ELECTRICITY AND MAGNETISM

IN

TELEPHONE MAINTENANCE

BY

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PREFACE.

In the daily routine of a man engaged in the practical application of an industry which is growing and changing as remarkably as is telephone work, new questions are constantly arising. The cause of a peculiar case of trouble, or the possible relationship between different cases; the reasons for certain behavior of apparatus; in short, the constant recurrence of the everlasting Why which Man's intelligence was created to solve, and ever to keep on solving; this it is that makes the work perennially fascinating and elevates it to the dignity of a life study.

The experience of the author, like that of every telephone man, has been a continual tackling of these every day problems, and the answers and methods given here are offered in the hope of helping others who are wrestling with them. The methods employed are those of the practical man rather than of the student, and differ materially, in many cases, from those given in the text books. For example, the subject of loaded cables is handled in a purely analytical manner, entirely devoid of mathematics. These methods are, in the main, those which experience in instructing repairmen and installers has shown to convey the clearest idea of the subject to one who is more familiar with apparatus than with principles; and the book is, in fact, largely an elaboration of lectures given in that instruction.

Acknowledgment is due to Mr. R. M. Bennett and other friends in the practical work for suggestions and other valued assistance in its preparation.

G. W. Cummings.

Chicago, Ill., October, 1908.

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CHAPTER I.

INTRODUCTION.

The mastering of a trade or profession may be approached by either one of two radically different paths. The methods of study and work differ correspondingly. If, through choice or force of circumstances, we have taken the so-called "practical" path, we have familiarized ourselves first with the appearance and makeup of the apparatus and material used and have found out by observation and, to a limited extent, by experiment, that certain effects are apparently caused by certain changes in conditions. For example, we find that adjusting the armature of a pair of ringers or of a relay farther from the coil weakens its action. In the course of time we have in this manner accumulated a stock of experience and in clearing a case of trouble or designing a circuit will probably be able to find in our memory a case or circuit sufficiently similar to guide us to its solution. Unless we have learned to systematize our data, and by analyzing it find the general principles which are common to seemingly unrelated phenomena, we have not made the best possible use of it and are comparatively helpless when confronted with a case not exactly covered by previous experience.

If, on the other hand, we have taken the "theoretical" path, we have learned, chiefly at second hand, the so-called natural laws and fundamental principles upon which we are accustomed to say that all phenomena depend; we have learned to use the theory and the working hypothesis, and to take advantage of many short cuts and of many time and labor saving methods, mathematical and otherwise.

From this point of view the actual phenomenon, instead of being the matter of chief interest, becomes merely an index to the underlying principle, and an experiment or observation is simply "a question put to nature." On our ability to read her answer correctly, depends, to a very great extent, our advancement theoretically.

Herein, however, lies the weakness of the purely theoretical man. He has learned abstract principles rather than concrete phenomena; he is, of necessity, more familiar with hypothesis than with apparatus; and, when placed in the actual work, is apt to find difficulty in applying theory to the countless forms of apparatus and to the many phenomena in which natural law finds expression, and in acquiring the dexterity which marks the good workman and which comes only with experience.

The object sought by both paths is the same, that of mastering a certain branch of the world's work. Each has its disadvantages and the students of each have, to some extent, misunderstood and underestimated the nature and importance of each other's method. A combination of the essential elements of both is necessary to success in our chosen vocation. It is in the hope of at least pointing a way to this combination of theory and practice, so far only as it concerns our work, that this is written.

Science has been defined as "classified knowledge." The original investigator collects, by observation and experiment, sufficient data which have evidently a common basis to justify him in assuming that certain conditions will always produce certain results. If there is no conflict between this and the body of previously developed knowledge he announces his conclusion as a working hypothesis; not as a definite, unquestioned, truth but as a provisional guide and index to phenomena, to be proved or disproved by weight of evidence as our knowledge advances. The distinction between hypothesis and theory is essentially one of degree rather than of kind. A theory is a hypothesis which has so far fitted all observed phenomena and is thus so strongly supported by the evidence as to be generally accepted.

