the condenser usually has a non-inductive resistance in series, its purpose being to avoid oscillatory effects which are discussed in a later chapter.

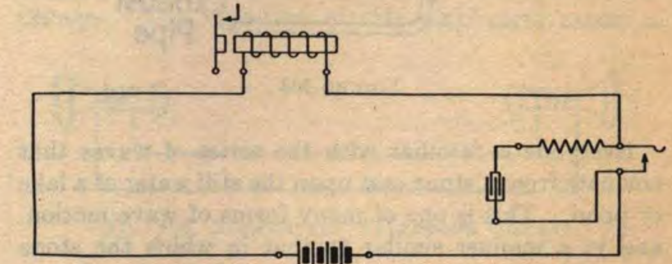


FIG. 102. CONDENSER AS SPARK-KILLER

CHAPTER IX

PRINCIPLE OF THE TELEPHONE

59. Sound

The telephone accomplishes the electrical transmission of speech by employing the mechanical energy of the speaker's voice to produce electrical energy having similar characteristics, and in turn converting this electrical energy into sound waves having similar characteristics at the listener's station. To understand its principle of operation we may well consider the nature of "sound".

Sound in the scientific sense has two distinct meanings. To the psychologist it means a sensation, to the physicist it means an atmospheric disturbance or a stimulus whereby a sensation is produced in the human ear. In other words, it is a form of wave motion produced by some vibrating body such as a bell, tuning fork, the human vocal cords, or similar objects capable of producing rapid to-and-fro or vibratory motion.

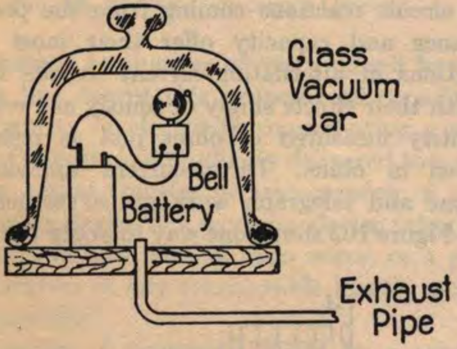


FIGURE 103

Everyone is familiar with the series of waves that emanate from a stone cast upon the still water of a lake or pond. This is one of many forms of wave motion, and in a manner similar to that in which the stone coming in contact with the water establishes radiating rings formed by circular wave crests alternating with wave troughs, there emanates from a source of sound alternate condensations and rarefactions of the air. Instead of being rings on a single plane or surface, however, they are a series of concentric spheres expanding at a definite rate of travel. This rate of travel (or the velocity of the sound wave) is approximately 1,075 feet per second but varies to some extent with altitude and atmospheric conditions. The velocity of sound is very low as compared with the velocity of light, heat or wireless waves, which are also a form of wave motion. We thus see a flash of lightning before we hear a clap of thunder or see the smoke dispelled from the muzzle of a gun before we hear the gun's report.

Unlike light, heat or electrical wave transmission, sound is an atmospheric disturbance. If as shown in Figure 103, a vibrating bell is placed under an inverted glass bowl resting on a brass plate that has an outlet through its center to which an exhaust pump is connected, it may be heard almost as distinctly as though there were no glass container. But if the air is exhausted until there is a vacuum about the bell, no sound can be heard; yet the bell may be seen vibrating as clearly as before the glass container was exhausted. We thus learn that there must be an atmospheric medium for the transmission of sound.

If the sound's source is a vibrating mechanism in simple form, such as a simple to-and-fro motion of the prong of a tuning fork, and is sustained without decay for a definite interval of time, the wave motion is said to be "simple harmonic". (A simple harmonic wave may be represented by the sine curve already discussed in Article 43.) On the other hand, if the source consists of a complex mechanical motion or an object vibrating by parts as well as in its entirety, the wave is **complex,** or a fundamental sine wave with **harmonics,** which give it **quality.** A sine wave without harmonics is called a pure wave. A complex wave is called an impure wave.

The sound sensation produced by a series of successive waves identical in form is called a **tone,** and if each wave is complex, it is a tone having **timbre or quality,** but if simple or a sine wave, it is a **pure tone.**

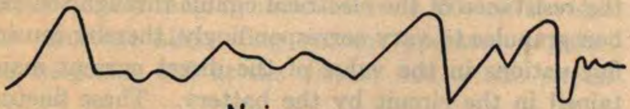
A vibrating mechanism giving a pure tone is said to establish a tone of low pitch if it is vibrating slowly, but if vibrating rapidly, it establishes a tone of high pitch. The lowest pitch which is audible to the average ear lies somewhere in the octave between 16 and 32 vibrations per second. The ear does not respond to a slower vibration. On the other hand, the average ear has an upper limit of audibility lying somewhere in the octave between 16,000 and 32,000 vibrations per second. These two octaves are the extreme limits of the scale of audibility.

Audible sound is thus defined as a disturbance in the atmosphere whereby a form of wave motion is propagated from some source at a velocity of 1,075 feet per second, the transmission being accomplished by alter-

nate condensations and rarefactions of the atmosphere in cycles having a fundamental frequency ranging somewhere between 16 per second and 32,000 per second.

The superposed waves on the fundamental, which we have called harmonics, are present in most distinctive sounds, and particularly in the human voice. They permit us to distinguish notes of different musical instruments when sounded at the same pitch. They also establish subtle differences in the voice which may indicate anger or joy, or permit us to distinguish the voice of one person from that of another. Figure 104 illustrates wave forms for different kinds of sound and, similarly, Figure 105 shows the predominating wave shapes of certain spoken vowels.

Musical Note



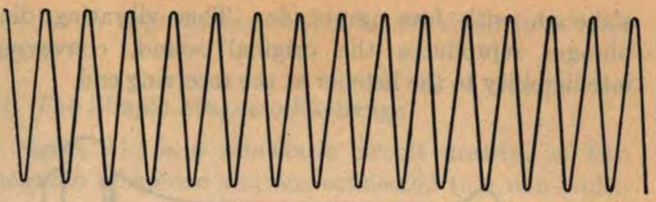
Noise.

FIGURE 104

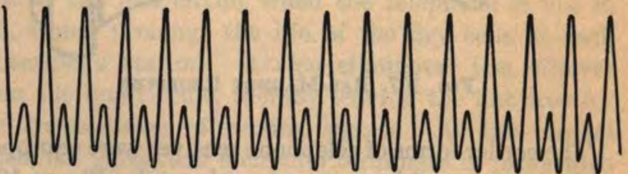
Fortunately, in telephone transmission, which is essentially a problem of conveying "intelligibility" from the speaker to the listener, we are not seriously concerned with sounds having either fundamental or harmonic frequencies that extend throughout the entire scale of audibility. The sound frequencies which play an important part in rendering the spoken words of ordinary conversation intelligible are the band of frequencies within the audible scale ranging from approximately 200 to 2,500 cycles per second. Within this band the frequencies between 700 and 1,100 cycles per second are perhaps of greatest importance.

60. The Simple Telephone Circuit

The original telephone, as invented by Bell in 1876, consisted of a ruggedly constructed telephone receiver. It was used both as a transmitter and a receiver at that time. The telephone circuit in its simplest form consisted of two wires terminated at each end by such an instrument but without transmitter or battery and without signaling features. Figure 106 shows such a circuit.



Simple Sound.



ōō as in Loose.

ō as in Low.

FIGURE 105

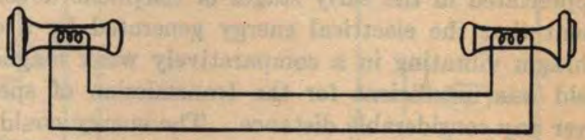


FIG. 106. ELEMENTARY TELEPHONE CIRCUIT

At the speaker's station, the sound waves of the voice strike the metal diaphragm of the telephone receiver, and the alternate condensations and rarefactions of the air on the side of the diaphragm establish in it a sympathetic vibration. Behind the diaphragm is a permanent bar magnet and the lines of induction leaving the magnet are crowded in the vicinity of the metal diaphragm. The vibration of this diaphragm causes a corresponding change in the number of lines that thread through the receiver winding, resulting in the turns of the winding being cut by the building up and decaying lines. This establishes a varying electrical current in the winding of the telephone receiver, having wave characteristics similar to the characteristics of the sound wave. This current, in passing through the receiver winding at the distant end, alternately strengthens and weakens the magnetic field of the permanent magnet, thereby lessening and increasing the pull upon the receiving diaphragm, which causes it to vibrate in unison with the diaphragm at the transmitting end, although with less amplitude. This vibrating diaphragm reproduces the original sound, conveying intelligibility to the listener at the receiving end.

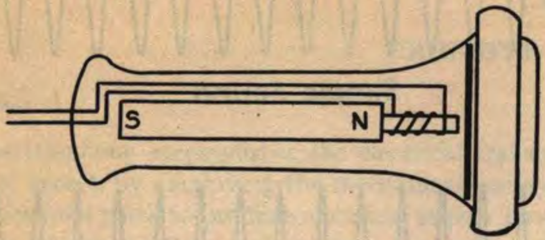


Fig. 107. Bar-Magnet Receiver

The earlier forms of telephone receiver were equipped with a permanent bar magnet as shown by Figure 107. The instrument's efficiency was greatly increased by the use of a horseshoe magnet, as illustrated by Figure 108, which permits the lines of induction to pass from one magnetic pole to the other through the iron diaphragm. This, with additional refinements which have been developed from time to time, constitutes the present telephone receiver.

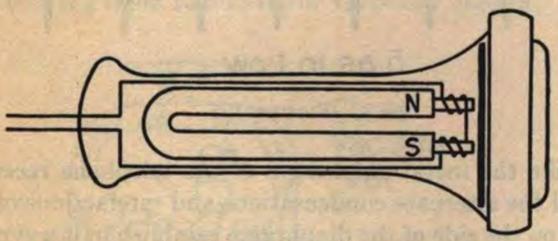


Fig. 108. Horseshoe-Magnet Receiver

Although the principle of Bell's original telephone applies to the present day telephone receiver, it was appreciated in the early stages of telephone development that the electrical energy generated by a diaphragm vibrating in a comparatively weak magnetic field was insufficient for the transmission of speech over any considerable distance. The energy could, of course, be increased by using stronger magnets, louder sounds, and the best possible diaphragms, but even with any ideal telephone receiver that might be perfected, voice transmission would be limited to comparatively short distances. One year after the invention of the original telephone, the Blake transmitter was introduced. It worked on the principle of a diaphragm varying the strength of an already established electrical current, instead of generating electrical energy by means of electromagnetic induction. By this means it was possible to establish an electrical current with an energy value much greater than that conveyed to the instrument by a feeble sound wave. The battery in this case was the chief source of energy and the vibration of the diaphragm acted as a means for regulating this energy supply rather than as a generating device.

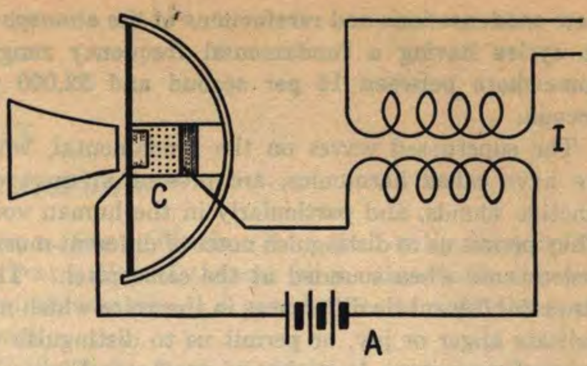


Fig. 109. Principle of the Telephone Transmitter

The principle of the transmitter may be better understood by referring to Figure 109. Battery *A* establishes a direct current in a local circuit consisting of the primary winding of an induction coil *I*, and a cup of carbon granules *C*. One side of this cup rests against a small carbon disk rigidly connected to the transmitter diaphragm. The vibrating transmitter diaphragm varies the pressure on the carbon granules, which causes the resistance of the electrical circuit through the carbon granules to vary correspondingly, thereby causing fluctuations in the value of the direct current maintained in the circuit by the battery. These fluctuations, though represented by varying direct-current values instead of by an alternating current, as in the case of the telephone circuit in Figure 106, establish an alternating E.M.F. in the secondary winding of the induction coil. This, in turn, sets up an alternating current through the local receiver, over the line, and through the distant receiver. The operation of the distant receiver is no different than that explained in connection with Figure 106.

Figure 110 shows transmitters used at the ends of a simple telephone circuit. When the magnetic field is established by the fluctuating current through the primary of the induction coil, an alternating current is induced in the secondary of the coil. This current flows through the receiver at the same end of the cir-

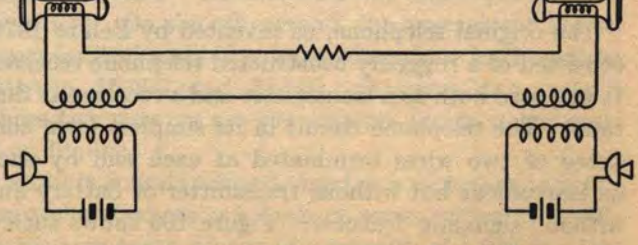


Fig. 110. Telephone Circuit with Local Battery Transmitters

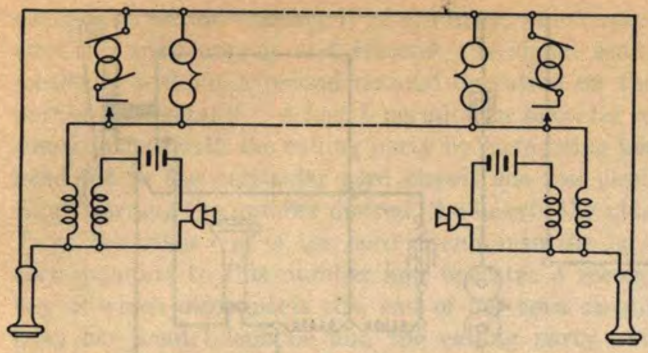


Fig. 111. Telephone Circuit with Signaling Equipment

cuit, giving "side-tone" to the receiver at the home station. It is also transmitted to the distant station, operating the receiver at that point.

A simple two-party magneto telephone circuit without central office connections and with the hook switch omitted for clearness, is shown in Figure 111. Signaling is accomplished by means of a magneto hand generator, which when turned at normal speed is automatically connected in the circuit by a spring mechanism associated with the crank and generates an alternating voltage of approximately 20-cycle frequency and ranging in value from 50 to 75 volts. The resultant alternating current operates a polarized telephone bell at the distant end of the circuit similar in type to one which is described in a later article.

61. The Simple Magneto Exchange

Figure 112 is a schematic circuit drawing of two magneto telephone stations connected to a non-multiple magneto switchboard. In this figure, the hook switch has been added to the subscriber's station circuit. This permits opening the transmitter circuit as well as the line circuit when the telephone is not in use, which prolongs the life of the dry cells at each subscriber's station. It also eliminates the receiver from the line circuit, thereby leaving the line free for the transmission of ringing signals. At the central office, the subscriber's circuits terminate in jacks with bridging "drops". There are several types of these drops but the one shown in the figure will illustrate the operation of a simple self-restoring type. Referring to the drop designated as D_1, the ringing current of the calling party's generator sets up a pulsating magnetization in magnet M. This attracts the armature A_1 and trips the armature A_2 which in dropping forward lifts the shutter S, displaying before the operator a number on the armature A_2.

The operator answers this incoming call by inserting the plug P_1 of her cord circuit into the jack J_1. This disconnects the bridged drop winding M, preventing it from affecting the talking current transmission, and