The distinction between theory and natural law is somewhat vague. In general, a natural law may be defined as a statement of well ascertained facts and sequences, or of definite uniformities in nature. For example, Newton noted the fall of an apple to the ground. Comparing this with similar observed facts he found a general statement which fitted them all, and announced the hypothesis of gravitation, which has been amply proven to be a law by its demonstrated ability to fit all conditions. This may be taken as a typical instance of the evolution, not of natural law, for that is a fixed fact in nature, independent of our individual consciousness, but of our comprehension of it.

The hypothesis, incomplete as it is, has still another use. It may be disproved as a statement of actual fact while still of great assistance to us in special cases. If a given class of phenomena act as if a certain hypothesis were true then it is often allowable to consider it true for the time being, so long as we do not go beyond the limits of that given class, instead of using a more complicated statement which, while it might be nearer the actual truth, would be less convenient and of no more assistance in that particular case. In this way we often use the old exploded single and double fluid hypotheses in electricity. It is needless to say, however, that the utmost caution must be exercised in this, and the results carefully checked.

We are accustomed to say that we have explained a phenomenon when we have found under what natural law it comes. What we really mean by this is that we have classified it among a multitude of other more or less familiar cases, all of which have the same general underlying sequence of cause and effect. Herein lies the practical value of the theory, in reducing the number of so-called "ultimate facts" to the lowest possible number, thus lessening the burden on the memory and training us to analyze our cases, bring them under the general classifications to which they belong and in that way compare them with familiar cases, the behavior of which is well known to us.

We often hear the statement that electricity is mysterious and elusive beyond all other natural agencies and cannot be handled in accordance with fixed rules. This statement is not only entirely erroneous, but is confusing and discouraging. It is true that we do not know what electricity is, but it is also true that we do not know what matter is, what force is, or even whether these things have any separate existence of their own aside from mind. What we do know, and all that—for our purposes—we need to know, are the general rules and formulas in accordance with which they manifest themselves; and in no other branch of physics have we so full and exact a code of natural law as in electricity. The confusion of thought and consequent inaccuracy of work which has resulted from this misstatement form our excuse for mentioning it here.

A prime essential to accurate work is definite standards of measurement, and in this we have a system ideal in its simplicity and convenience. The unit of quantity, which corresponds to the gallon or cubic foot in liquid measure, is the coulomb. This, while not in everyday practical use, forms a convenient starting point and a basis to which the others may be referred. It is the quantity of electricity which, under proper conditions, will deposit 0.017253 grains of metallic silver from a solution of silver nitrate.

To state the amount of current or flow in a stream of water we have recourse to the somewhat clumsy expedient of a unit which combines in its expression standards of both cubic measurement and time, the unit being a flow of one cubic foot per second. In electricity we use the single word "ampere" to cover the same ground, it being a flow of one coulomb per second. As the volume of current in a telephone circuit is very small we usually divide the ampere into thousandths, or milliamperes.

In computing the pressure back of a stream of water, causing it to flow, we again use a wordy unit and speak of a pressure of a pound per square inch, while in electricity we use the more convenient term "volt."

When we come to resistance, ordinary mechanics, clumsy on the other two units, fails to give us any unit at all, while in electricity we can take a length of wire or any conducting substance whatever and know that it will offer a certain definite obstruction to the passage of electricity, and a resistance which requires a pressure of one volt to force a current of one ampere through it we call an "chm."

In measuring a water tank we speak of it as having a capacity of so many cubic feet. Similarly, in electricity we speak of a condenser as having a capacity of so many farads and a condenser of one farad capacity will hold one coulomb at a pressure of one volt. In practical use this unit is extremely unwieldy and is hence usually divided into millionths, or microfarads.

The other units belong rather to the laboratory than to the telephone exchange and need not interest us at present. As a graceful tribute to the early investigators, the name of each unit is derived from the name of some student prominent in the development of the science. For example, Ampere was a French scientist to whom electrical research owes much, the farad is named from Faraday, etc.

Among the many labor saving methods which science has furnished us there are two with which it is essential that we become familiar; the use of the formula, and the graphical or curve method of representation. The formula bears much the same relation to the figures in each individual problem that the natural law does to the statement of events in each phenomenon. For example, a lighting circuit carrying six lamps takes three amperes, while one with ten lamps requires five. By representing the number of lamps in the first case by the letter L and in the second by l, while A represents the amperes in the first and a those in the second, we have the formula $\frac{A}{a} = \frac{L}{l}$, which would be read A is to a as L is to l, or, A divided by a equals L divided by l. Writing it out in the form of a rule we have, " The number of amperes in a lighting circuit is proportional to the number of lamps connected to it." Another way of developing this formula would be as follows: If six lamps take three amperes, one lamp will take one-sixth of three or one-half ampere. Ten lamps will evidently require ten times this or five amperes. Expressing it in general terms, if L lamps take A amperes, one lamp will take $\frac{A}{L}$ amperes (A divided by L). Then l lamps will require l times this, or $a = l\frac{A}{L}$, the same formula as before, although arranged somewhat differently. The corresponding rule would be, " The number of amperes in a lighting circuit equals that through one lamp, multiplied by the number of lamps."

To find the current required for any number of lamps by using this formula, we would substitute the known figures for three of the letters, and then, knowing the values of A, L, and l in the formula, it is a simple matter of arithmetic to find a.

The curve, like the formula, is a method of representing by symbols the figures found in any individual case or class of similar cases and is invaluable to us because it shows at a glance the varying conditions, which we would otherwise have to go through a mass of figures to find. It is usually drawn or " plotted " on paper closely ruled with vertical and horizontal lines, the vertical lines, counting from left to right, representing, for example, time, while the horizontal, counting from bottom up, represent quantity.

Fig. 1 is a traffic curve and is plotted from an actual count of the number of calls per hour in a residence exchange between 4 a.m. and midnight. The vertical lines represent the hours as marked and the horizontal lines the number of calls. To find the number of calls at, for example, 9 p.m., we follow the vertical line representing that hour until we reach the curve, which in this case we do at the horizontal line which, according to the figures at the left of the drawing, represents 3000 calls. The curve shows at a glance the variations in the load during the day, starting from almost zero at 4 a.m., increasing gradually to 7 a.m., rapidly to 8, more gradually until it reaches nearly 9500 between 9 and 10, falling to 5800 about 12.45, rising somewhat during the afternoon, falling to 4500 at 6:30, rising sharply to 7400 at 7:30,

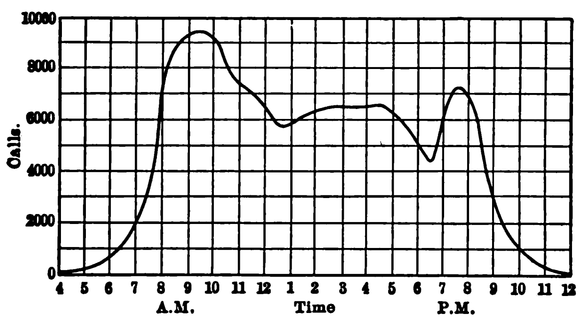

Fig. 1.

thence falling in a regular curve, nearly to zero at midnight. It is evident that this conveys a much clearer idea of traffic conditions to the mind and is of much more practical use to us than the array of figures from which it was drawn. The curve of street car traffic, of the load on an electric light plant, of the voice current, of the efficiency of an engine, generator, or motor, etc., would be the same in principle although of course differing in shape. Where it is desired to represent a reversal of conditions as in alternating current the horizontal base line is placed at the center of the page and current in one direction represented by a curve above and in the opposite direction by one below it. Science has given us no working tool of more general utility than this, and we will have frequent occasion to use it in succeeding pages.

Questions.