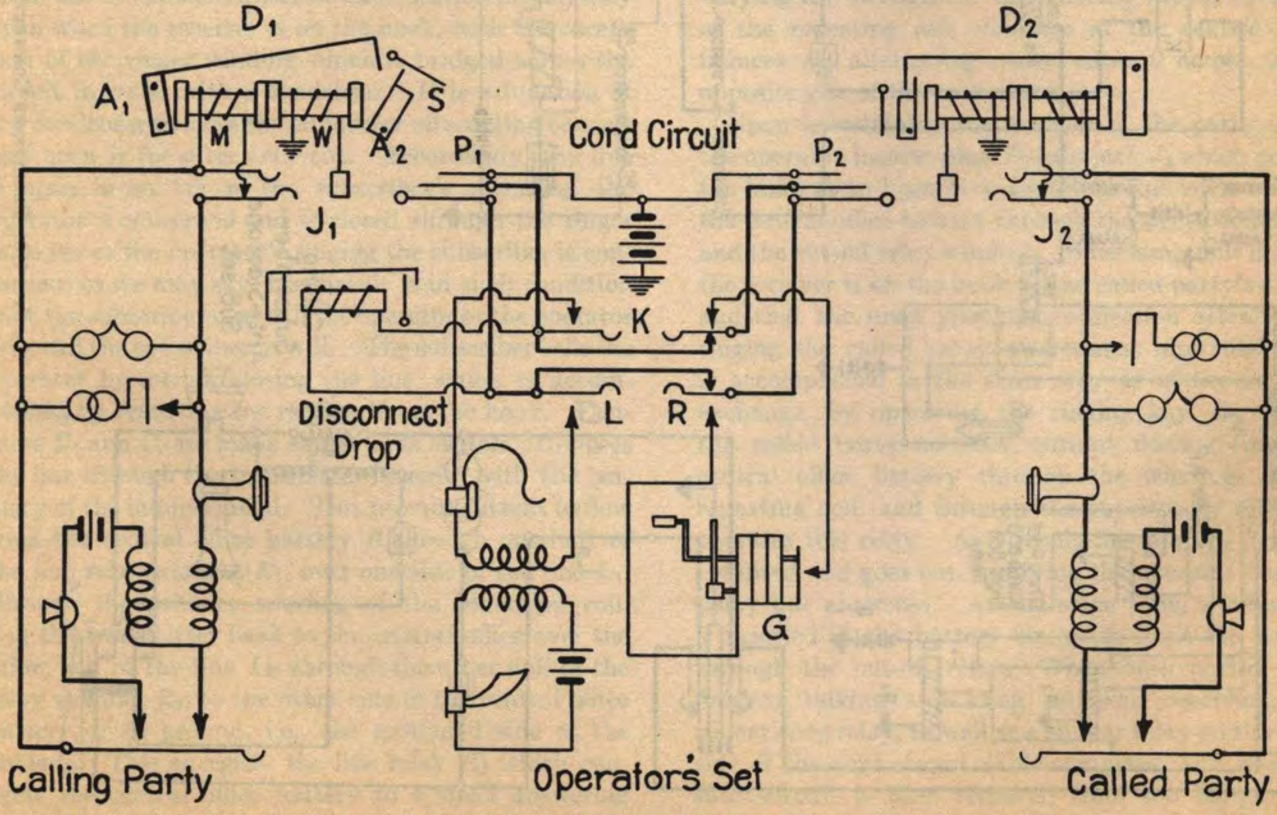


Fig. 112. Telephone Connection Through Magneto Exchange

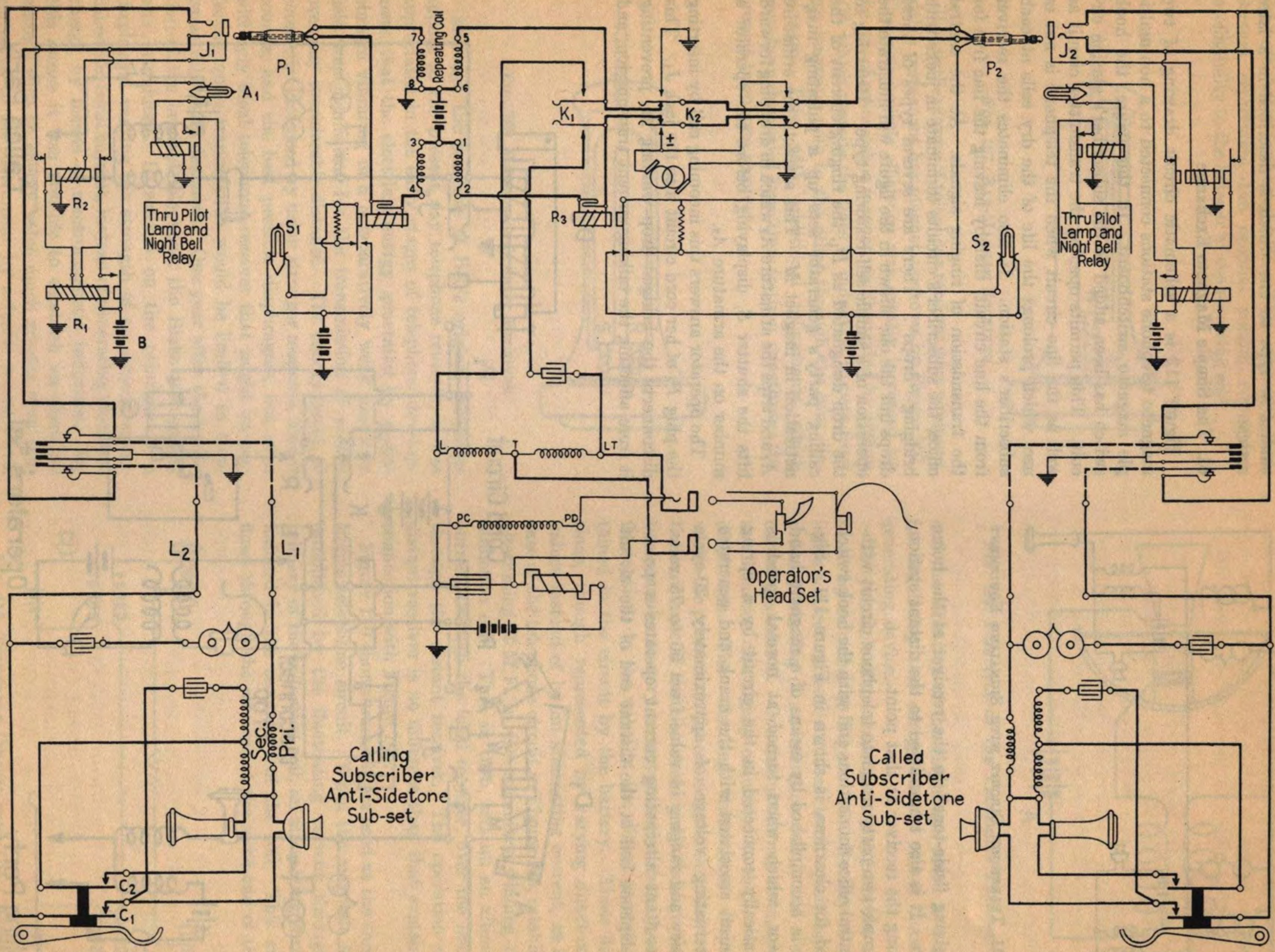


FIG. 113. TELEPHONE CONNECTION THROUGH COMMON BATTERY EXCHANGE

energizes a second winding W of the drop, which operates the armature A_2 and restores the signal automatically without a second manual operation on the part of the operator. A key L permits the operator to communicate with the calling party by connecting her head set to the particular cord circuit she has used. After learning the number desired, she inserts the plug P_2 of the other end of the cord circuit into the jack corresponding to this number and operates a second key R which disconnects this end of her cord circuit from her head telephone and the calling party and connects it to the generator G. She is now able to ring the called party by turning the generator crank. In the larger magneto offices, which are equipped with ringing machines, the operation of key R connects the cord circuit with ringing leads that are energized at all times and the necessity of turning a ringing generator associated with the switchboard position is eliminated.

62. The Common Battery Telephone Exchange

In Chapter VII we learned that it is possible for a number of circuits to be energized from a single battery, and that if the battery has a very low internal resistance, the operation of any one of these circuits does not interfere with the operation of any other. Figure 113 shows a telephone connection between two common battery stations terminating at the same central office. Here the telephone circuit at each station is normally open when the receiver is on the hook, with the exception of the ringer winding which is bridged across the circuit in series with a condenser. It is a function of the condenser to close the circuit for alternating current and open it for direct current. Accordingly, the line is open in so far as the subscriber's signaling the operator is concerned and is closed through the ringer in so far as the operator's ringing the subscriber is concerned; or we may say, the circuit is in such condition that the subscriber may call the operator or the operator may call the subscriber at will. The subscriber calls the operator by merely closing the line, which is accomplished by removing the receiver from the hook. Contacts C_1 and C_2 are made at the hook switch. C_1 closes the line through the transmitter in series with the primary of the induction coil. This permits current to flow from the central office battery B through one-half of the line relay winding R_1, over one side of the line L_1, through the primary winding of the induction coil, and the transmitter back to the central office over the other half of the line L_2, through the other half of the relay winding R_1, to the other side of the central office battery or to ground, i.e., the grounded side of the battery. This energizes the line relay R_1 which connects the central office battery to a small answering lamp A_1 in the face of the switchboard in front of the operator. This lamp lighting, indicates to the operator that this particular line is calling. She answers the call by inserting plug P_1 into the jack associated with the lighted lamp and to which the line of the calling party is connected. A third battery connection to the sleeve of the plug closes a circuit through the winding of a second relay R_2, known as a "cut-off" relay, which disconnects the line relay from the circuit, putting out the burning answering (or line) lamp A_1. The operator learns the calling subscriber's wishes by connecting her telephone set to the cord circuit by means of the listening key K_1. She talks over the two heavy conductors of the cord circuit through the windings of the repeating coil, which, by means of transformer action, induces current into the other windings of the same coil; this flows back over the calling subscriber's line and induces a current in the secondary of the induction coil, which flows through the telephone receiver.

Not only does the operator's voice current flow from the central office cord circuit to the subscriber's receiver, but there is a direct current furnished by the central office battery through two of the four windings of the repeating coil of the cord circuit, over the line, and through the subscriber's transmitter. This corresponds to the transmitter current furnished by a local battery in the magneto set. It permits the subscriber to talk by virtue of the transmitter carbon resistance varying the strength of the current, which, by means of the repeating coil windings at the central office, induces an alternating voice current across to the opposite side of the cord circuit.

Upon ascertaining the number of the party called, the operator inserts plug P_2 into jack J_2 which permits the lamp S_2 to burn because the circuit is closed from the central office battery through the sleeve connection and the cut-off relay winding. This lamp tells her that the receiver is on the hook at the called party's station and that she must give this connection attention by ringing the called party at frequent intervals. This is accomplished in the same way as in the magneto exchange, by operating the ringing key K_2. When the called party answers, current flowing from the central office battery through the windings of the repeating coil, and through the supervisory relay R_3, operates this relay. As a result the lamp S_2 is short-circuited and goes out, notifying the operator that the party has answered. At the same time, a resistance is inserted in the battery circuit to limit the current through the cut-off relay. When both parties have finished talking and hang up their receivers, this supervisory relay, as well as a similar relay on the other side of the cord circuit, is de-energized, and since the short-circuit is then removed from the lamps, they light. This notifies the operator that both parties are through talking and that both cords are to be taken down. When the operator pulls down both cords, the sleeve circuit of the cord is opened at the jack and the lamps go out.

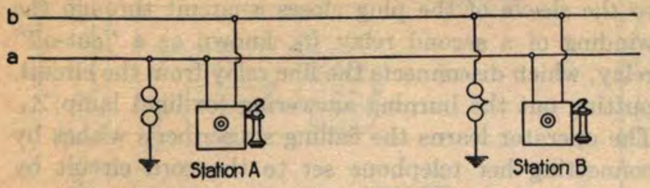


Fig. 114. Signaling on Two-Party Line

It is seen that the operator depends upon burning lamps for each operation excepting that of connecting the calling cord to the jack of the called station. In all common battery operating, **a burning lamp means attention.** Thus a burning lamp in the face of a switchboard signifies "line to be answered"; one burning lamp on a cord signifies "continue ringing on the corresponding cord"; two burning lamps signify "disconnect both cords as both parties have 'hung up' ". A flashing lamp means one party is not hanging up but wishes to place another call or desires the operator to answer in on the connection.

63. Party Lines and Selective Ringing

In order to put more than one subscriber on the same line in common battery operation, it is necessary that some means be provided for signaling each party independently. One method of doing this is represented by Figure 114, where the same 2-wire circuit is used for two subscribers, but one subscriber is rung over wire *a* to ground and the other over wire *b* to ground. A more complex system makes use of the "biased" ringer, which is shown in Figure 115. In this ringer, the magnetic circuit through the cores of the two windings is completed through a permanent steel magnet which gives what is known as a "polarized magnetic circuit". To give the bias effect, a small spring is provided to keep the soft iron armature normally in one position. Without tension on the biasing spring, a current flowing through the windings in one direction will increase the pull on one end of the armature and decrease the pull on the other. This permits the tapper to strike one gong. Likewise, if the current flows in the opposite direction, it will permit the tapper to strike the other gong. An alternating current will, therefore, ring the bell. But if two such ringers are placed in the same circuit and they are biased in opposite directions, a pulsating direct current in one direction will operate the first ringer, while a similar current in the other direction will operate the second.

These two systems may be combined by placing two biased ringers between each wire and ground, thus making a four-party system.

Another system that is used to some extent is known as the "harmonic system". Each ringer is constructed with a special spring armature having a weighted tapper to give it a natural period of vibration. The period of vibration is different for each ringer on a single line and the alternating ringing current must have a corresponding frequency to select a particular ringer. This system requires ringing current taps at the operator's cord circuit of various frequencies, instead of the several arrangements of a single frequency required for the systems described above.

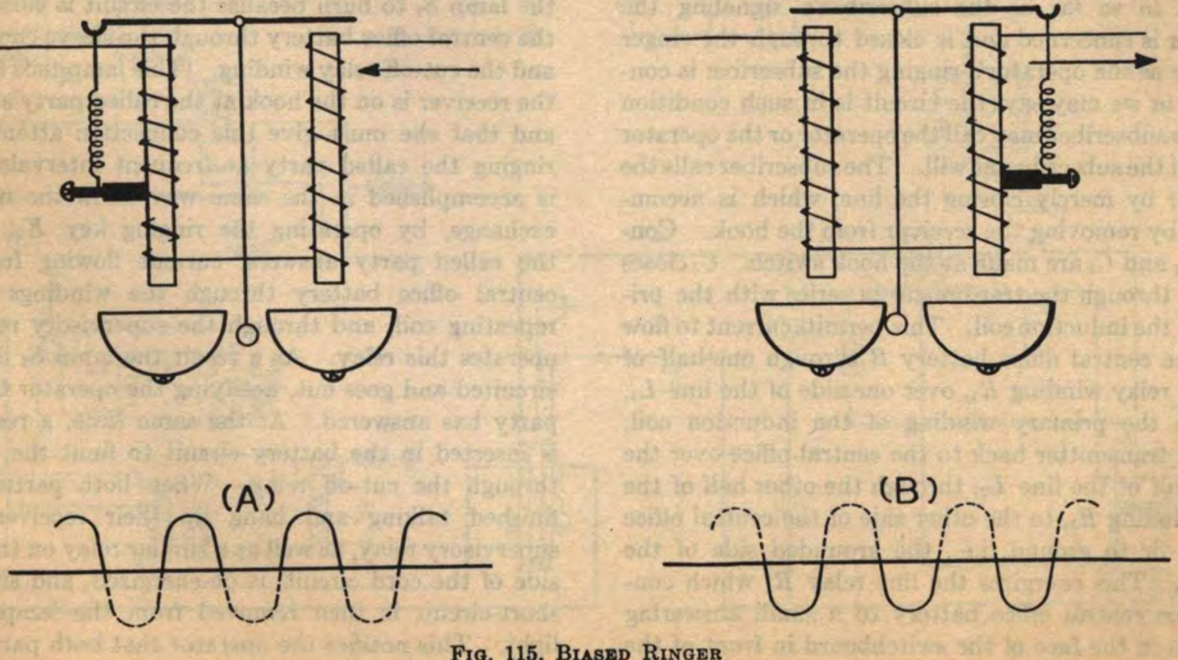


Fig. 115. Biased Ringer

"A" SWITCHBOARD

64. The Multiple Switchboard

In a small exchange where a single operator can handle all of the subscribers, it is possible to connect any two subscribers together when each subscriber's line terminates in a single jack only. As described in the foregoing, if subscriber "A" signals the operator, she will plug into his answering jack, which is next to the signal by which he calls her, and upon ascertaining the number he is calling, for example subscriber "B", she will connect him by plugging into the answering jack of subscriber "B" with the other plug of the same cord circuit. However, when there are more than a few hundred subscribers, all of whose lines terminate at the same switchboard, it is obviously impossible for one operator to answer all of these lines. To apportion the work and to make it possible to mount the switchboard apparatus in such a way that it will permit interconnection for a large number of lines, the **multiple switchboard** was developed.

The principle of the multiple switchboard is that the answering jacks and signals are divided up among the various operators, each operator handling on the average about two hundred lines and being responsible for answering any signals from these subscribers. In addition to these answering jacks, there may be as many as 3,300 **calling jacks** in the position in front of each operator. These calling jacks do not have any signals mounted with them, as they are for calling only. The calling jacks are each multipled, that is, connected in parallel with a similarly located jack in the third position to the left and right, and with the answering jack. Any operator can reach any one of about 10,000 calling jacks, either directly in front of her or in the adjacent positions on her left or right. A multiple switchboard is shown diagrammatically in Figure 116. In this figure should subscriber Number 109 call subscriber Number 567, the signal would come in at position "1" where the answering jack for subscriber 109 is located and the operator would connect him by plugging into calling jack Number 567 in the multiple to her right (Position 2). On the other hand, if subscriber 567 called subscriber 109, the operator at position 3 would answer his call and connect him to subscriber 109 by means of the calling jack in the multiple to her right (Position 4). Each operator is warned against plugging into a busy line by means of a "click" which is heard in her head receiver when she starts to

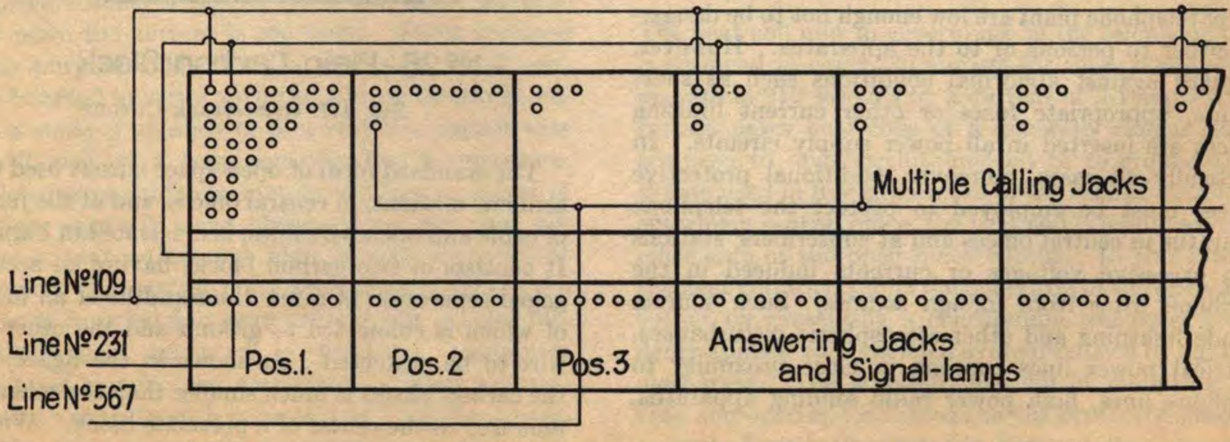
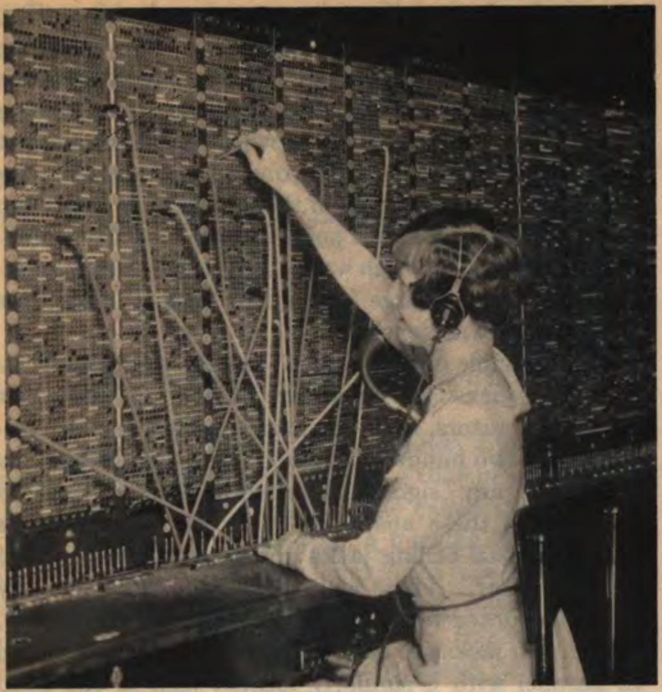


FIG. 116. MULTIPLE SWITCHBOARD



"B" SWITCHBOARD

plug into a calling jack already in use somewhere else in the multiple.

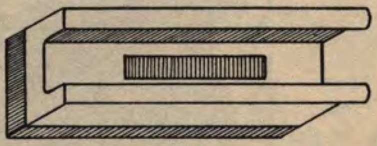
Note: It is not practicable to take up here any comprehensive study of the apparatus and switching systems used for providing local telephone service. Some branches of the subject, such for instance as machine or dial switching systems, are much too specialized to lend themselves to brief analysis. Trunked connections between subscribers where lines terminate at different central offices, however, involve apparatus features essentially similar to those of the toll switching trunk described later in connection with toll switchboard circuits.

65. Protection Against Foreign Currents and Voltages

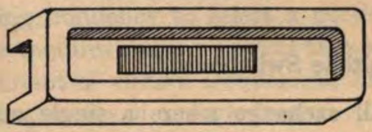
The currents and voltages used in the normal operation of telephone plant are low enough not to be dangerous either to persons or to the apparatus. However, to guard against abnormal conditions such as short circuits, appropriate fuses or other current limiting devices are inserted in all power supply circuits. In practically all cases, moreover, additional protective devices must be employed to protect the telephone apparatus in central offices and at subscribers' stations from excessive voltages or currents induced in the telephone wires from foreign sources. Such sources include lightning and other atmospheric disturbances, electrical power lines running in close proximity to telephone lines, high power radio sending apparatus, etc.

Practically all outside telephone plant, except such conductors as are completely underground from terminal to terminal, may be exposed from time to time to one or more of these foreign hazards. Accordingly, whenever exposed wires are led into a central office or a subscriber's station, they are connected first through certain protective apparatus. The particular protective units employed and the manner in which they are connected into the telephone circuits vary somewhat with particular situations, but in general protective devices are of three principal types—namely, open-space cutouts, fuses, and heat coils.

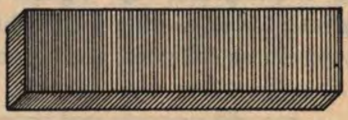
The first and last of these devices ordinarily operate to ground the protected wire, while the fuse opens the wire in which it is inserted. Each of the protective units is designed so that, for the particular situation in which it is used, it will be sufficiently sensitive to operate before the plant which it is protecting is damaged, but on the other hand, not so sensitive as to cause an unnecessary number of service interruptions.



Nº 26 and Nº27 Protector Blocks



Opposite side of Nº27



Nº26 - Plain Carbon Block

FIG. 117. OPEN-SPACE CUTOUT

The standard form of open-space cutout used at subscribers' stations, in central offices, and at the junctions of cable and open wire lines, is illustrated in Figure 117. It consists of two carbon blocks having an accurately gaged separation of a few thousandths of an inch, one of which is connected to ground and the other to the wire to be protected. As shown in the figure, one of the carbon blocks is much smaller than the other and is mounted in the center of a porcelain block. When the voltage of the telephone wire becomes too high, the wire will be grounded by arcing across the small air-gap between the carbon blocks. If a considerable current flows across the gap in this way, enough carbon may be pulled from the blocks by the arc to partially fill in the gap and cause permanent grounding. Or, in the extreme case, when the discharge is prolonged and sufficiently high, the glass cement with which the small carbon insert is held in the porcelain block may be melted, with the result that the blocks are forced into direct contact by the mounting springs in which they are held. However, in the majority of protector operations the blocks do not become permanently grounded.

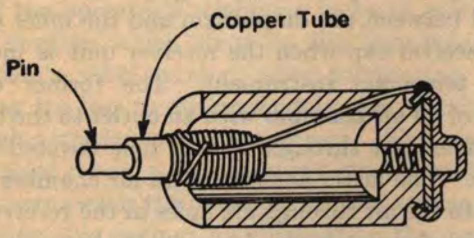


Fig. 118. Heat Coil

The air-gap space between the blocks is designed so that the operating voltage of the protector will be less than the breakdown voltage of the weakest point of the circuit which it is designed to protect and greater than the maximum working voltage of the circuit. The average operating voltage of the open-space cutouts used at subscribers' stations and in central offices is about 350 volts. For the cutouts used at junctions between open wire and cable lines, an average operating voltage of about 710 volts is standard.

When a telephone conductor is grounded by the operation of an open-space cutout, current will continue to flow through the telephone conductor to ground so long as the exposure continues. This current may be large enough to damage the telephone conductor or the protective apparatus itself. Accordingly, it is necessary to insert in the conductor, on the line side of the open-space cutout, a device which will open the conductor when the current is too large. Fuses are used for this purpose. The fuse is simply a metal conductor inserted in series with the wire to be protected, which is made of an alloy or of a very fine copper wire that will melt at a comparatively low temperature. Short lengths of cable conductors (six feet or more) of 24 or finer gage will serve effectively as fuses and will fuse on current values not high enough to overheat dangerously the central office protectors. Where the use of such inserted fine gage cable is not practicable, lead alloy fuses, mounted in fire-proof containers or fire-proof panels, are employed. These are also designed to operate with a current of 7 to 10 amperes.

Finally, it is frequently necessary to protect telephone apparatus against external effects in which the voltage is not high enough to operate the open-space cutout, nor the current high enough to operate fuses, but still high enough to damage apparatus if allowed to flow over a long period. Such currents are usually called "sneak" currents and are guarded against by the use of heat coils. As illustrated in Figure 118, the heat coil consists of a small coil of wire wound around a copper tube which is connected in series with the wire to be protected. Inserted within the copper tube and held in place by an easily melting solder is a metal pin which is connected to the line side of the coil. If sufficient current flows through the coil to melt the solder, this pin will move under the pressure of its mounting spring and thus connect the line to ground.

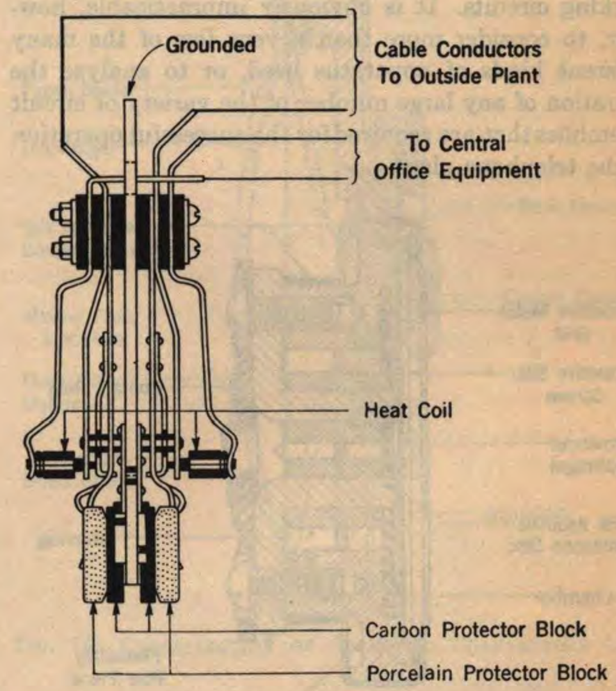


Fig. 119. Heat Coils and Cutouts Mounted on Protector Frame in Central Office

The heat coil now in general use in the telephone plant is designed to carry .35 ampere for three hours and to operate in 210 seconds on a current of .54 ampere. In certain cases heat coils of a generally similar nature are used to open circuits instead of to ground them. Where used in line circuits, as in the case of conductors entering a central office, the heat coil is mounted on the office side of the open-space cutout. In this position the heat coil wiring aids the operation of the open-space cutout by presenting a considerable resistance to suddenly applied voltages such as are produced by lightning discharges. The standard method of mounting heat coils and open-space cutouts on the protector frames in central offices is illustrated in Figure 119.

CHAPTER X

TELEPHONE APPARATUS AND CIRCUITS

66. The Telephone Receiver

The next subject for consideration in our study of electricity would logically be that of the theory of alternating currents. But before, taking up that subject, it may be profitable to examine in more detail certain of the more common and relatively simple types of apparatus used in telephone work, and to observe how apparatus units are connected together to form working circuits. It is obviously impracticable, however, to consider more than a very few of the many different kinds of apparatus used, or to analyze the operation of any large number of the variety of circuit assemblies that are required for the successful operation of the telephone plant.

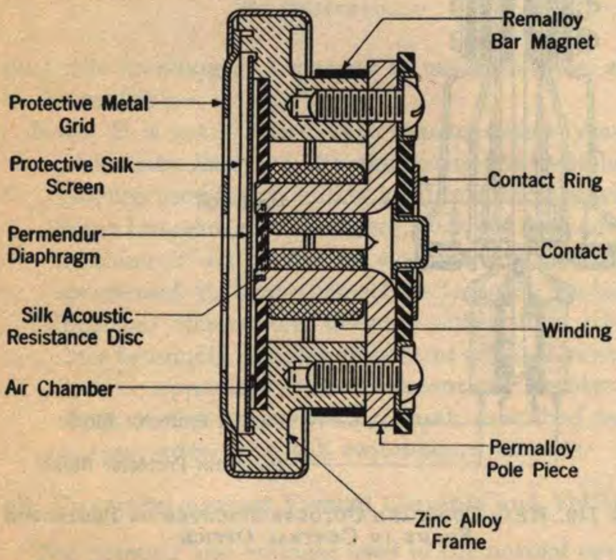


FIG. 120. CROSS-SECTION OF STANDARD RECEIVER UNIT

As the earliest and perhaps most fundamental of telephone apparatus units we may consider first the telephone receiver. Many models of this device have been designed and employed in service since Bell's original invention, and numerous different models are still in use. All operate on the same general principle as was outlined in Article 60, but the details of design show substantial variations.

Figure 120 is a cross-sectional view of the receiver unit which is the present standard in the Bell System. This receiver which is of the bipolar permanent magnet type employs in its construction no less than three of the comparatively new magnetic alloys that were mentioned in Article 23. It is substantially more efficient than any previous design. It also differs notably from earlier types in the extent to which the motion of the diaphragm, which is made of vanadium-permendur, is affected by "acoustic controls". One acoustic control is directly behind the diaphragm, and the other is enclosed between the diaphragm and the inner surface of the receiver cap when the receiver unit is mounted in the telephone instrument. The former control consists of an air chamber with an outlet to the back of the receiver unit through a small hole covered with a silk disc. The latter consists of an air chamber which opens into the air through six holes in the receiver cap. These air chambers are designed to have "acoustic impedances" which match the "electrical impedances" of the receiver and improve its overall efficiency very appreciably. The diaphragm, which is unclamped, rests on a ring-shaped ridge and is held in place by the pull of the magnet. In this way variations in receiver efficiency at different frequencies are practically eliminated. The two permalloy pole pieces are welded to a pair of very strong remalloy or cobalt-steel bar magnets, and the assembly is fastened to a zinc alloy frame. The whole unit is held together by a brass ferrule on the back of which are mounted two silver plated contacts for the electrical connections.

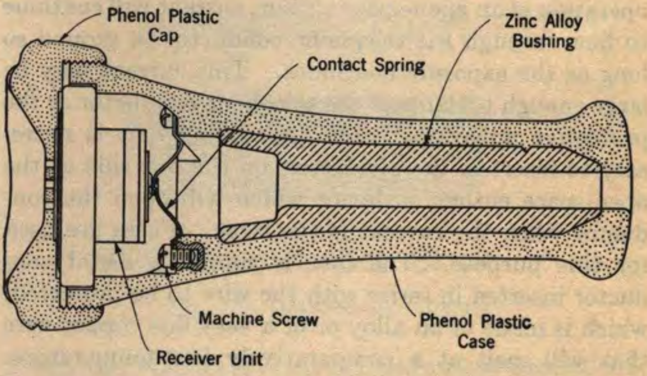


FIG. 121. RECEIVER UNIT AS MOUNTED IN DESK STAND

The receiver unit is designed so that it can be mounted in the standard hand set or in the standard receiver casing used with desk stands, as shown in Figure 121. The receiver cap and other external casings are made of a phenol plastic material and suitable terminals and contact springs are included for connecting the receiver unit contacts to the external wiring. The receiver shell of Figure 121 also encloses a zinc alloy bushing which is included merely to give the instrument sufficient weight to operate the hook switch properly.

The small metal-cased receiver used in standard operators' head sets is coded #528. Formerly monitoring arrangements for operating supervisors, chief operators, and testboardmen involved the use of a special high resistance receiver, coded #525, which could be bridged across a talking connection without causing appreciable transmission loss. However, the #528 receiver with vacuum tube monitoring is now used with most testboards. Similarly, a repeating coil is now installed in the receiver leads of the left-hand pair of the operator's telephone jacks of each switchboard position which steps up the impedance of the supervisor's #528 receiver when monitoring, thereby reducing the loss to approximately that obtained with the high impedance #525 receiver. The use of but one type of receiver for operators, chief operators, and supervisors avoids the changing of head sets and results in considerable savings by eliminating the duplication of sets required under the former plan of monitoring.

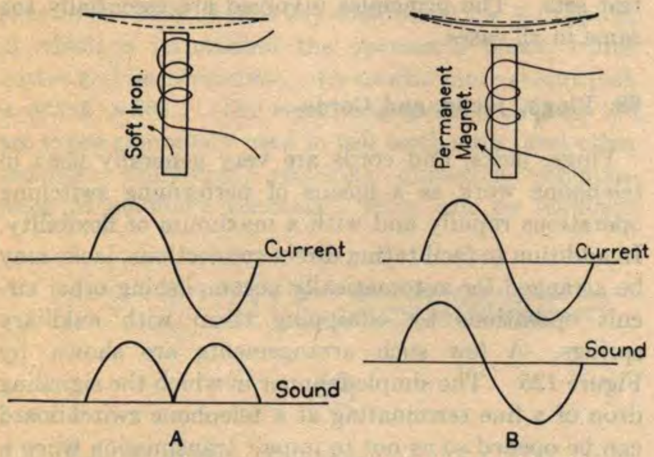


FIGURE 122

The telephone receivers discussed above are equipped with permanent magnets, and it is of course important that the magnetism should not be impaired by jarring or other abuse. A permanent magnet not only increases the amplitude of vibration of the diaphragm when the voice current is flowing through the windings but prevents the diaphragm vibrating at twice the voice frequency. This principle is illustrated in Figure 122. When a piece of soft iron is held near an electromagnet, it is attracted by the magnet regardless of the direction of the current in the windings. Thus, an alternating current in a winding on a soft iron core will assert an attraction during each half cycle, which in the case of the receiver diaphragm will establish a vibration with a frequency twice that of the current. If, on the other hand, a permanent magnet is used, the alternating current establishes a vibration of the same frequency as the current by merely increasing or lessening the pull already exerted on the diaphragm.

67. The Telephone Transmitter

As we have already learned (Article 60), the operation of the telephone transmitter depends upon the variation in resistance of carbon granules with changes in pressure. Figure 123 shows in cross-section the transmitter unit which is the present standard for subscribers' telephone sets. This transmitter is of the "direct action" type; that is, the movable element attached to the diaphragm which actuates the granular carbon is an electrode, and serves the dual purpose of contact and pressure surface. As the drawing shows, this dome-shaped electrode is attached to the center of a conical diaphragm, and forms the front center surface of the bell-shaped carbon chamber.

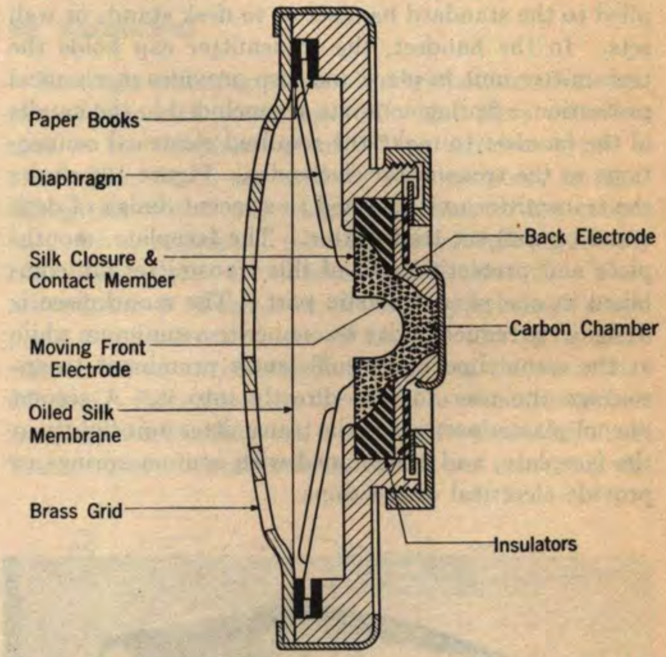


FIG. 123. CROSS-SECTION OF STANDARD TRANSMITTER UNIT

The diaphragm is made of aluminum alloy .003 inch thick with radial ridges to increase stiffness. Paper books, which consist of a number of thin impregnated paper rings, support the diaphragm at its edge on both sides. The carbon chamber is closed on the front side by a silk membrane clamped under the flange of the diaphragm electrode. A light spoked copper contact member, clamped under the diaphragm electrode, is the means of providing a flexible connection between this front electrode and the supporting metal frame. The fixed back electrode is held in place in the frame by a threaded ring and is insulated by a phenol fibre washer and a ceramic insulator which also forms one of the surfaces of the carbon chamber. The active surfaces of both electrodes are gold plated. A brass plate which is perforated with large holes protects the vibrating parts against mechanical injury. Moisture is kept out of the working parts by an oiled silk moisture-resisting membrane placed between the brass plate and the diaphragm.

The shape of the electrodes and the carbon chamber provides sufficient contact force between the diaphragm electrode and the granular carbon in the zone of maximum current density so that this transmitter operates satisfactorily in any position. When new, it has a resistance of around 30 to 40 ohms.

This transmitter unit is designed to be readily applied to the standard handset or to desk stands or wall sets. In the handset, the transmitter cap holds the transmitter unit in place and also provides mechanical protection. Spring contacts are included in the handle of the handset to make the required electrical connections to the transmitter electrodes. Figure 124 shows the transmitter unit adapted to a recent design of desk stand or wall set transmitter. The faceplate, mouthpiece and protective grid of this transmitter are combined in one phenol plastic part. The mouthpiece is designed to reduce cavity resonance to a minimum while at the same time being sufficiently prominent to encourage the user to talk directly into it. A second phenol plastic part holds the transmitter unit tightly in the faceplate, and is equipped with contact springs to provide electrical connections.

Standard Handset

The above description is confined to recent transmitter designs only. Many older types of subscribers' transmitters are of course in use in the telephone plant. Different designs are also used for the standard operator's breast-set transmitter, and in linemen's test sets. The principles involved are essentially the same in all cases.

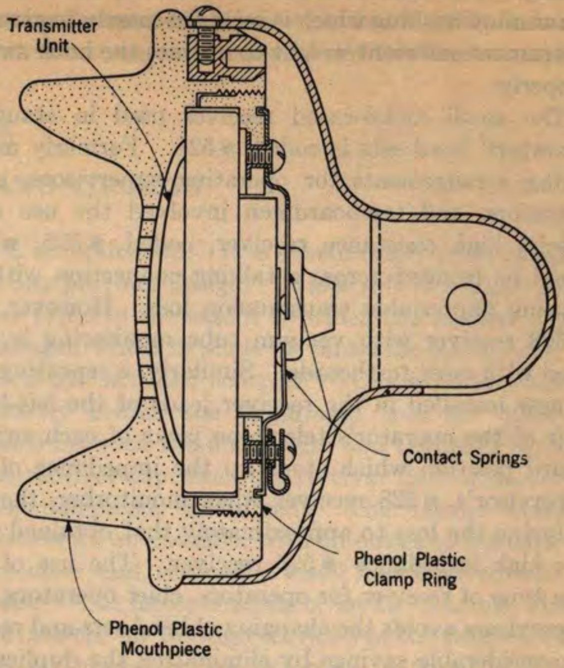
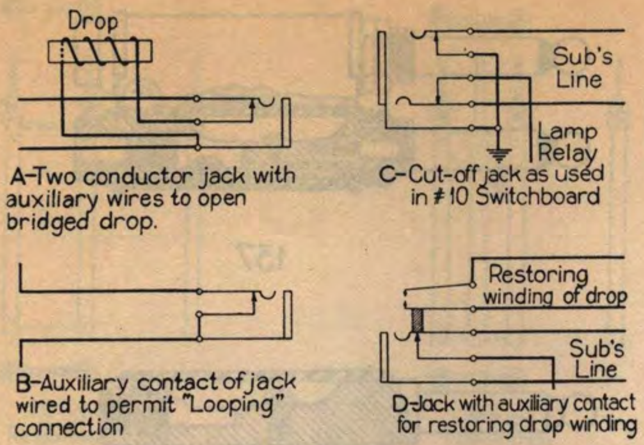


Fig. 124. Transmitter Unit as Mounted In Desk Stand

68. Plugs, Jacks, and Cords

Plugs, jacks, and cords are very generally used in telephone work as a means of performing switching operations rapidly and with a maximum of flexibility. In addition to facilitating direct connections, jacks may be arranged for automatically accomplishing other circuit operations by equipping them with auxiliary springs. A few such arrangements are shown by Figure 125. The simple manner in which the signaling drop of a line terminating at a telephone switchboard can be opened so as not to impair transmission when a plug is inserted in the jack is illustrated by Figure 125-A. Figure 125-B shows another use of the same auxiliary contact. Here a telegraph set terminated with a two-conductor plug may be looped with the wire at a single operation, or an ammeter connected to a cord may be inserted for measuring the current in the wire. Figure 125-C illustrates the use of normals for two springs of a three-conductor jack such as is used in connection with the #10 local switchboard to perform a function similar to that of the cut-off relay in the #1 switchboard. Figure 125-D illustrates a commonly used two-conductor jack which in this case is wired to operate a self-restoring drop in the same way as the three-conductor jack shown in Figure 112.

The mechanical construction of a few types of jacks widely used in connection with long distance service, is illustrated in Figure 126. The #49 jack is mounted



A–Two conductor jack with auxiliary wires to open bridged drop.

C–Cut-off jack as used in #10 Switchboard

B–Auxiliary contact of jack wired to permit "Looping" connection

D–Jack with auxiliary contact for restoring drop winding

FIG. 125. TYPICAL USES OF AUXILIARY JACK CONTACTS

in strips of 5, 10, or 20 for use in the face of both local and toll switchboards. It takes the #110 plug. A smaller jack, coded as the #92, takes the #109 plug, and is used in the face of larger switchboards where the multiple must accommodate a greater number of lines than the toll or small local switchboard multiple. The #99 jack, illustrated in the same figure, is mounted in pairs in the switchboard key shelf to take a #137 plug, in which is terminated the operator's breast transmitter and head receiver. (A similar more recent jack is coded #364.) The remaining jacks in Figure 126 are types commonly used in toll testboards, and other testroom equipment, requiring numerous combinations of auxiliary contacts. They can be mounted either singly or in pairs to accommodate single one- or two-conductor plugs such as the #116 and #47 or 2-, 3- or 4-conductor plugs such as the #209, #241, and #289 types, respectively. Jacks of this type are made with a sherardized metal frame having a brass sleeve mechanically fastened to its front face. The channel shape readily permits the mounting of german silver contact or auxiliary springs properly insulated from each other by bushings and washers.

Figure 127 illustrates both the mechanical and electrical features of various plugs and Figure 128 shows the construction of a commonly used type of switchboard cord. While this is only one of many cords in use, it represents the standard features and gives an insight into cord manufacturing processes.