1. State the distinction between hypothesis and theory.
2. State a natural law, other than the law of gravitation.
3. State the electrical units commonly used in practical telephone work.
4. How many grains of silver will be deposited by a current of five amperes existing for one minute?
5. If ten incandescent lamps connected in the usual manner use five amperes of current, how many amperes will seven lamps require? Work out in full, using formula on page 6.

CHAPTER II.

CURRENT.

For practical purposes the electrical current may be most simply considered as a form of energy which is readily derived from other forms and is as readily converted into them, thus enabling us, first, to transmit energy from one place to another, or, second, to convert it more conveniently and more effectively than by direct mechanical connection. Work is done at one place, either in setting up a current or in modifying one already flowing, and this work can be recovered by properly designed apparatus at some other place. As an example of the first application, it is impossible to transmit sound waves mechanically more than a short distance, but we can, by means of a telephone transmitter, convert them into electrical waves, convey these through a wire to almost any distance desired, and there, by passing them through a receiver, convert them back into sound waves.

As an example of its second use, we can, by means of the electrical current as an intermediary, convert the chemical energy latent in a battery or in a coal pile into the light of an arc or incandescent lamp.

Its flexibility and efficiency, and the ease with which it may be transmitted and converted, make the electrical current an indispensable factor in modern civilization, and form the basis for the oft-repeated assertion that electricity is "the force of the future." The importance to us, then, of a general knowledge of its laws and its behavior under varying conditions is obvious.

The first essential to intelligent study of current is a correct idea of values or of measurement. If we lead two wires from the terminals of a battery into acidulated water or a solution of copper or zinc sulphate or silver nitrate, forming a voltameter, and connect in series with it a galvanometer, an electromagnet, and a piece of fine wire; we will find a certain amount of chemical decomposition in the voltameter, a deflection of the needle of the galvanometer, an attractive force exerted by the electromagnet, and a heating effect in the fine wire. If we increase the strength of the battery, these results will be increased, but not at all in the same ratio. If the chemical action in the voltameter is doubled the deflection of the galvanometer and the pull of the electromagnet may be either more or less than doubled while the heating effect on the wire will be much more than doubled. To determine which result is an accurate indication of the proportional change in current strength, we may add a second set of apparatus of totally different shapes and designs, and we will find that the chemical decomposition is the only effect which shows the same value in the two sets of apparatus, irrespective, within wide limits, of variations in shape, size, or design of the apparatus. Chemical decomposition, then, is the only one of these different methods of measurement which furnishes us, at least without elaborate precautions and calculations, with a definite and uniform standard, and we can say that an ampere of current, or a flow of one coulomb per second, will, for example, always deposit 0.017253 grain of silver per second. With this as a standard we may take a properly designed galvanometer, find, by comparison with a silver voltameter, the actual values of its deflections, and by marking its scale accordingly we have an ampere meter, or, more briefly, an ammeter, which will tell us at a glance the amount of current in the circuit to which it is connected. As a rough approximation to the value of our unit, an ordinary sixteen candlepower 110-volt lamp takes about one-half ampere.

The average transmitter current in common battery exchanges is about 100 milliamperes or 0.1 ampere, varying from something over 200 on very short lines to 30 or 40 on long ones. The latter amount is, of course, too low for the best transmission, although transmission is by no means proportional to the amount of current, but depends on the fluctuations set up in the current by the transmitter. This difficulty is somewhat aggravated in branch exchange work, both from the fact that our branch exchange battery is, when charged from the office battery, several volts lower, and because of varying conditions in the retardation coil cord circuit. As we use the transmitter current for both talking and signalling, it is important to keep it up, and this is accomplished, where necessary, by various methods of boosting. The plan now most commonly followed is to increase the electromotive force, and methods for accomplishing this will be considered under electrical pressure.

Current has assumed added importance to us since the adoption of the current method of relay adjustment. The strength of an electromagnet depends, other things being equal, on the number of ampere turns, that is, on the number of amperes through its winding, multiplied by the number of turns of wire around the core. If we double the current we approximately double—within certain limits depending on the carrying capacity of the wire and the amount and quality of the iron—its attractive force. The standard adjustment of all our battery relays is obtained by cutting in series with them a milliammeter and variable resistance, adjusting the current by varying the resistance until the milliammeter shows the value desired, and then adjusting the relay on that current, using three different current strengths called operating, non-operating and releasing. The relay is adjusted to pull up on the first, not to pull up on the second, and, when pulled up, to fall back when the current is reduced to the third.