69. Resistances

No single unit of apparatus is more fundamental than the resistance, several types of which have countless uses in the telephone plant. Two common types of resistances, which are used for such purposes as regulating the central office supply current to the proper value for operating and releasing relays, lighting switchboard lamps, etc., are illustrated in Figure 129. They are coded as #18 and #19, the #18-type being a single plain resistance, and the #19-type having a third connection to an intermediate point of the resistance winding. Both types are furnished in resistance values ranging from less than one ohm to a few thousand ohms. The accuracy is ordinarily within 5 per cent, and the

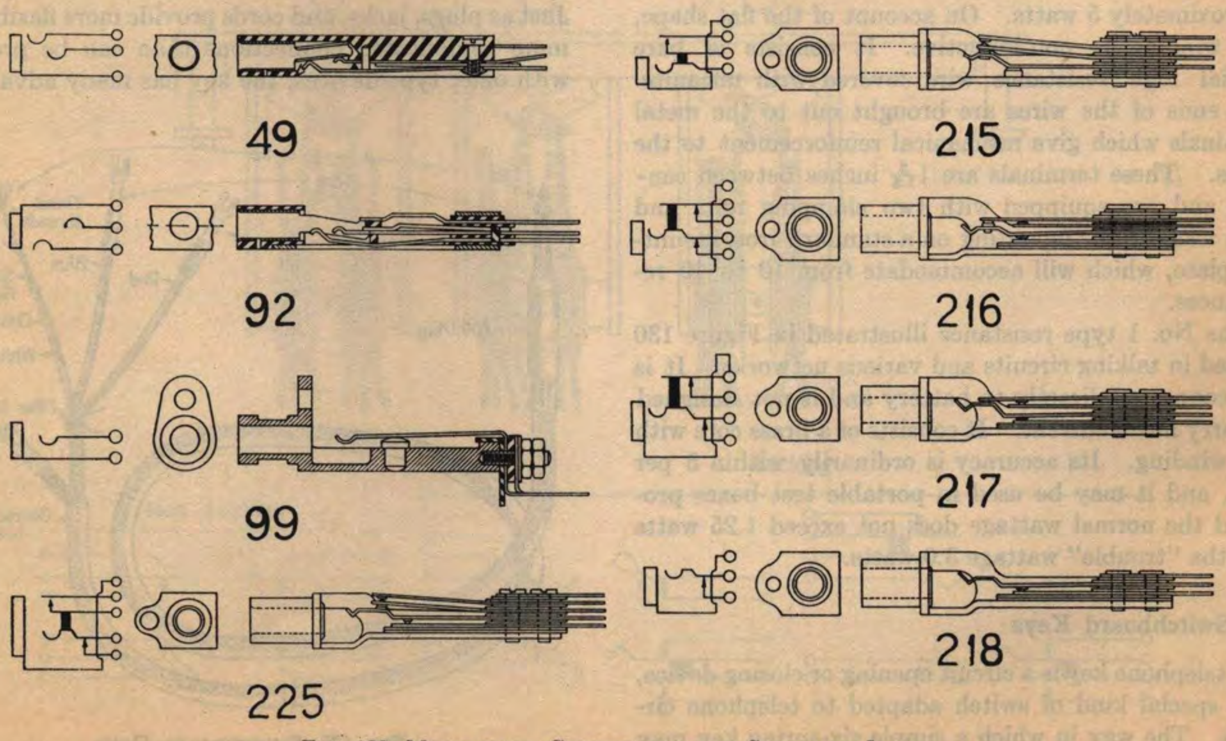


FIG. 126. MECHANICAL CONSTRUCTION OF STANDARD JACKS

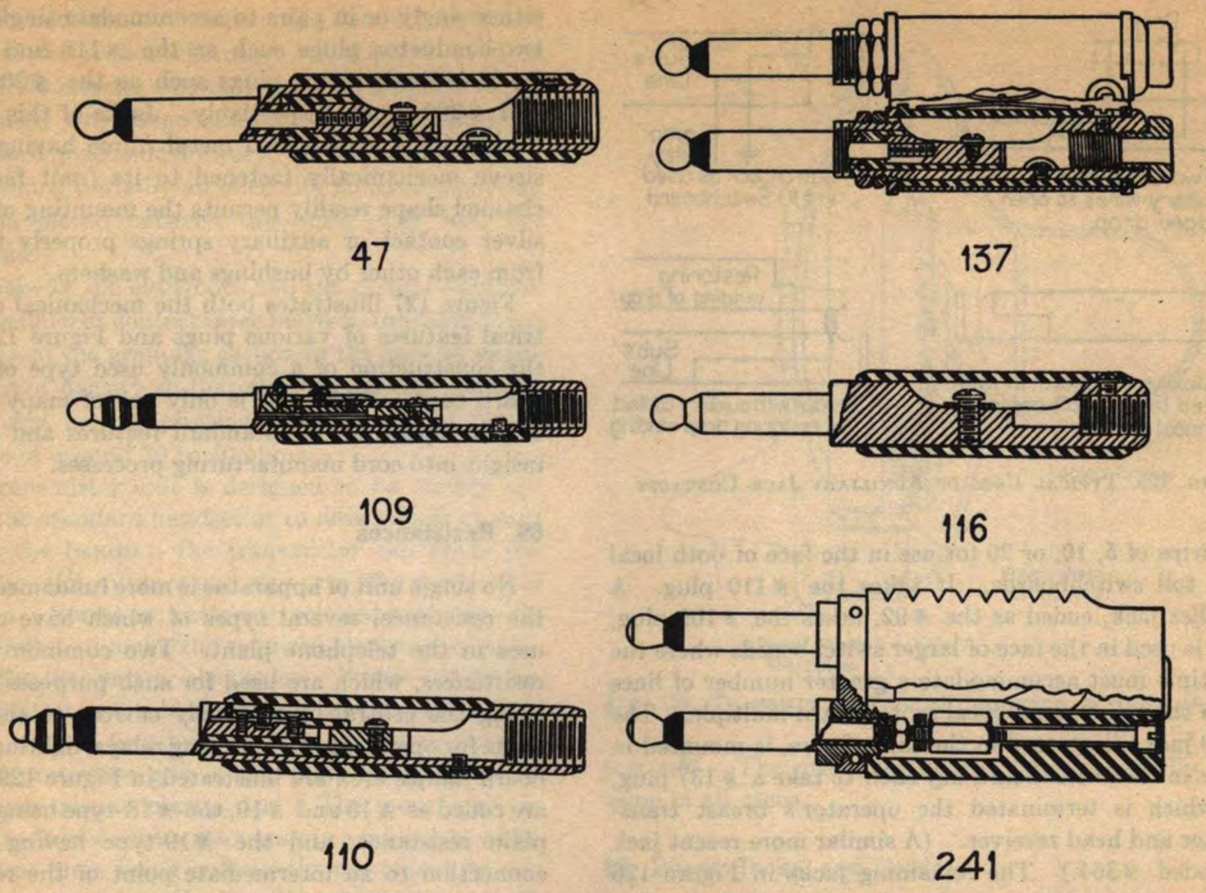


Fig. 127. Mechanical Construction of Standard Plugs

safe radiating capacity, which depends upon the mechanical design rather than the resistance value, is approximately 5 watts. On account of the flat shape, the winding is non-inductive. It consists of bare special high resistance wire covered with micanite. The ends of the wires are brought out to the metal terminals which give mechanical reinforcement to the edges. These terminals are $1\frac{5}{16}$ inches between centers, and are equipped with two clamping nuts and fibre washers for mounting on a standard iron mounting plate, which will accommodate from 10 to 40 resistances.

The No. 1 type resistance illustrated in Figure 130 is used in talking circuits and various networks. It is not connected directly to battery and is not designed to carry much current. It consists of a brass core with one winding. Its accuracy is ordinarily within 5 per cent, and it may be used in portable test boxes provided the normal wattage does not exceed 1.25 watts and the "trouble" wattage 3.0 watts.

70. Switchboard Keys

A telephone key is a circuit opening or closing device, or a special kind of switch adapted to telephone circuits. The way in which a simple six-spring key may perform the same circuit functions as a double-pole, double-throw switch, was illustrated in Figure 6. Just as plugs, jacks, and cords provide more flexible and more complicated connections than can be provided with older type devices, the key has many advantages

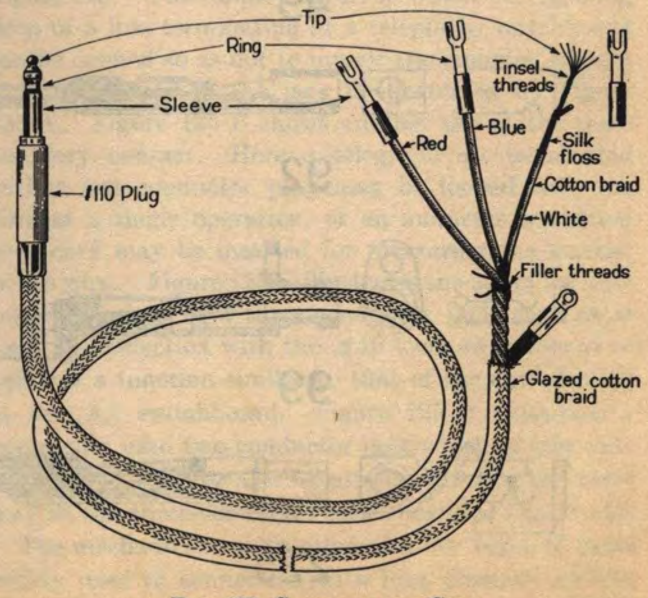


Fig. 128. Switchboard Cord

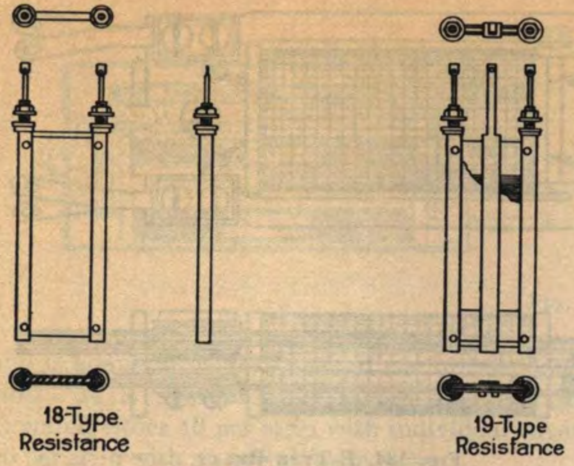


Fig. 129. Flat Resistances

over the knife switch, and facilitates additional features essential to telephone operation. Contacts to be made or broken may be delicately adjusted through the use of german silver springs. These contacts, which are adequate for carrying the current values ordinarily used in telephone circuits, are made through special contact metal welded to the springs, thereby preventing excessive resistances from being inserted in the sensitive telephone circuits. Auxiliary contact springs permit the operation of additional or more complicated circuit features, which could not be easily provided on any other form of switch.

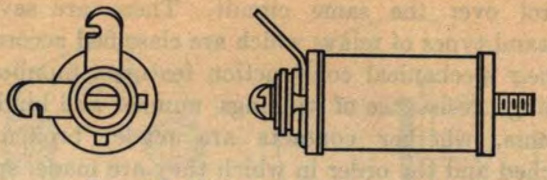


Fig. 130. No. 1 Type Resistance

Figure 131 illustrates a key used in the operation of switchboard circuits, which is especially important. This key was designed for use in connection with the universal switchboard key shelf and has the so-called "unit" construction. This permits one or more key spring units to be mounted, as illustrated, on a standard metal base which is equipped with a hard rubber top. Two types of spring units are provided, the lever type (Figure 131) and the push-button type. The convenient manner in which individual units can be removed, and in which any key combination can be had by selecting various units for one standard base, has certain obvious maintenance advantages.

71. Relays

A relay may be defined as an electrically operated switch or key. It gives one electrical circuit control over one or more other electrical circuits; or as in the case of the locking type relay, it may give certain

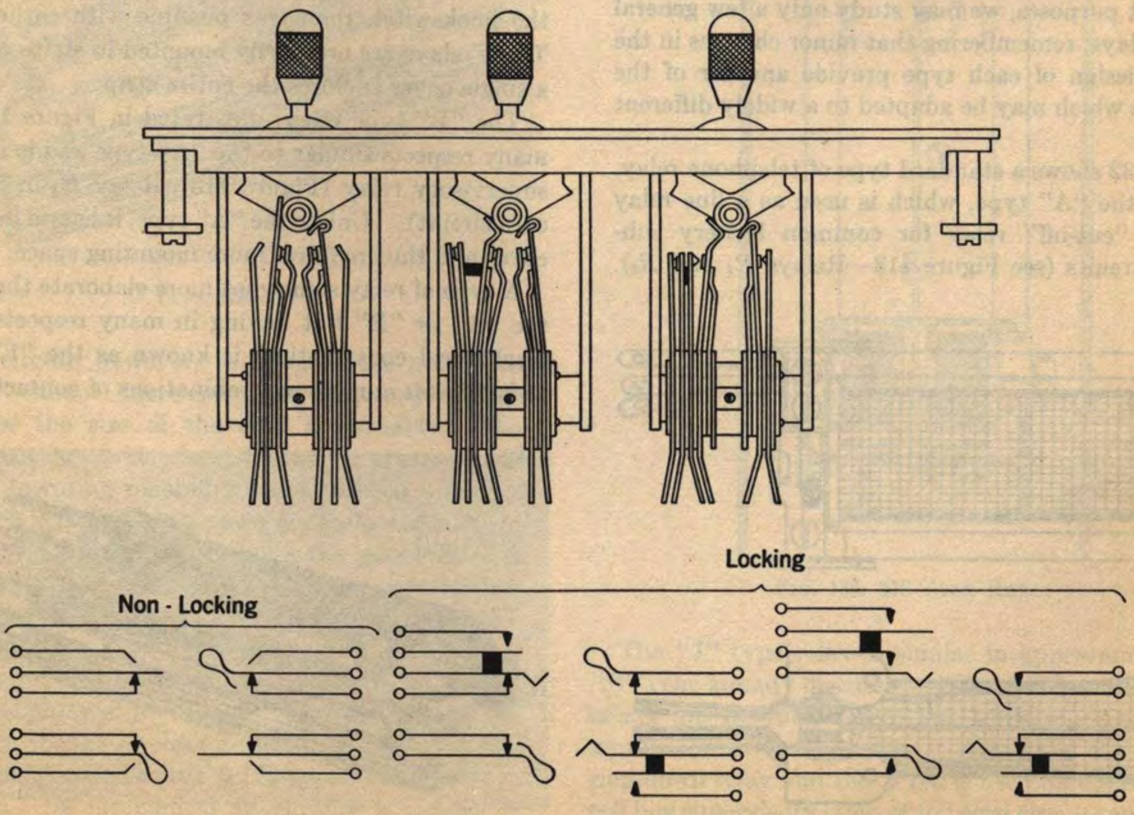


Fig. 131. Standard Switchboard Key Assembly

control over the same circuit. There are several thousand types of relays which are classified according to their mechanical construction features, number of windings, resistance of windings, number and kinds of contacts, whether contacts are made, broken or switched and the order in which they are made, speed of operation, and current values required for operation. In connection with speed of operation, relays may be designed to have a time-delay in operating or releasing.

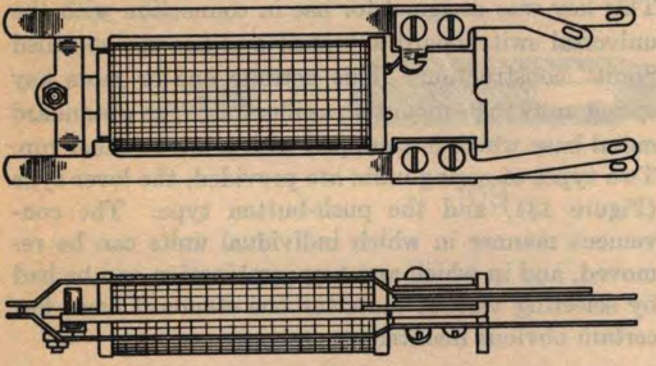


FIG. 132. A-TYPE RELAY

Such relays are classified as "slow operate" and "slow release" respectively. Relays which are termed "marginal" are also used. These are usually designed to operate only on a fairly high current value but to stay operated with a considerably reduced current. For our present purposes, we may study only a few general types of relays, remembering that minor changes in the electrical design of each type provide another of the same series which may be adapted to a widely different use.

Figure 132 shows a standard type of telephone relay, known as the "A" type, which is used as a line relay and as a "cut-off" relay for common battery subscribers' circuits (see Figure 113—Relays R_1 and R_2).

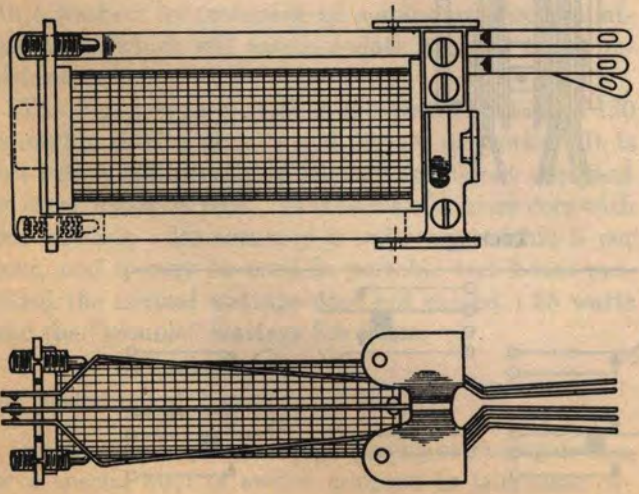


FIG. 133. B-TYPE RELAY

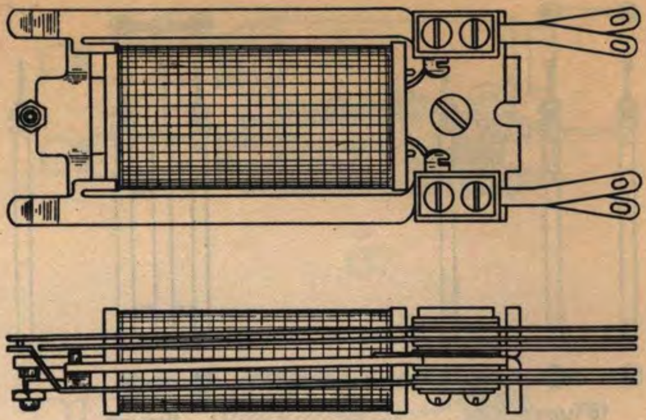


FIG. 134. E-TYPE RELAY

The mechanical construction of the "A" type is typical of the great majority of modern relays. In dimensions it is both small and narrow, thereby permitting a large number to be mounted in a comparatively small space, which results in a notable saving of relay rack space in local central offices where many line and cut-off relays are in use. The soft iron armature forms a loop which completes the magnetic circuit from the core through the two halves of the loop, and mechanically operates the contact springs. The winding is of enamel insulated wire, which also aids in reducing the size of the relay. The "A" type is very quick in operation, and gives a "flashing line lamp" for more rapid moving of the hookswitch than was possible with earlier types. These relays are ordinarily mounted in strips of 20 and a single cover encloses the entire strip.

The "B" type relay, illustrated in Figure 133, is in many respects similar to the "A" type and is used as a supervisory relay (Figure 113—Relay R_3 in the local cord circuit). Unlike the "A" type, it has an individual cover and thus requires more mounting space.