Trip relays used to cut off the ringing on trunks when the called subscriber answers by operating on the increase in the amount of ringing current when the receiver is taken off the hook, are still adjusted by the old resistance method on account of the difficulty of measuring this type of current accurately with an ordinary direct current milliammeter. A trip relay is adjusted not to operate when ringing through a certain resistance and then to operate when this resistance is reduced to a certain point, allowing more current to pass through it.

The chemical effects of a current, valuable as they are to us in some respects, are very much of a nuisance in others. The same action which causes one plate of a copper or zinc voltameter to be eaten away while the other increases in weight, corrodes our water and gas pipes and ground wires. In general it may be said that when water or any damp material forms part of the circuit the positive pole will be eaten away where the electricity leaves it, the metal being dissolved and going with the current. This is one reason why, in common battery circuits, the positive pole of the office battery is nearly always grounded, the negative going to line, in order that, when a line is grounded at a subscriber's station, the direction of the current will always be from the ground to the line, preventing any corrosion at the ground connection.

Loose connections are a bugbear in all electrical work, but especially where dampness is present, as electrolysis sets in and corrodes the wire.

Cables are especially subject to this trouble, as they are largely underground and hence exposed to stray currents of every description. The principal damage is caused by return currents of street railway systems which, straying from the rails, find a convenient path along the cable armor and corrode it where they leave it. This is minimized as much as possible by careful bonding, either to adjacent cables, to the track circuit, or to a local ground, the object being in all cases to prevent a flow of electricity from the cable armor into the damp earth.

One of the most valuable and at the same time most dangerous of electrical phenomena is the heating effect of the current. Theoretically a current always produces some amount of heat in all parts of the circuit, although in many cases the heat is too slight to be detected by measuring instruments. Familiar examples of the utilization of this effect are the arc and incandescent lamps, the soldering iron, the street car heater, etc. Equally familiar are the disastrous fires often caused by defective wiring, and the burned out windings in our relays, receivers and induction coils caused by a heavier current than the wire can carry.

The simplest method of guarding against overheating is to insert a short wire or strip of some easily fusible metal, which will heat up and melt, opening the circuit, before the current reaches the danger point. Fuses are put up in a large number of different designs and are rated according to the amount of current they can safely carry. It is impossible, however, to manufacture a fuse which will give uniform results under all conditions, and fuses, especially in the smaller sizes, will usually carry considerably more than their rated capacity before operating and often allow a momentary rush of current which may do serious damage. For this reason it is important not to over-fuse, or use a fuse wire which will carry more current than the circuit it is expected to protect.

Although not minutely accurate, the fuse is sufficiently so to serve the purpose of protection in most cases. In specifying the size to be used in each case the circuit is gone over, the carrying capacity of the weakest point determined, and a fuse decided upon whose capacity is well below this point. On a fuse board using several different sizes as, for example, those in our exchanges, it is of the utmost importance that the specifications be followed strictly, as the danger of fire incurred by any variation from instructions is great.

Where greater accuracy is required, or where for any other reason a fuse is undesirable, two other methods of protection are in extensive use. For heavy currents, a circuit breaker is often used, operating in a very similar manner to a trip relay. It consists of a solenoid or electromagnet attracting an iron armature, which is held back by a weight or spring until the current reaches a certain point, when it pulls up and strikes a trigger. This in turn releases a switch, which is thrown open by a spring. The circuit breaker is a very accurate and reliable piece of apparatus, and is convenient as it can be restored simply by closing the switch. Although somewhat expensive it is extensively used in power circuits, as for example, in the charging leads on telephone power boards.