A type of relay somewhat more elaborate than either the "A" or "B" but having in many respects similar mechanical construction, is known as the "E" series. It facilitates numerous combinations of contact springs

E-TYPE RELAY

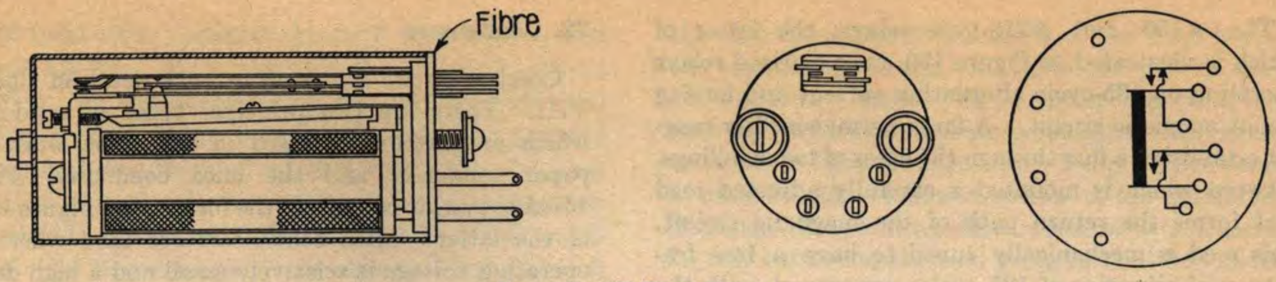
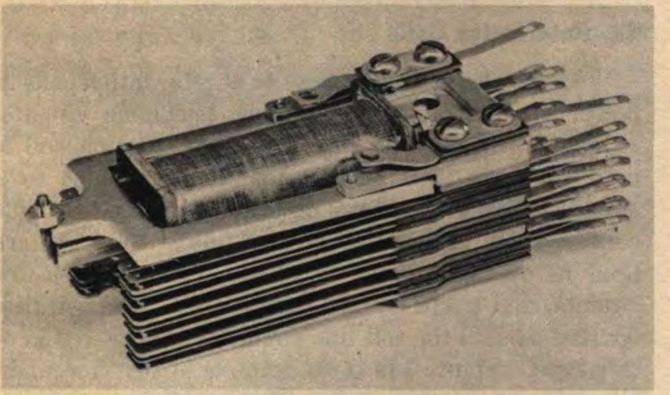


FIG. 135. 122-TYPE RELAY

and is adapted for very general use in telephone circuits. It is illustrated in Figure 134. It can be mounted either 10 per strip with individual covers, or 20 per strip with an overall strip cover.

The "R" type relay is a flat relay which is similar to the "E" type, except that the core, although having the same cross-sectional area, is of a semi-elliptical shape. This affords a greater winding space and permits of a shorter length of turn than is possible on the "E" type core.

The "U" type relay is an all-purpose relay of the same general design as those already mentioned. Certain improvements have been incorporated in its magnetic circuit, however, to increase the pull of its armature without increasing the required current strength or the size of the core appreciably. This permits this type of relay to be built with as many as 24 springs. Operating reliability has also been increased above older types by using two separate contacts on each spring. This greatly reduces the possibilities of faulty operation due to dirt particles between contact points. The "Y" type relay is similar to the "U" type except that it is especially designed for accurately timed slow-release operation.



U-TYPE RELAY

A type of relay still standard for certain telephone circuit uses, though of older design than the types discussed above is coded as the #122-type. It is shown in Figure 135. Its mechanical appearance is similar to the #178-type and with the exception of the number of springs, it is similar to the #125 (3 groups), #149 (one group) and #162 (one group). It has a spool winding and a laminated iron core with the magnetic circuit completed through the armature and the soft iron framework at each end of the core. Relays of this design ordinarily have round caps which are fastened by means of a nut as shown in the figure.

The relays thus far described are intended to operate only on direct current. There are a few other types that may be classified as alternating-current relays, the more common of which are the "J" type, the #87-type, the #172-type, the #196-type, the #150-type, and the #218-type.

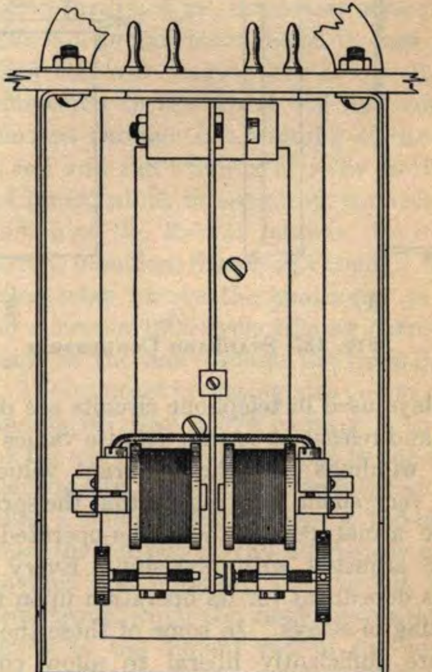


FIG. 136. 218-TYPE RELAY

The "J" type relay is similar in appearance to the "B" type already discussed. The #172 and the #196 relays are not illustrated, but these more nearly resemble direct-current types. The #172 is a toll line ring-down relay and the #196 is used for operating the toll line supervisory lamp of toll cord circuits and in telephone repeater circuits designed for 20-cycle signaling.

The #150- and #218-type relays, the latter of which is illustrated in Figure 136, are polarized relays operating on 135-cycle alternating current and having a split magnetic circuit. A large permanent bar magnet establishes a flux through the cores of two windings, between which is mounted a carefully adjusted reed that forms the return path of the magnetic circuit. This reed is mechanically tuned to have a free frequency of vibration of 135 cycles per second, with the result that a very weak alternating current of that frequency in the relay windings will set it into active motion. The vibration of the reed controls the operation of an associated direct-current relay by opening and closing a pair of contacts connected in series with its windings. The #150- and #218-type relays are used in composite ringer circuits and in connection with telephone repeaters designed for 135-cycle signaling.

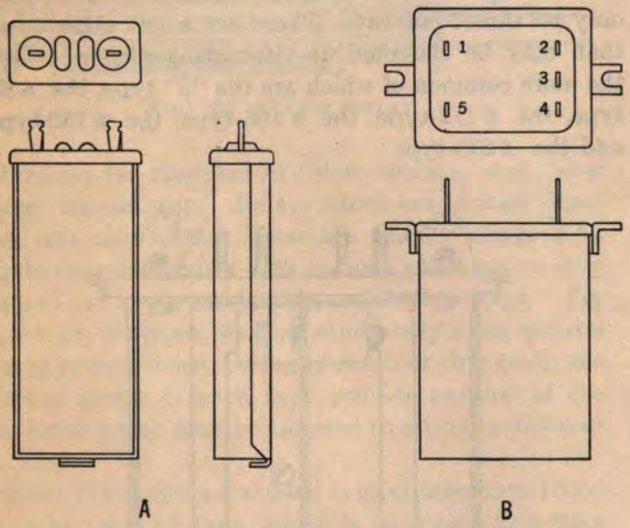


Fig. 137. Standard Condensers

All relays used in telephone circuits are designed to operate and release at certain definite values of current in their windings. As these current values are frequently very small, this means that the springs which hold the armatures in their non-operated positions must be adjusted with precision. Every telephone circuit is dependent for its operation upon the proper functioning of relays. In some of these the operating limits are sufficiently liberal to allow considerable margin in adjustments. But in others—and these are frequently the more important ones—the difference between an adjustment giving satisfactory operation and one under which the relay will fail to function properly, may be very small. In practice, specific instructions, giving the exact operating and release current values for which each type of relay should be adjusted for each kind of circuit in which it may be used, are provided.

72. Condensers

Condensers are discussed in some detail in Chapter VIII. There are two principal types of condensers which are extensively used in telephone work—the paper condenser and the mica condenser. Figure 137-A shows an example of the former and Figure 137-B of the latter. Mica condensers are used where the operating voltage is relatively small and a high degree of stability with respect to temperature changes and time is required. The mica condenser illustrated here should not be subjected to more than 200 volts. Paper condensers are designed to withstand much higher voltages with safety. They are ordinarily less stable than mica condensers and their capacity values are naturally less precise. On the other hand, they are more economical.

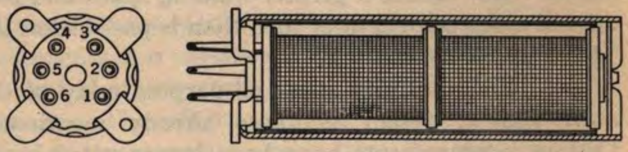


Fig. 138. Straight Core Retardation Coil

73. Retardation Coils

We have already noted the use of retardation coils in power circuits and certain other telephone circuits. In general, it may be said that a retardation coil is used wherever it is desired to add inductance to a circuit. Figure 138 shows an example of the "straight core" type of retardation coil. Coils of this type are used in operators' telephone sets, incoming selector circuits, dial trunk circuits, and so on. The coil designated 54-L in the toll line circuit of Figure 140 is of this type. Figure 139 is an example of the "toroidal" type of retardation coil. This particular type is designed for use in the balancing network of composite ringers where the network is mounted on the relay rack. It has two windings, the rated resistance of each being approximately 202 ohms.

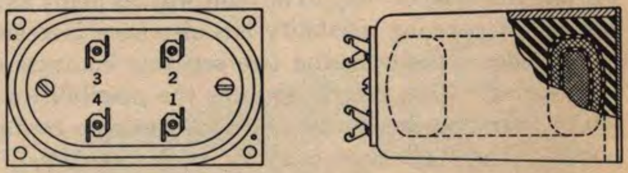


Fig. 139. Toroidal Retardation Coil

74. Typical Long Distance Central Office Circuit

Telephone apparatus such as we have been discussing, is wired together in practice to form a very large number of different types of circuits, each designed to perform some particular function necessary in providing service. As a representative example, let us consider the circuit—or series of circuits—illustrated in Figure 140. This is intended to show schematically the typical circuits required at one terminal of a long distance toll circuit for establishing the connection between a subscriber's telephone and the toll circuit itself. In this example it is assumed that the toll switchboard is of the No. 3 type, and that the toll line circuit is a 4-wire cable circuit. Other types of switchboard, as well as other types of line facilities are, of course, also in use in the telephone plant.

It may be noted that the drawing is separated by heavy dividing lines into three principal parts in which are shown (1) the subscriber's station circuit, (2) the local central office circuit, and (3) the long distance central office circuit. The latter two parts of the drawing are again divided by the open dashed lines into a number of parts, each of which can be considered more or less separately from the other parts in analyzing the circuit. Thus, the circuit units associated directly with the toll switchboard are shown in several blocks in the left part of the large section of the drawing devoted to long distance central office circuits. These separate units include (1) the long distance central office end of the toll switching trunk circuit, (2) the toll line circuit, (3) the toll cord circuit, (4) the operator's position circuit, and (5) the operator's telephone set circuit. The various apparatus units installed in the toll terminal room are shown in a similar way in the group of blocks at the right of the drawing. The drawing includes a large amount of circuit detail, although numerous minor signaling and auxiliary functions are omitted. It should be particularly noted, however, that the drawing is not necessarily a true picture of actual circuit connections at any existing central office. It is intended to be merely representative in a general way and may differ in various respects from the layout in any particular office, which is naturally designed to fit the specific operating requirements applying.

In analyzing the entire circuit drawing, it will be convenient to follow through the completion of a long distance telephone connection, beginning at a point where the outward long distance operator has received an order for placing a call from a telephone subscriber in her city, and is ready to pick up the toll line to the called city. We shall also assume that this is a delayed call and that the calling subscriber is not "on the circuit" when our analysis starts.

The operator's first step is to connect the rear plug of a toll cord circuit to the outward jack of an idle toll line circuit to the called city. This establishes a connection from battery through the supervisory lamp of the Toll Cord Circuit, contacts of the Talk key, and the cord sleeve, to the winding of the B-1025 relay in the Toll Line Circuit. This relay operates but, due to its relatively high resistance (1800 ohms), the current is too weak to light the supervisory lamp. The operation of relay B-1025 is followed by that of the R-1500 relay. This relay in operating closes a contact which connects 24-volt battery to the lead going to the idle indicating lamp circuit. Relays on this circuit (which are not shown in the drawing) then operate to give visual indications that the circuit is busy at all points where it appears in the switchboard multiple. Another contact of the R-1500 relay is opened to lift off from across the line a bridge of 600 ohms in series with a 1 mf. condenser, the purpose of which is to provide the proper termination of the toll line when it is idle. The purpose of the remaining contacts of the R-1500 relay will appear later in the discussion.

The operator now signals on the circuit by operating the ringing key (Toll Cord Circuit) toward the left. The lower contacts of this key break the connection of the tip wire of the cord to the R-857 relay and connect it instead to 24-volt battery through 60 ohms. At the same time, the upper contacts bridge a 600-ohm resistance in series with a 1 mf. condenser across the front cord to give it a proper termination in case it is connected when the rear ringing key is operated. The battery connected to the tip of the rear cord establishes a current through one winding of the 54-L retardation coil and the winding of relay R-1649 in the Toll Line Circuit, which in operating, connects battery to the winding of the R-1721 relay in the 1000-Cycle Direct-Current Terminal Signaling Circuit. The operation of this relay breaks the continuity of the line circuit and connects 1000-cycle ringing current to the outgoing side of the line through the leads designated T and R. One contact in closing also connects ground to the winding of relay E-374 causing it to operate. This opens the signal receiving circuit to the amplifier, thus preventing any possibility of ringing "kick-back". It also closes a contact that bridges a 750-ohm resistance across the output of the 1000-cycle generator, which provides the outgoing line circuit with the proper termination while the ringer is operating.

Now, going to the distant end of the circuit and assuming that the terminal circuit arrangements there are identical with those at the near end, we may follow the effect of the incoming 1000-cycle signaling current. The repeating coil circuit connected across the line in the ringer circuit is designed to offer an attractive path to the incoming 1000-cycle current. It accordingly passes through the windings of this coil, the contacts of the 267-A testing jack, and contacts of the non-operated E-374 relay, to the amplifier. After amplification, the signaling current is sufficiently strong to operate the B-1042 relay. The operation of this relay shorts out the winding of relay 149-CD, which, in releasing, connects ground to the winding of relay E-6035. This relay, in turn, grounds the lead to the winding of relay R-233 and the latter, in operating, connects battery to the signal lead. As a result, a current is set up through the 320-ohm winding of the R-1330 relay in the Toll Line Circuit, causing its operation. One armature of this relay, in closing, operates the busy signals; another closes a circuit from the inward line lamps through contacts of relays R-1648, R-1330, R-994, and R-6015, to the 600-ohm winding of the latter relay, and thence to battery through a contact of the R-1500 relay. This causes the inward lamp signals to light and also operates the relay R-6015, which locks up under control of relay R-1500. Relay R-6015, when operated, connects another battery to the lead to the inward signal lamps and also closes a contact by means of which the R-1330 relay is locked up through its 410-ohm winding under control of relay R-1500.

The inward operator recognizes the lamp signal by connecting one end of a cord circuit to the corresponding inward jack. This permits current to flow from the sleeve, through contacts of the non-operated R-1648 relay, to the winding of the B-1025 relay. The operation of this relay is followed by that of the R-1500 relay, which disconnects the battery from the locked up R-6015 and R-1330 relays, permitting them to release and extinguish the lamp signals. At the same time, operation of the busy signals, now relinquished by the R-1330 relay, is continued by the closing of an auxiliary contact of the R-1500 relay. Another pair of contacts of the same relay opens to lift the 600-ohm terminating bridge from the incoming toll line.

The inward operator answers on the connection by throwing her talk key which, through the resultant operation of the R-857 relay in the toll cord circuit, and the two R-1084 relays, as well as certain other relays in the operator's position circuit to be discussed later, connects her telephone set across the line.

The operator has a standard operator's telephone circuit, which consists of a 528 receiver and a 396A transmitter. The receiver is connected through contacts of the non-operated E-106 relay to the terminals of the #65 induction coil designated T and LT. The transmitter is connected to the primary winding of the same coil, in series with a 24-volt battery and a 54-R retardation coil. The retardation coil tends to steady the transmitter current, thereby reducing noise and compelling the fluctuations (which are in effect a superimposed alternating current) to flow through the 4 mf. bridged condenser instead of through the 24-volt battery. This tends to give the effect of a lower voltage battery, which is preferable for the operator's transmitter in that it prevents both loud clicks and other disagreeable loudness being heard in the receiver as side-tone. The talking current is induced from the primary of the #65 induction coil to the secondary winding, and flows over the connections to the contacts of the closed R-857 relay and thence to the tip and ring conductors of the cord. The 20-G repeating coil and the associated 239-FL relay, shown in the telephone set circuit, are required for the ordinary busy test. Thus, if a trunk circuit is busy when the operator tests it with the tip of her cord, the 239-FL relay will operate. This will cause a rush of current through the 40-ohm winding of the 20-G coil, which will produce a sharp click in the operator's receiver connected across the other winding of the coil.

We now have the outward operator at the near end of the circuit in communication with the inward operator at the distant end of the circuit (assuming, of course, that the outward operator has also operated her Talk key). When the distant operator gets the called party on the line, she throws her talking key to normal. This leaves the procedure in connection with handling the call entirely up to the outward operator at this end, with the exception of taking down the connection at the distant end when the conversation is finished. This is merely a matter of disconnecting the plugs when that operator finds the supervisory lamps associated with her cord circuit burning.

In the meantime, the outward operator at the near end has connected the other end of the cord circuit into the proper jack of the toll switching trunk multiple. This operation closes a sleeve connection through the 1800-ohm winding of the B-199 relay in the outgoing end of the trunk. The B-199 relay then operates to close a circuit through the winding of the B-1009 relay, over the trunk and through the two windings of the 124-F relay in the incoming end of the trunk, operating both relays.

At the same time, the B-operator in the local central office, having been passed the number, connects the plug of the incoming trunk to the proper subscriber's jack in the B-board multiple. When this connection is made, the E-122 relay (300 ohms) of the incoming toll switching trunk circuit is operated by a 24-volt battery circuit through its winding, through the sleeve of the B-board multiple jack, through the cut-off relay (A-26) of the subscriber's line circuit, to ground. The operation of the E-122 relay, in addition to disconnecting the B-operator's busy test, connects a guard and disconnect lamp, associated with the cord of the incoming trunk, to the contact of the 124-F relay, and disconnects it from the contact of the B-15 relay and the 30-ohm winding of the E-126 relay. If the B-board operator finishes her connection to the subscriber's line before the outward long distance operator finishes her connection with the trunk, this lamp will burn but as soon as the outward operator finishes her connection, it will go out. This assures the B-board operator that the long distance operator has plugged into the right trunk.

The reason the guard and disconnect signal goes out is the operation of the 124-F relay, which breaks the lamp connection to ground, and in turn, closes a ground connection to the 30-ohm winding of the E-126 relay but does not operate it because the other side of this winding is open. As we have seen, the 124-F relay is operated because the operation of the B-199 relay in the toll office end of the trunk closed a path from the 24-volt battery at the 124-F relay, through a 500-ohm winding of this relay to the contact of the E-126 relay, through one winding of the 25-S repeating coil, over one conductor of the trunk to the long distance office, through a contact of the E-65 relay and one winding of the repeating coil, to the winding of the B-1009 relay; and thence back by a like path to the other 500-ohm winding of the 124-F relay. The resistances shown in series with the 500-ohm windings of the 124-F relay and designated as "X" are adjusted in value to compensate for different lengths of trunk circuits.

We now have a connection established from the long distance operator to the subscriber's station. The 124-F relay in the local office end of the switching trunk is operated and the B-operator's guard and disconnect lamp is not burning, telling her that the trunk is in use, needs no attention, and must not be disconnected. It will be remembered that the same current that operated the 124-F relay also operated the B-1009 relay in the outgoing end of the trunk. The operation of this relay connects the 85-ohm winding of the B-199 relay, in parallel with its 1800-ohm winding, to the sleeve wire. The resultant reduction in series resistance permits sufficient current to flow to light the cord circuit supervisory lamp, thereby signifying to the long distance operator that she must ring the subscriber. She then operates her ringing key to the front position which connects battery to the tip wire of the cord and so operates the E-65 relay in the outgoing trunk. This relay operates to connect 20-cycle ringing current across the trunk, which causes the operation of the 87-A relay during the interval that the ringing current flows. This is followed by the operation of the E-122 (220-ohm) relay, which connects ringing current to the subscriber's line. Incidentally, this ringing current flows through the contacts of a special key so wired that it can be set to reverse the ringing connection and permit party line ringing from the toll cord circuit. This key is set at the same time the trunk is plugged into the B-board multiple, in case the called number is for a party line.

Outward Long Distance Switchboard

We thus have the ringing current properly relayed at the local office. When the subscriber answers, a 48-volt battery current flows through the winding of the B-15 relay, through a 40-ohm non-inductive resistance and one winding of the 25-S repeating coil, over the subscriber's line; and back to ground through the other winding of the 25-S repeating coil and a second 40-ohm non-inductive resistance. This 48-volt circuit is the subscriber's battery supply and is used in connection with toll switching trunks to improve the subscriber's transmission over long subscriber's loops. The 40-ohm resistance in series with the repeating coil prevents the current being too great on very short loops. Neither this resistance nor the winding of the B-15 relay can appreciably weaken the voice current on account of a condenser being bridged between terminals 3 and 8 of the 25-S repeating coil; likewise, the winding of the 87-A relay between terminals 1 and 6 does not weaken the voice current on account of the bridged condenser on the other side of the repeating coil.

When the B-15 relay operates, due to the subscriber taking his receiver off the hook, its armature contact closes the 200-ohm winding of the E-126 relay through a 600-ohm resistance, through the 30-ohm winding of the same relay, to the ground connected to the armature of the 124-F relay. This operates the E-126 relay, which disconnects the 124-F relay from its bridged position across the trunk, but connects one of its windings to ground, thus holding it operated and keeping the guard and disconnect signal from burning. The interruption of the current through the trunk bridge releases the B-1009 relay and thus puts out the cord circuit supervisory signal, thereby notifying the long distance operator to cease ringing because the subscriber has answered. She then, having her talking key depressed, notifies the subscriber that she is "ready on his long distance call". After this she throws the key lever of her talking key in the other direction to the monitoring position. This disconnects her telephone circuit but connects the 94-G repeating coil across the cord and also operates the E-106 relay. The E-106 relay connects the telephone receiver of the head set circuit directly to terminals 1 and 2 of the 94-G repeating coil, thereby permitting the operator to monitor on the circuit.

As soon as the subscriber starts talking, the operator stamps the ticket and dissociates her head set from the connection altogether, unless for some reason it is desirable to continue monitoring.

When the E-106 relay is operated it establishes contacts other than those for connecting the operator's telephone receiver to the 94-G repeating coil. These additional contacts are associated with monitoring taps which connect the operator's circuit with the service observing board, thereby permitting the service observer to listen in on the circuit either when the operator is talking or monitoring.

When the subscriber has finished talking and hangs up his receiver, the B-15 relay of the toll switching trunk circuit is released. This, in turn, releases the E-126 relay and again connects the 124-F relay across the trunk. The B-1009 relay then operates, lighting the supervisory signal, thus notifying the long distance operator that the subscriber has finished. After stamping the ticket, she pulls down the connection to the toll switching trunk, releasing the 124-F relay and in doing so, lights the guard and disconnect signal in front of the B-operator. This time the B-operator knows that the burning lamp means "disconnect" and pulls down the cord. This releases the E-122 relay which lets the guard and disconnect signal again go out, telling the B-operator that the trunk is not in use and no further attention is needed.

At the same time that she takes down the trunk connection, the outward operator rings on the toll line. Since the circuit is now connected at the distant end, the effect of the incoming ringing signal is somewhat different from the former case. The terminal signaling circuit operates in exactly the same way to connect ground to the 320-ohm winding of the R-1330 relay in the toll line circuit. However, because a cord is now connected to the circuit, the R-1500 relay is operated. Accordingly, the operation of the R-1330 relay closes a circuit from ground through the winding of relay B-1020, the non-operated contacts of relay E-661, and the operated contacts of relay R-1500, to the energized sleeve wire, operating the B-1020 relay. The low resistance of this latter relay, now connected in parallel with the 1800-ohm winding of the B-1025 relay, reduces the series resistance of the sleeve wire to about 80 ohms, and so permits the cord circuit supervisory lamp to flash. The operation of relay B-1020 also connects interrupted ground to the winding of the E-661 relay, which then operates intermittently to open and close the connection of relay B-1020 to the sleeve wire. The latter relay is held operated, however, by battery supplied through a closed contact of the E-661 relay to one end of its winding, the other end being grounded through a pair of its own operated contacts. The net result is to cause the cord circuit signal lamp to flash intermittently, and this will continue even after ringing stops until the inward operator either pulls down the cord or answers on the circuit.

The inward operator may answer by throwing the talking key in her cord, which disconnects the sleeve wire from the lamp circuit and connects it to battery through the windings of the B-1022 and B-1023 relays in the operator's position circuit, in series. The combined resistance of these two relays is about 600 ohms, a value sufficiently high to so reduce the current flowing in the sleeve wire that the B-1020 relay, which is marginal, is released. This breaks the connection to the E-661 relay, stopping its action, and also increases the sleeve resistance to 1800 ohms. The B-1022 relay in the operator's position circuit is also marginal and does not operate but the B-1023, and following it, the R-1084, are operated. The operation of the talking key also establishes a circuit through a non-operated contact of the R-1586 relay in the position circuit and the 175-ohm winding of the R-857 relay in the cord circuit, operating the latter. This breaks the direct connection between the two ends of the cord and connects them to the splitting key from which they are connected to the telephone set circuit through closed contacts of the two R-1084 relays, which are both operated if both ends of the cord are connected to jacks.

The operator's position circuit is, as its name implies, common to all the cord circuits at a position. This means that each wire shown in Figure 140 as connecting from this circuit to the cord circuit, is also connected in the same way to every other cord circuit in the position. It may be noted that with the monitoring and talking keys of the cord normal, every one of these wires is open at one end or the other. When the position circuit is connected to a cord by operation of the talking key, the cord may be split for talking in either direction by operation of the splitting key in the position circuit.

Overseas Toll Switchboard

If when the talking key is operated, a ringing signal is received over the line, it will operate the relays in the signaling circuit and the R-1330 relay of the toll line circuit. The latter connects ground through the winding of the B-1020 relay, the non-operated contacts of relay E-661, and operated contacts of relay R-1500 to the sleeve, and thence through contacts of the talking key and the windings of the B-1022 and B-1023 relays, to battery. The current set up is not great enough to operate the B-1020 relay but, due to the connection of the B-1020 relay in parallel with the B-1025 relay in the sleeve circuit, the current is of sufficient value to operate the marginal B-1022 relay in the position circuit. Its operation reduces the resistance of the circuit of the cord circuit supervisory lamp from 1800 ohms to 80 ohms, by connecting an 85-ohm resistance in parallel with the 1800-ohm resistance already connected to the lamp and grounded through a closed contact of the R-1084 relay, and permits the lamp to light.

Similarly, a switch-hook signal from the subscriber, when the talking key is operated, will operate the B-1009 relay in the trunk circuit. This will connect the low resistance winding of the B-199 relay into the sleeve, reducing its net resistance, and so allowing the B-1022 relay associated with that end of the cord to operate and light the other signal lamp.

The position circuit is so designed that if the talking keys of two cords are operated, only the cord whose key was thrown first will be connected to it. This is effected by means of the R-1586 relay which, it will be noted, operates immediately after the operation of the R-857 relay in the cord circuit whose key is thrown first, because a circuit is closed from its winding through a closed contact of the R-857 relay and a contact of the Talk key to ground. This operation of the R-1586 relay opens the ground connection to the 175-ohm winding of the R-857 relay and replaces it with a ground connection through auxiliary contacts of the R-857 relay to its own 700-ohm winding. This holds the R-857 relay in the first cord operated but makes it impossible for the R-857 relay in any other cord to operate even though its talking key is operated, because both windings will be opened, one by its own non-operated contacts and the other by the operated armature of the R-1586 relay.

It is possible, on the other hand, to monitor on two or more cords at the same time by operating the monitoring keys. It is possible also to talk and listen on two cords simultaneously by operating the talking key of one and the monitoring key of the other. In this case, only the cord whose talking key is thrown is connected through the position circuit for splitting or transferring, but the operation of the R-506 relay in the operator's position circuit (which follows the operation of the Talk key) connects the monitoring leads through two 2 mf. condensers to the leads running to the telephone set circuit. Operation of the monitoring key of another cord will accordingly connect the telephone set across the cord.

The position circuit of Figure 140 is arranged for transferring an incoming call from an inward to an outward position. The circuit may also be arranged for transferring from inward to "through" or, by adding several more relays in the toll line circuit, for transferring from inward to both through and outward. The transfer from inward to outward is accomplished by operating the transfer key shown in the drawing. This connects battery through 1000 ohms to the ring wire of the cord, establishing a current over this wire through the 1–2 winding of the 54-L retardation coil and the 370-ohm winding of relay R-1648, to the grounded lead to the switching pad circuit. The resultant operation of the R-1648 relay opens the sleeve connection from the inward jack, thus releasing the B-1025 and R-1500 relays. The simultaneous establishment of a ground connection to the 340-ohm winding of the R-1330 relay, however, causes it to pull up and hold the busy signals operated. At the same time a circuit is completed from battery at an open contact of the R-1500 relay through the 600-ohm winding of relay R-6015 and a pair of its contacts, through open contacts of relay R-994, and through closed contacts of relays R-1330 and R-1648 to the outward lamp signals. Relay R-6015 operates and locks up, connecting another battery to the outward lamps. Its operation also closes a contact which causes the R-1330 and R-1648 relays to lock up through their 410- and 457-ohm windings respectively, under control of relay R-1500. The lamps at the outward position therefore remain lighted until an outward operator plugs into a jack, even though the inward operator restores the transfer key to normal and takes down her cord. When the outward operator connects to the circuit, the resultant operation of the R-1500 relay breaks the battery connection to relay R-6015, which releases, followed by relays R-1330 and R-1648, and extinguishes the lamp signals.

From the switchboard, the line circuit is led through two pairs of jacks at the "patching jack board", the purpose of which is to facilitate quick changes in the inter-connections between line and drop facilities. It is to be noted that while the line circuits at this board may include several different types of layouts, the drop circuits are all identical and may therefore be interchanged in any desired manner. Before it reaches the drop jacks at the patching jack board, the test and control board multiple is bridged to the circuit. The connections to the jacks of this multiple, which is provided solely for testing purposes, are the same as those to the jacks of the toll circuit multiple at the outward switchboard. The make-busy key associated with each jack of the test and control board multiple, is operated by the testboardman whenever he picks up a circuit at this point for testing. Its operation connects ground to the winding of the R-994 relay in the toll line circuit. This relay operates the busy signals, connects busy tone to the sleeve wire, and opens the circuit to the line signaling lamps at the switchboards. It also operates signal lamps at the Plant and Traffic "control boards" through contacts not shown in the drawing. Its purpose is, of course, to prevent any attempts by operators to use the circuit while it is being tested.

Leaving the line jacks in the patching jack board, the circuit is next connected to the "switching pad circuit". This is an artificial line causing a loss of 2, 3 or 4 decibels, which is normally connected in the circuit but is automatically removed through the operation of the R-1124 relay when the circuit is used for a switched or through connection. When two such circuits are connected together, therefore, the net loss of the overall connection is reduced by the sum of the loss values of their respective switching pads. The effect is the same as if a "cord circuit repeater" were used.

As we have already noted, the signaling circuit is bridged across the line between the switching pad circuit and the 4-wire terminating set circuit. This latter is a device for breaking the circuit into two parts, a transmitting and a receiving circuit, each requiring a pair of wires. It consists of two 124-A repeating coils connected in the hybrid coil arrangement to be discussed in a later chapter.

From the terminating set, the transmitting and receiving circuits pass through four-jack circuits in and

No. 8 Test and Control Board

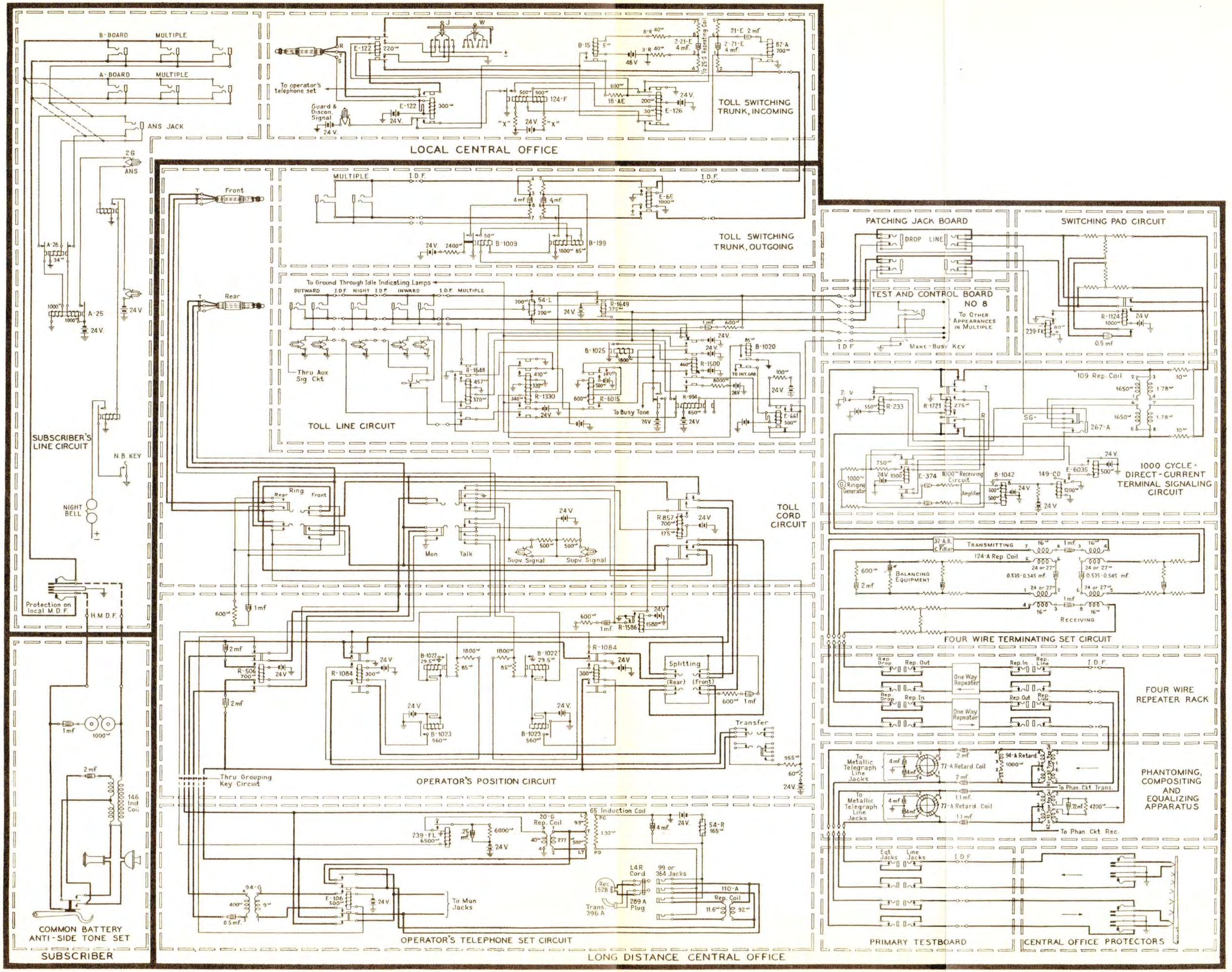


Fig. 140. Typical Long Distance Terminal Circuits—Four-Wire Cable Circuit—No. 3 Switchboard

out of the terminating amplifiers or repeaters, indicated by blocks in the drawing, and from thence to the line equipment. This consists of composite sets, equalizing equipment, and phantom sets. The composite sets shown in this drawing are arranged for metallic telegraph circuits. The equalizing apparatus consists of arrangements of resistances, inductances and capacities connected across the line on the line side of the phantom repeating coil in the transmitting circuit and in series with the drop windings of the repeating coil in the receiving circuit. The purpose of this is to broaden the band of frequencies through which transmission over the circuit will be practically uniform.

For line testing purposes and for patching the equipment, the line circuits are next connected through four-jack circuits at another testboard position called the primary testboard, where a large number of cable pairs may be terminated conveniently since each pair occupies only a relatively small space in the testboard jack panels. From the line jacks here, the circuits are connected to the distributing frame again, and thence through protectors to the toll cable itself.

CHAPTER XI

TELEGRAPH CIRCUITS

75. Means of Obtaining Telegraph Circuits

As a medium of communication, telegraphy depends upon the transmission of electrical signals which are arranged according to some definite code that can be readily translated into a language form by an operator or a machine. In the usual practice, telegraph signals are formed by interrupting or reversing the direction of a continuous current between the sending and receiving stations according to some standard code pattern.

Many telegraph circuits are derived from wire facilities created and used primarily for telephone service, through the aid of apparatus and circuit designs that make possible the simultaneous use of the same facilities for both telephone and telegraph transmission. There are three principal methods commonly employed for accomplishing this result, as follows:

1. "Simplexing" or "compositing" open wire or cable facilities to obtain direct current grounded telegraph circuits.
2. Superposing on open wire facilities high-frequency alternating-current circuits known as "carrier telegraph channels".
3. Superposing on two wires of a cable telephone circuit a very low current "metallic" telegraph circuit.

In addition to the circuits obtained from facilities which are also used for telephone service, telegraph circuits are often secured by the use of a carrier system employing much lower channel frequencies than the open wire system mentioned above. This is known as the "voice-frequency carrier system". Facilities employed for this purpose, however, cannot be used at the same time for telephone service.

It is not practicable here to describe fully all of these methods of obtaining telegraph circuits but we may take up those electrical principles that are fundamental to each and more or less common to all. In general, these are applications of theory already discussed.

It is obvious that where the same wire facilities are used for both telephone and telegraph circuits, some means of separating the telephone and telegraph currents at the line terminals must be employed. The oldest device for this purpose is the simplex set by means of which one grounded telegraph circuit is obtained from the two wires of a "non-phantomed" telephone circuit, or from the four wires of a "phantom group" by applying the simplex to the "phantom" circuit. The simplex principle is illustrated by Figure 141. The telegraph currents cannot interfere with the telephone currents because they divide equally at the mid-point of the line winding of the simplex or "repeating" coil to which each telegraph set is connected. Any change in current value at the "make" or "break" of the telegraph key is not induced into the telephone circuit because the magnetic field established by half of the telegraph current in one-half of the repeating coil winding is exactly neutralized by the field produced by the other half of the telegraph current in the opposite direction in the other half of the same winding.

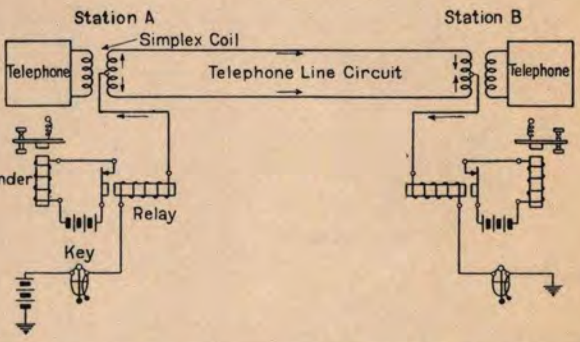


Fig. 141. Telegraph Circuit on Simplexed Telephone Circuit

Referring to Figure 141, the arrows represent the telegraph currents and the total current is shown dividing at the mid-point of the simplex coil line winding at Station A. The two halves join again at the mid-point of the line winding of the coil at Station B. It is imperative that the two line conductors have identical electrical characteristics, including not only equal or "balanced" series resistances but equal capacities and leakages to other conductors and to ground. If the two line conductors are not so balanced, the telegraph current will not divide into equal parts at the mid-points of the simplex coil windings and the larger part will induce a current in the "drop winding" of the coil, which will not be neutralized by the current induced by the lesser part.

Differing radically in principle from the simplex set, the composite set, illustrated by Figure 142, permits a grounded telegraph circuit to be derived from each of the two wires of a telephone circuit, and this without interfering with the use of the telephone circuit as one side of a phantom circuit. Referring to the figure, it may be seen that there are two reasons why the telegraph currents do not interfere with the telephone circuit. In the first place, the inductance of the retardation coil in series with the telegraph "leg", together with the capacitance of three 2 mf. condensers connected in parallel to ground, prevents sudden changes in the telegraph current values, which would tend to be audible as "clicks" in the telephone circuit. The inductance serves here as a "choke coil"; that is, it opposes the sudden building up of the current at the make of the key and retards the rate of decay of the current when the key is opened. The condensers assist the inductance by storing up a small quantity of electricity while the key is closed and discharging this through the inductance when the key is opened. The net result is that the current reaching the line wire changes in value less abruptly than the current at the telegraph key; also, the voltage induced at the break is kept at a relatively low value, thereby preventing a voltage substantially greater than the operating voltage being impressed on the line at that instant.