When the current is too small to be effectively cared for by either a fuse or a circuit breaker a heat coil is the general standard for protection. This as a rule grounds the line instead of opening it. Like the others, heat coils assume in practice a multitude of widely varying forms, all depending on the same principle and consisting essentially of a small pin held in a thin metal tube by a drop of solder having a very low melting point. Around the tube is a non-inductive winding of german silver wire of only a few ohms resistance, so proportioned as to heat sufficiently to melt the solder when the current through it reaches a certain point. A fairly stiff spring is held away from a ground plate by the pin and touches it when the pin is released by the melting of the solder. In some cases a combination arrangement is used, which opens the line in one direction and grounds it in the other. The heat coil is of course, far cheaper than the circuit breaker and fully as accurate. It can be constructed to operate on almost any desired current.

Loose connections constitute a fire risk which cannot be guarded against by any automatic method of protection. A loose connection or a cord with several strands of tinsel broken may heat dangerously on a normal current. As this usually occurs in the 110 or 220 volt nickel or lighting leads, and the resultant fire destroys the defective part, it is frequently difficult to determine the precise nature of the original trouble. The only safeguard of any value against this danger is constant watchfulness, replacing lamp cord at all worn or ragged, and making absolutely sure of all soldered or screw connections.

Every telephone repairman has noticed the heavy increase in trouble in damp weather. This applies as much to the switchboard as to the outside plant, but in a different and in one respect more serious way. While aerial trouble caused by dampness consists simply of grounds and short circuits, affecting only a line or group of lines until the dampness is cleared, in a switchboard the leakage develops the weak points in the insulation of keys, relays and wires, resulting frequently in burned out relays and occasionally in serious fires. Like the former, this trouble is confined mainly to the higher voltage circuits, such as the generator or nickel, and in the more serious cases the evidence is usually destroyed by the fire. It can be guarded against only by substantial construction, providing ample insulation in the first place, and by careful maintenance, using every effort to keep up the insulation, as well as by proper fusing. To obtain high and fairly waterproof insulation we use double wrappings of silk and cotton on the most of our switchboard wire, waxing and shellacing it where not protected by the braided covering of a cable. While this combination effectively obtains the desired result, it is highly inflammable and a fire once started will be disastrous.

The electrical current is usually considered under two headings: direct, where it is in one direction only, and alternating, where it reverses its direction many times a second. Direct current may be subdivided into continuous, where its value is constant, and pulsating or fluctuating where its value is constantly changing. In the narrower sense, a pulsating current consists of a regular succession of equal impulses in the same direction, sometimes with dead intervals of equal length between them, while a fluctuating current simply changes its value constantly, without any regular sequence. Alternating currents are divided into single phase, consisting of regular impulses succeeding each other in opposite directions; and polyphase or multiphase, which consist virtually of two or more single phase currents, the changes in one occurring a definite interval later in the revolution of the generator armature than those in the other, combined into one circuit.

Fig. 2 shows the graphical representation of each one of these forms, the heavy base line in each case being taken as the point of zero current. Continuous current, having a uniform value, is represented by a straight line at a uniform distance above the zero or base line; pulsating by a curve which shows its regular rise to a maximum

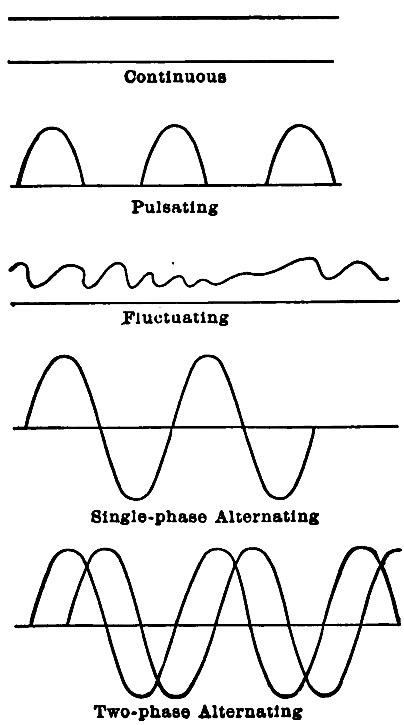

FIG. 2.

and fall to zero; and fluctuating, by an irregular curve showing its irregular rise and fall; all of these, being direct current, or current in one direction only, are represented entirely above the base line.