The second feature of the set that is necessary for keeping the telephone and telegraph signals separated is the 2 mf. condenser in series with the telephone drop, which prevents the direct telegraph currents from reaching the telephone equipment. The bridge across the telephone circuit on the drop side of the series condensers is provided to prevent "crossfire", a condition where telegraph signals sent on one wire of a telephone circuit induce voltages sufficient to interfere with telegraph signals on the other wire, or to operate the signaling relays of the telephone circuit. The bridged arrangement of two 2 mf. condensers in series with the windings of a second retardation coil, which is connected to ground at its mid-point, tends to stabilize the potential of the two line wires by providing a path for unbalance currents to "leak" to ground.

76. Principle of Neutral Telegraph Operation

A telegraph circuit in its simplest form consists of a single wire between two points, equipped at each end with a manual telegraph set consisting of relay, sounder and key. These are so arranged that one set is connected to ground and the other to grounded battery, or both sets are connected to grounded batteries of opposite polarities. Because the operation of the relays is independent of the direction of the current through them, such a system is called a "neutral" system to distinguish it from "polar" systems in which the direction of operation of the relays is determined by the polarity or direction of the current through their windings.

Neutral operation makes use of a flow of current on the line for the operated or "marking" position of the relay armature and zero current for the open or "spacing" position. The line current furnishes the power to operate the receiving relay to marking position while either a spring on the armature or a "biasing" current in another winding of the relay furnishes the energy to operate the relay to the spacing position.

Figure 143 illustrates such a simple neutral telegraph circuit. To analyze its operation, let us assume that the West Station key is closed and the East Station key is open ready for sending. If now the East operator closes his key for only an instant, current flows through

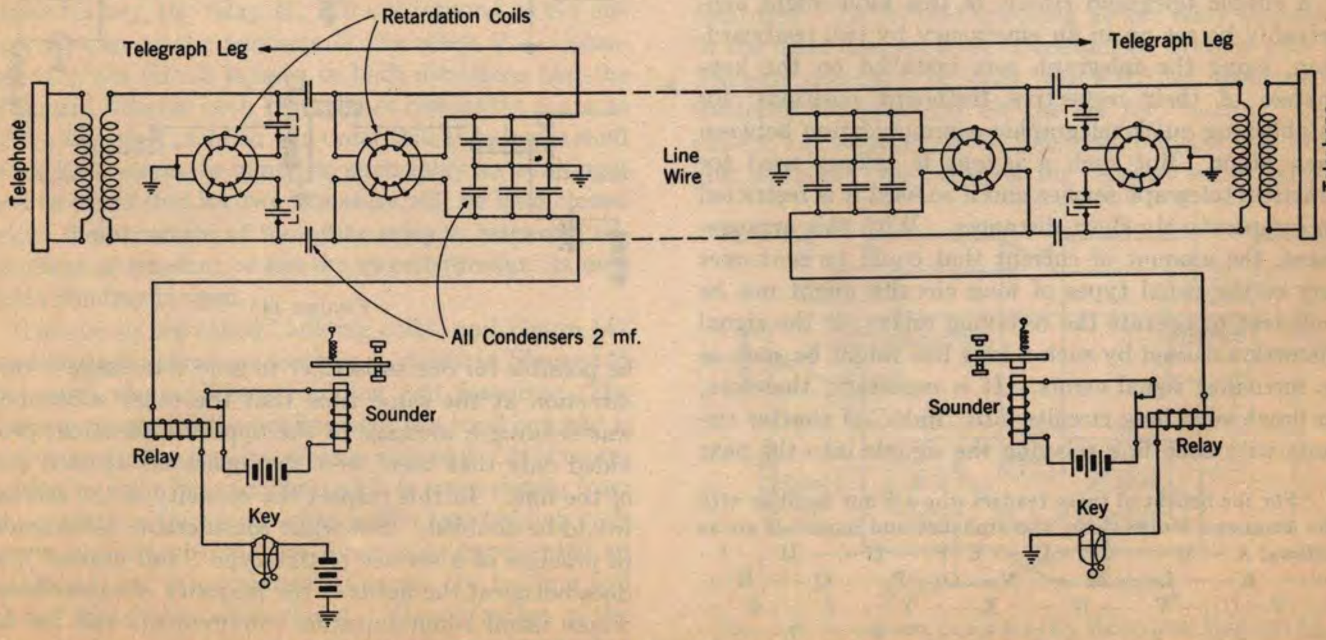


Fig. 142. Telegraph Circuit on Composited Telephone Circuit

both the East and West relay windings in series and both relays operate. This in turn closes the local sounder circuits causing a quick, complete stroke of the sounder lever corresponding to a "dot". If the key lever is held closed for a little more than one-tenth of a second, a longer signal is transmitted giving a greater interval between the up and down strokes of the sounder lever corresponding to a "dash".* If the West Station operator desires to stop the East Station from sending, he "breaks", i.e., he opens his key, thereby opening the circuit and the operator at the East end, noting the failure of his own relay to respond to his signals, knows that the West operator wishes to send to him. He accordingly closes his key by means of the "locking" lever, which short-circuits the contacts of the sending or "non-locking" lever, and the operator at the West Station can then send.

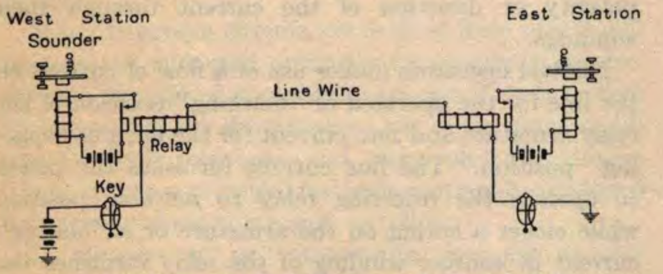


FIG. 143. ELEMENTARY NEUTRAL TELEGRAPH CIRCUIT

From Figure 143 it may be noted that **neutral transmission is that form of transmission in which the sending end "impedance" (resistance) changes from some finite value under the marking condition, to infinity in the spacing condition.**

A simple telegraph circuit of this kind might conceivably be set up in an emergency by two testboardmen, using the telegraph sets installed on the key-shelves of their respective testboard positions, for establishing quick telegraphic communication between each other. But such a layout is seldom used for practical telegraph service and if so used it is restricted to comparatively short distances. With this arrangement, the amount of current that could be sent over any of the usual types of long circuits might not be sufficient to operate the receiving relays; or the signal distortion caused by such a long line might be such as to introduce signal errors. It is necessary, therefore, to break such long circuits into "links" of shorter circuits with each link relaying the signals into the next adjacent one. Figure 144 represents a telegraph circuit similar to that shown in Figure 143 but with an intermediate relay at a central point in the circuit. This will permit the West Station to send to a much more distant East Station because the signal is re-energized at the intermediate station by a new battery connected to the contacts of the relay at that point. However, the East Station cannot send to or "break" the West Station; the circuit will work in one direction only. Under these conditions, two separate circuits between the two stations would be required to provide communication in both directions. The two-circuit arrangement is indicated by Figure 145. It involves twice the number of wire facilities and is therefore economically less desirable than a system by which equally satisfactory service could be furnished using only one wire. From the telegraph subscriber's standpoint, the class of service which it would provide would be entirely different from that given by the circuit of Figure 143 and might or might not be preferable to it. With the two-circuit arrangement, it would be possible for one subscriber to send a message in one direction at the same time that the other subscriber was sending a message in the opposite direction, provided only that there were two operators at each end of the line. In this respect the capacity of the service would be doubled. But while considerable use is made in practice of a service of this type ("full duplex"), it does not meet the needs of the majority of subscribers, whose usual communication requirements call for an interchange of messages in the manner of a conversa-

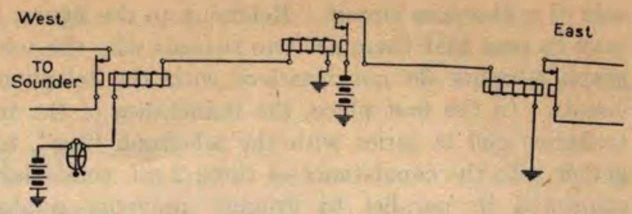


FIGURE 144

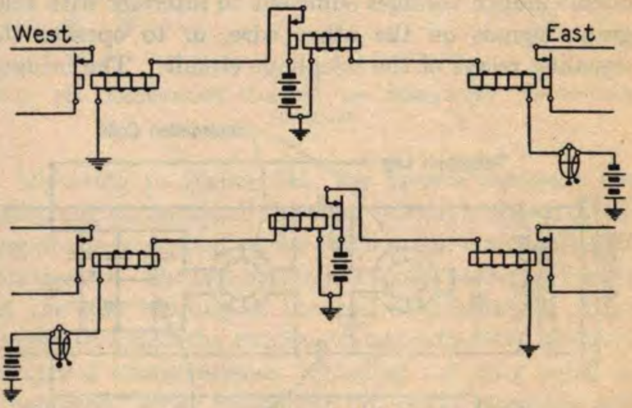


FIGURE 145

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*For the benefit of those readers who are not familiar with the American Morse Code, the alphabet and numerals are as follows: A·— B—··· C·· · D—·· E· F·—· G——· H···· I·· J—·—· K—·— L—— M — — N—· O· · P····· Q··—· R· ·· S··· T— U··— V···— W·— — X·—·· Y·· ·· Z··· · &· ··· 1·— —· 2··—·· 3···—· 4····— 5 — — — 6······ 7 — —·· 8—···· 9—··— 0——.

tion rather than for continuous simultaneous transmission in both directions.

77. The Single Line Repeater

One solution of the problem of providing two-way service over a long single circuit is the use of the "single-line repeater". The theory of this ingenious device can be best understood by studying its operating features step by step. As has been implied, it is expected to relay energy just as the relays in Figure 145 do, but its operation is restricted to a single circuit and it must permit one operator to break the other. First, let us suppose that two intermediate relays are connected into a single circuit as shown in Figure 146, with the winding of one relay in series with the contacts of the other and vice versa. Although a step in the right direction, such an arrangement is not by itself sufficient to effect the desired result. For let us assume as a test that the West operator starts to send a message to the East operator. He opens his key, which at the intermediate point lets the armature of the relay designated as R_w fall back and open the circuit east. This will result in the armature of the relay designated as R_e falling back and again opening the circuit west, which is already open at the key. If now the West operator closes his key, the relay R_w will not respond as the circuit is open at the contacts of the relay R_e. Consequently, the circuit is open in both directions and the closing of either or both keys cannot restore the contacts of the R_e and R_w relays. In order that this device shall work **it is necessary to add to each relay an additional coil so wired that its own armature will be held closed while the armature of the other relay is released, regardless of whether or not the circuit through its own main winding is open.**

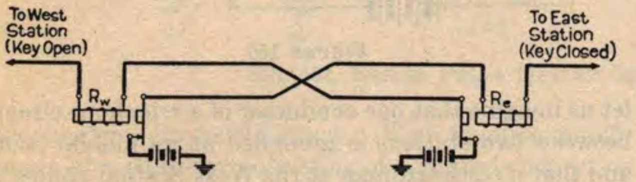


FIGURE 146

These coils are called "holding coils" and Figure 147 represents the same connections as shown in Figure 146 but with the additional holding coil features. The battery circuit for the holding coils is a local one and is not connected to the line wires in any way. It is represented by light lines to distinguish it more clearly from the main line telegraph wires. The two holding coils are in series and each line relay is equipped with an additional set of contacts that shunt the holding coil of the other relay when closed. The operation of the repeater is now as follows: As before, let us assume that the key at the west end of the line is open and that the main line contacts of the corresponding relay R_w of the repeater are open. The key at the distant end of the east line is assumed to be closed, i.e., we are assuming for the time being that a signal is being transmitted from west to east. This can now be accomplished because the holding coil of the R_e relay is not shunted and will not permit its armature to fall back and open the west line when the signal is repeated from the west line into the east line by means of the R_w relay's armature. If the East operator desires to break while the West operator is sending, he merely opens his key. As the West operator continues to send, the next signal that closes his circuit and so shunts the holding coil of the R_e relay, will render this holding coil inoperative and permit the R_e armature to fall back. Likewise if the East operator is sending to the West operator and the latter desires to break, the circuit will operate in exactly the same manner in the reverse direction.

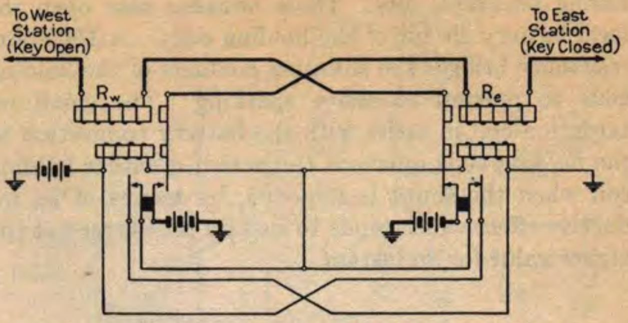


FIG. 147. SIMPLIFIED SINGLE LINE REPEATER CIRCUIT

A standard telegraph repeater set of this type is shown by Figure 148. Here a few other features of the circuit are shown that were omitted in Figure 147 for clearness. To prevent sparking at the relay contacts in the main line, each set of contacts is bridged with a 300-ohm resistance in series with a 0.5 mf. condenser. Switches are provided on the set for "cutting" the circuit, i.e., separating the line east from the line west and using the two halves of the repeater set as termi-

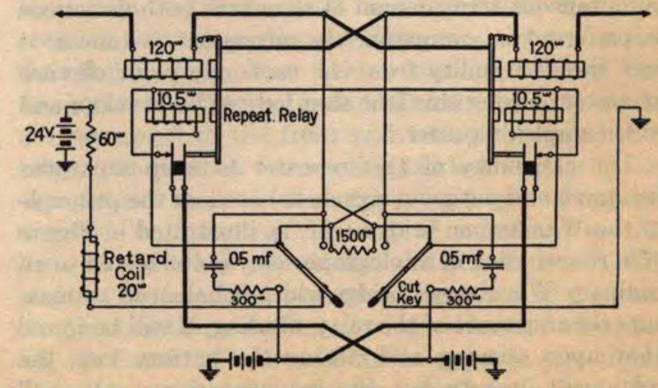


FIG. 148. STANDARD SINGLE LINE REPEATER EMPLOYING NEUTRAL RELAYS

nating telegraph sets. These switches also open the local battery circuit of the holding coils. A 1500-ohm resistance bridges the shunting contacts of the holding coils to prevent excessive sparking. The small retardation coil in series with the battery connection to the holding coils quickens the action of either holding coil when the shunt is removed, by means of its inductive effect which tends to sustain the current at the higher value for an instant.

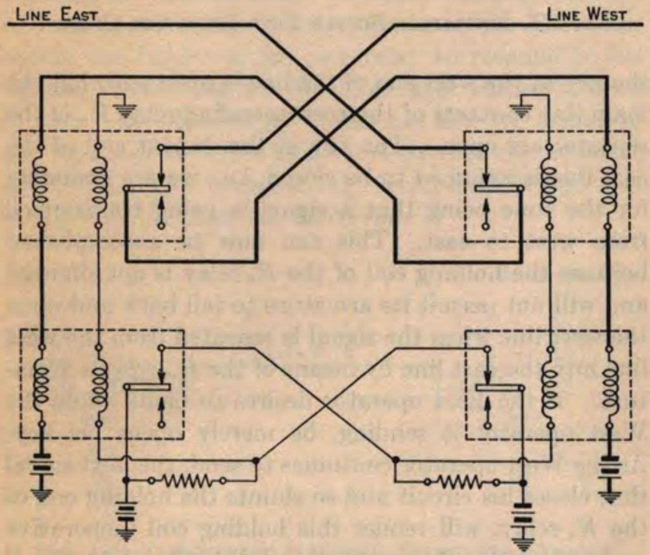


Fig. 149. Single Line Repeater With Polar Relays

Another design of single-line telegraph repeater is illustrated by Figure 149. In general principle it is not radically different from the set that we have been discussing but it employs "polar relays" instead of neutral relays. Its operation will be better understood after studying the discussion of how relays of this type are used in differential duplex systems as given in Article 81.

78. Principle of Polar Duplex Operation

While a type of telegraph service that permits the simultaneous transmission of signals in both directions is preferred in comparatively infrequent instances, it was the desirability from the economic point of view of accomplishing this feat that led to the development of the duplex repeater.

The capability of this repeater to keep separated incoming and outgoing signals is based on the principle of the Wheatstone bridge. If, as illustrated in Figure 150, the winding of a telegraph relay is connected to an ordinary Wheatstone bridge which is balanced to measure the resistance of the relay winding, it will be found that upon opening and closing the battery key, the relay will operate but the galvanometer needle will remain stationary because the bridge is balanced. Now let us imagine that one conductor of a telephone circuit between two stations is grounded at its middle point and that a testboardman at the West Station connects his Wheatstone bridge to the circuit to locate the ground by the Varley method. Further, let us suppose that the testboardman at the East Station instead of crossing the circuit for this test, connects his Wheatstone bridge to the circuit at the same time in order to locate the ground from his end. The connections will then be those shown in Figure 151. When the testboardman at the West Station adjusts the value of the variable resistance in his bridge to equal that of the line and the East Station bridge considered together as a complex network, the bridge will be balanced and no current will flow through the west galvanometer due to the battery at that station.

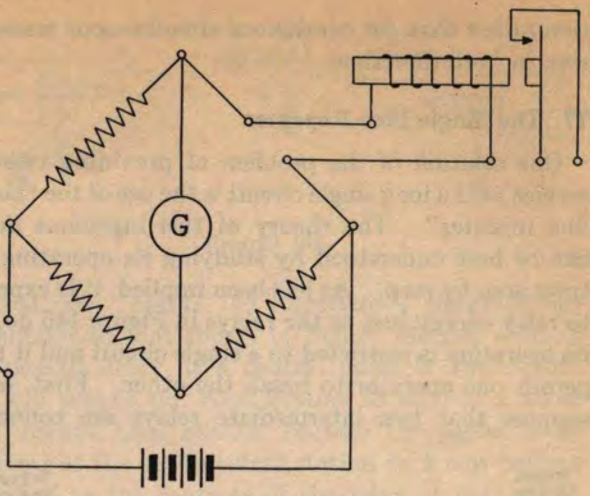


Figure 150

It is furthermore conceivable that the East Station testboardman might at the same time balance his bridge. Then, with the battery keys closed at each station, a current will flow in the East Station galvanometer due to the West Station battery and an equal current will flow through the West Station galvanometer due to the East Station battery, but no current will flow in either galvanometer from the battery at the same station. If either bridge battery key is opened, however, this condition will be upset because opening the key at one station will destroy the balance at the other and result in current flowing through its galva-

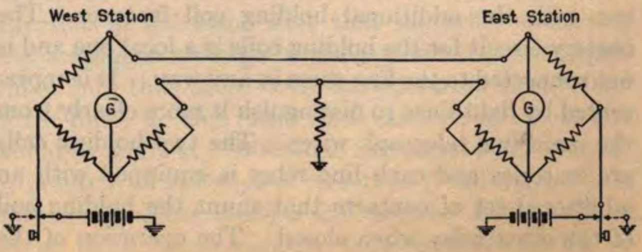


Figure 151

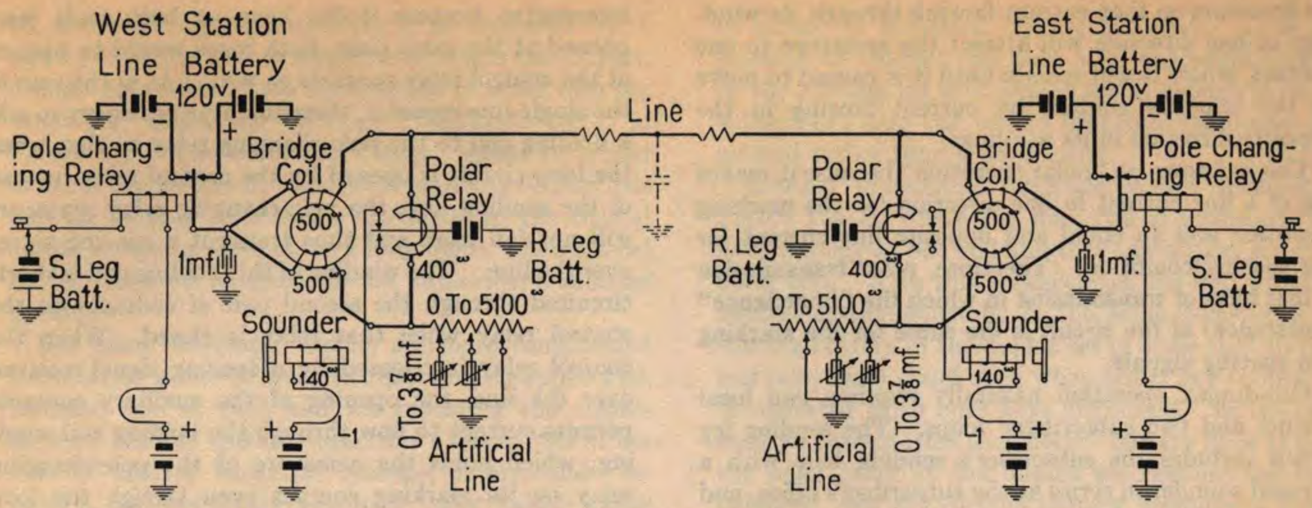


FIG. 152. BRIDGE POLAR DUPLEX SETS ARRANGED FOR FULL DUPLEX SERVICE

nometer from the local battery. With a simple modification of each bridge consisting of a ground connection to the back contact of the battery key (which will not interfere with its use as a bridge), balance will be maintained regardless of the position of the battery keys and the current in either galvanometer will be the same when the associated battery key is open as when it is closed. But opening the key at either station will cause the galvanometer current at the other station to fall from some finite value to zero.

Thus with the two bridges balanced, we have a condition where each station has control over the galvanometer at the other station but has no control over its own galvanometer. Consequently, the battery keys at both stations may be opened and closed at the same time and the operation in one direction will not interfere in any way with the operation in the other direction. It follows that if the galvanometers are now replaced with sensitive relays, and telegraph keys are substituted for the battery keys, the two stations can transmit telegraph messages to each other simultaneously. As in the arrangement pictured in Figure 145, however, one station can break the other only by sending a special break message over the channel transmitting in the opposite direction. The service provided by such a circuit arrangement is called "full duplex". Figure 151 illustrates the principle of the duplex system of operation; but in practice, instead of employing two line wires with a ground at the midpoint of one, the second or defective wire is replaced with an artificial line to ground at each station. These artificial lines take the place of the variable arms of the Wheatstone bridges as well as the resistance of the grounded wire.

79. Bridge Polar Duplex Systems

Figure 152 is a simplified schematic drawing of a telegraph circuit equipped at each end with a "bridge polar" duplex set arranged for full-duplex service. Here are shown the more fundamental modifications that adapt the Wheatstone bridge principle to practical telegraph service. Instead of the bridge arms consisting of simple non-inductive resistances, the two balanced windings of a retardation coil are employed. Each winding has a resistance of 500 ohms and an inductance of three to four henrys, but the two windings in series, i.e., considered as a shunt around the bridged receiving relay, have a very much larger inductance. The artificial line consists of a 0–5100-ohm rheostat variable in steps of 10 ohms which can be grounded, first, directly at any point, thereby simulating the resistance of the line grounded at the distant end or through any intermediate shunt leakages; and second, through two variable capacities at two other points, thus simulating the capacity of the line wire to ground. Together the adjustments are such that the artificial line may be made almost identical electrically to the actual line with another set at its distant end.

The telegraph key, instead of being inserted in the main battery connection to the bridge, is placed in the local "sending leg" circuit which includes the subscriber's transmitting loop and the winding of a "pole-changing" relay. The current transmitted over the line is furnished by batteries of opposite polarity which are connected to the front and back contacts of this relay. Thus when the sending leg key is closed, the armature of the pole-changing relay is pulled up and negative or "marking" battery is connected to the line; with the key opened and the armature released, positive or "spacing" battery is connected to the line. Accordingly there is a flow of current during both spacing and marking intervals, but in opposite directions. This requires that the receiving relay be polarized, i.e., that it have a split magnetic circuit completed through its armature so that current flowing through its windings in one direction will attract the armature to one contact, where it will remain until it is caused to move to the opposite contact by current flowing in the opposite direction in its windings.

This is known as "polar operation" because it makes use of a line current in one direction for the marking condition and an equal and opposite line current for the spacing condition. Therefore, **polar transmission is that form of transmission in which the "impedance" (resistance) of the circuit is the same for the marking and spacing signals.**

Full-duplex operation naturally requires two local circuits and two subscribers' loops. The sending leg circuit includes the subscriber's sending loop with a key and sounder in series at the subscriber's office, and a key and the winding of the pole-changing relay at the duplex set. Two batteries poled to aid each other are connected to the two ends of this circuit. Similarly the "receiving leg" circuit, which is connected to the operating contacts of the receiving polar relay, contains a sounder at the duplex set and a sounder and key at the subscriber's end of the receiving loop. As in the case of the sending leg circuit, grounded batteries aiding are connected to the two ends of the circuit.

The bridge polar duplex set may also be used as a "half-duplex" repeater on an "ordinary" telegraph circuit where the simultaneous transmission of messages in both directions is not desired, providing that a feature whereby one operator may break the other is incorporated. In practice any standard set may be quickly converted from a full-duplex to a half-duplex repeater, or vice versa, by the operation of certain switches. When arranged for half-duplex service, the essentials of the circuit are as shown in Figure 153. Here there is naturally only one loop to the subscriber's station since he will never be sending and receiving at the same time. The winding of the sending relay is connected in series with this loop as it was in the sending loop of the set when arranged for full-duplex service, but the receiving leg circuit instead of being connected into the loop, is connected in series with the winding of an additional relay known as the "control relay". One of the two sets of contacts with which this relay is equipped is in series with the loop. Received signals cause the operation of the receiving polar relay, followed by that of the control relay, which in turn opens and closes the loop in accordance with the incoming signals. For sending, the subscriber opens and closes the loop with his key which, assuming the control relay to be operated as a result of the key at the distant end being closed, operates the pole-changing relay and connects positive or negative battery to the line.

Under these conditions, however, and without any additional features, the circuit would be practically inoperative because if the keys at both ends were opened at the same time, both loops would be opened at the control relay contacts as well. As in the case of the single-line repeater, therefore, it is necessary to add a holding coil to the pole-changing relay so that when the loop circuit is opened by the control relay instead of the sending key, the pole-changing relay armature will not fall back and thus transmit a spacing signal over the line. The winding of this holding coil is short-circuited through the second pair of contacts on the control relay when that relay is closed. When the control relay is released by a spacing signal received over the line, the opening of the auxiliary contacts permits current to flow through the holding coil winding, which holds the armature of the pole-changing relay on its marking contact even though the loop circuit through its main winding is open.

Thus when a subscriber is receiving and has his key closed, the pole-changing relay will be held steadily on its marking contacts, while the loop is opened and closed at the control relay in accordance with the incoming signals. Now if this subscriber wishes to break, he opens his key. If at that instant a spacing signal is being received, this will have no effect because the loop is already opened at the control relay contacts and the pole-changing relay is held operated by the holding coil. But as soon as the distant station sends a marking signal, the holding coil windings will be shunted out and the pole-changing relay will release, thus transmitting a spacing signal back over the line to stop the distant station from sending. If the distant station happens to be sending a series of rapid dots when the near station breaks, the action of the control relay armature may be so rapid that the armature of the pole-changing relay will not have time to fall back during the short intervals that the holding coil winding is shorted out. To insure positive breaking action in such a case, an auxiliary pair of contacts on the pole-changing relay are provided and connected in series with the winding of a "repeating sounder". Then even though the control relay is not closed long enough to allow the armature of the pole-changing relay to fall back to the spacing contact, it will at least leave the marking contact, which will open the circuit through the repeating sounder, causing it to release. The release of this sounder short-circuits the contacts of the polar receiving relay thus locking up the control relay, which results in the pole-changing relay armature moving to the spacing contact and so transmitting the break signal.

Thus far we have considered the duplex set circuit only as a terminal set for repeating signals between a line wire and the subscriber's loop. At the terminal points, as we have seen, the subscriber's loops for full-duplex service are connected in series with the sending leg and receiving leg respectively, as indicated by *L* and L_1 of Figure 152; or when the service is half duplex, a single subscriber's loop is connected in series with the single leg, called the "dummy", indicated by *L* in Figure 153. The subscriber's loop consists of a pair of cable conductors or other local subscriber's facilities and all battery connections are made in the central office (except in cases of very long loops, when a local battery may be required for the subscriber's sounder circuit).

But many telegraph circuits are more complicated than merely a wire between two stations, equipped with terminal sets at each end for repeating the signals between the line and the subscriber's loops. As in the case of neutral telegraph systems, intermediate repeaters are frequently required. Any bridge polar duplex set can be used as half of an intermediate repeater. When so used for full-duplex service, it is only necessary to connect the sending leg of one set to the receiving leg of the other set and vice versa as illustrated by Figure 154-A. The half-duplex repeater, on the other hand, is made up by connecting the sending legs of the two sets in series as shown in Figure 154-B. In half-duplex service it frequently happens that the layout consists of a number of branches radiating from certain repeater points, instead of a single direct circuit between two stations. In this case it is necessary for all of the sets connected to branch lines at any one station to have their sending legs connected in series, as indicated by Figure 154-C. It is also possible to connect one side of a single-line repeater to the sending leg of a duplex set as though it were a subscriber's loop and work a branch of the layout on a neutral rather than a polar basis.

Another practicable telegraph layout is shown in Figure 154-D, where the line wire is connected to a neutral relay at one end and to a half-duplex set at the other end. With this arrangement the battery at the neutral station must be of the same polarity as the spacing battery of the duplex set in order that the neutral relay shall stand open when either key is open and be operated when both keys are closed. In the latter case, no current from the "home" battery flows through the polar relay at the duplex set because the set is balanced, but the distant battery produces a flow of current in the polar relay in such a direction as to hold its armature to the marking contact. When the key at the neutral station is opened, the duplex set balance is "upset" and current from the home battery flows through the polar relay in the opposite direction, causing the armature to move to the spacing contact.

It is not only possible to operate a neutral station in conjunction with a half-duplex set in the manner just described, but also at an intermediate point on a circuit equipped at both ends with a half-duplex set, as illustrated in Figure 154-E. It is necessary for such operation, however, that the marking and spacing batteries at one of the duplex sets be reversed in order that there

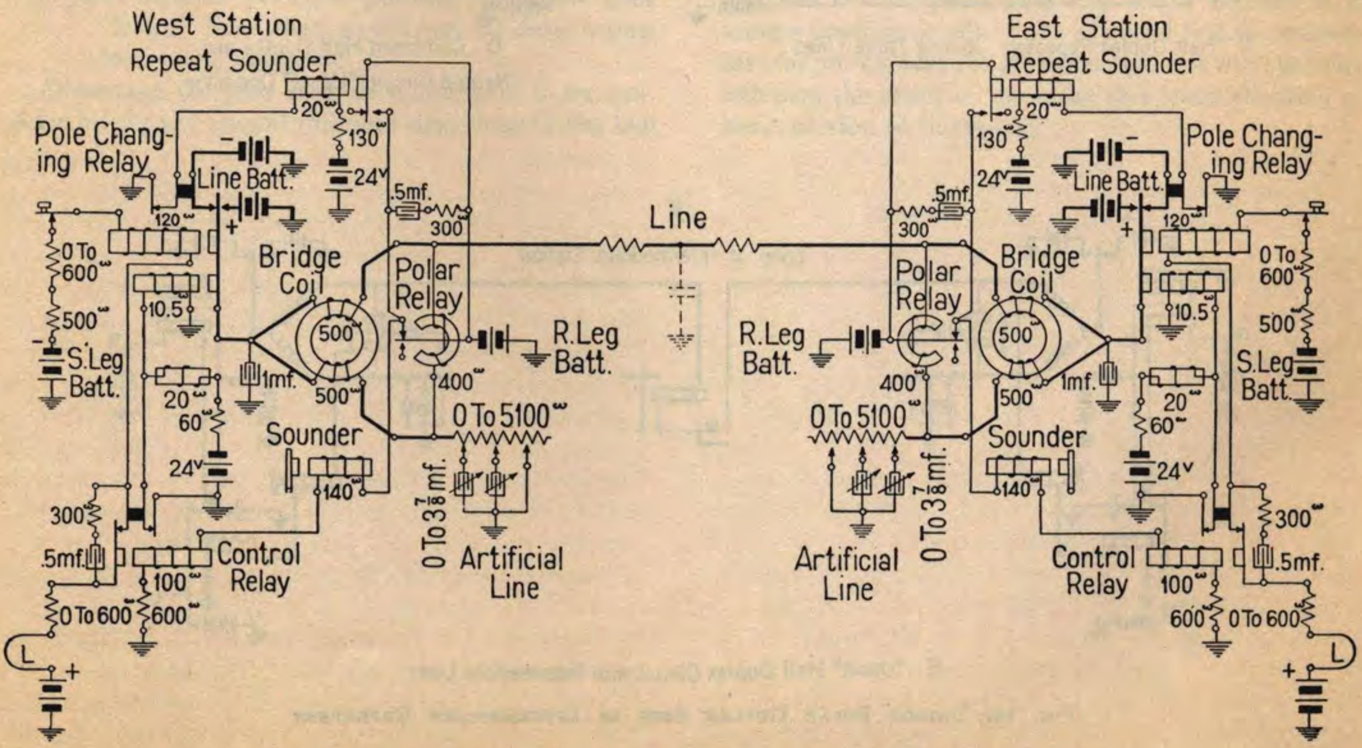
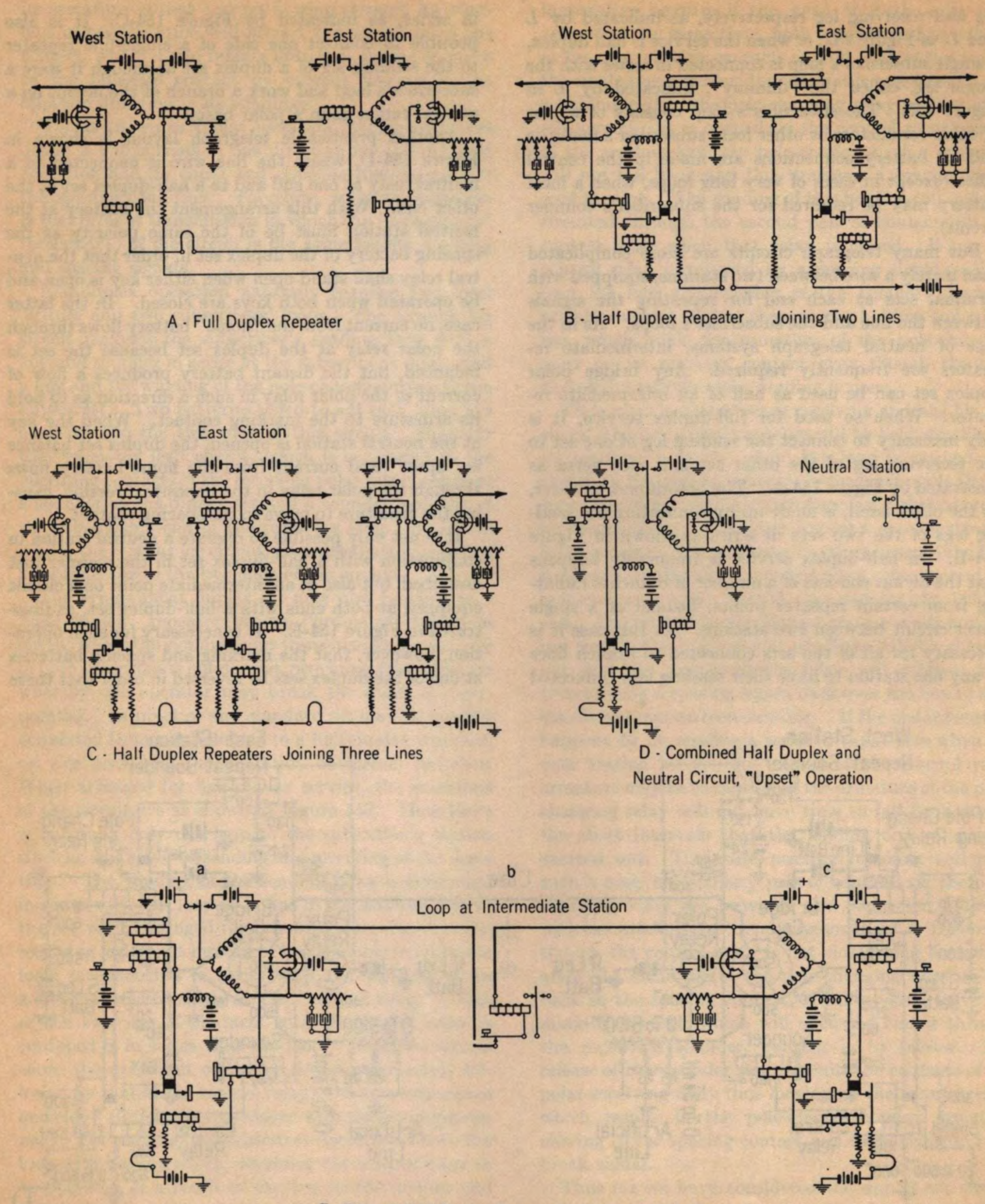


FIG. 153. BRIDGE POLAR DUPLEX SETS ARRANGED FOR HALF DUPLEX SERVICE



A - Full Duplex Repeater

B - Half Duplex Repeater Joining Two Lines

C - Half Duplex Repeaters Joining Three Lines

D - Combined Half Duplex and Neutral Circuit, "Upset" Operation

E - "Upset" Half Duplex Circuit with Intermediate Loop

Fig. 154. Bridge Polar Duplex Sets as Intermediate Repeaters

shall be current in the line to hold the intermediate neutral relay closed when the keys are closed at both duplex stations. When either duplex key is opened, the current in the line is reduced to zero because batteries of like polarity are then connected to the line at each duplex set. The neutral relay is accordingly released. When sending from the neutral station, opening the line circuit upsets the balance of both duplex sets, thereby causing both receiving relays to operate to the spacing position.

80. Advantages of Half Duplex Over Neutral System

Since in half-duplex service messages are sent in only one direction at any one time, and this same type of operation is provided by neutral systems, it is natural to inquire why the latter, requiring less equipment, should not be used exclusively. Upon analysis it will be found that half-duplex operation has several marked advantages over neutral operation, the more important of which are briefly as follows:

a. The same set can be used for either full- or half-duplex service, thereby making for maximum flexibility in office layout and keeping the total number of sets at a minimum.

b. The transmission of current for spacing gives the effect of increased voltage without increasing the current values in any part of the apparatus or subjecting the circuit to high working voltages that might be unsafe.

c. The balance principle permits operation over "leaky" lines that would not be satisfactory for neutral operation.

Advantage (b) may best be understood if we consider briefly the magnitudes and directions of the line currents for the two methods of operation. In neutral operation the nominal line current for the marking condition is in the order of 60 milliamperes, and of course, zero current for the spacing condition. As the half duplex operates on a polar basis, the line currents for the marking and spacing conditions are in the order of 30 milliamperes, but flow in opposite directions depending upon whether a mark or space is being transmitted. Therefore, in effect the magnitude of the line currents in the half duplex are only half that in the neutral circuit. Incidentally, it will be noted after studying Articles 91 and 93 of Chapter XIII, covering both neutral and polar "wave shapes", that certain circuit conditions change the signal length during transmission on neutral circuits but have no effect on polar circuits.

For an explanation of (c) above we may refer to Figure 179 of Article 91. If here the East Station is sending to the West Station, there will be a definite current through the shunt, *S*, and the West Station relay while the key at the East Station is open. This tends to keep the relay energized all of the time and requires that it be so adjusted that its normal release current is appreciably greater than the current that flows as a result of the shunt. In other words, each relay when receiving must work as a "marginal" relay, which makes it very difficult to keep in adjustment when the value of the leakage resistance to ground is varying with changing weather conditions, etc. In half-duplex operation there are no such limitations imposed on the polar receiving relays because it is always possible to adjust the artificial line to compensate for normal leaks to ground on the line wire, thereby reducing the effect of the leaks to a mere shunting of some portion of the energy.