Single phase alternating current is represented by a succession of equal curves, each similar to those used for pulsating, but alternating in position above and below the base line to indicate the reversals in direction; and two phase, as an example of polyphase, by two similar single phase curves drawn together in such a way as to show that the changes in value of one take place slightly later than in the other.

In any electrical circuit the current, which is measured in amperes, is the important factor and the one which does the work, just as in a water mill it is the flow of water, through properly designed apparatus, which drives the machinery. We have now briefly outlined the more important ways in which the current manifests itself—except the phenomena of magnetism and induction, which will require more detailed treatment later—and we have indicated how these may be utilized or should be guarded against. We are now ready to inquire how this current is produced and controlled, and will next investigate the pressure or electromotive force which establishes and maintains it.

Questions.

1. What is an ammeter?
2. What do we mean by boosting a telephone line? Why is it ever necessary?
3. What is the object and principle of the trip relay on a trunk?
4. What is the object and principle of a fuse? Of a heat coil?
5. Name some common causes of switchboard fires.

CHAPTER III.

ELECTRICAL PRESSURE.

Nothing has ever been accomplished in any field without effort, without the expenditure of energy, without an impelling force, and whether we call this interest or enthusiasm, as in our mental life, or pressure, as in physical phenomena, the principle is the same.

It is a popular error, caused probably by careless phraseology, that an electrical generator—so-called—generates electricity. A familiar sight in our stores is a tube through which a carrier containing money and sales slips is forced by a current of air set up by an engine—or motor—driven air pump. The air pump in no sense generates the air; it simply causes the pressure at one end of the tube to be higher than at the other, and the current of air which we utilize to move the carrier is the natural and inevitable result of connecting two sections of tubing which are at different pressures. If we pump water into a tank on the roof of a building in order to draw it from the faucets we do not in any sense generate or make the water, nor do we, except in an indirect and limited sense, generate the current; but we do raise the water to a higher level and the resultant flow simply represents its effort to relieve the pressure, or to seek the lowest possible level. While electricity is not, at least in the ordinary sense of the term, a material substance like air or water, it follows in this respect, precisely the same law; and an electrical generator, whether it be a battery, a dynamo, or any other of the many causes of the current, is simply an apparatus for disturbing the equilibrium of the normal charge of electricity existing in all substances; raising its pressure or potential at one point and lowering it at another. The current which ensues on connecting these two points is simply nature's effort to restore the disturbed equilibrium.

If we stop the air pump which is operating the cash carrier in a store, the flow of air will at once equalize the difference in pressure and will then stop. If we wish to keep in motion twice as much air in one system as in another we will evidently have to expend twice as much energy in the one case as in the other, not to move the air directly, but to maintain the difference of pressure which the larger current of air tends to equalize more quickly. Similarly, if we set up a difference of potential between two bodies, but provide no means of maintaining that difference—as, for example, in the case of two thunder clouds—when the circuit is closed there will be a sudden rush of electricity between them which will bring them both to the same potential; we will have merely an impulse, not a current. Following the same analogy, as our larger current of air required twice as much effort to maintain the pressure as did the smaller one, so a current of ten amperes will require twice as much energy to maintain, or to maintain the difference of potential as will one of five amperes, because, left to itself, it will equalize that difference in one half the time. The point which we desire to make is this: that all experience, without exception, is governed by certain fundamental and familiar principles or laws, and that electrical phenomena, so far from being exceptional in their behavior, are simply illustrations of the universality of these principles.

As an example of this particular principle, if we dip a sheet of copper and one of zinc in dilute sulphuric acid, the acid will show a much greater affinity for the zinc than for the copper, and this difference in affinity will raise the electrical potential of the copper and lower that of the zinc. A voltmeter will tell us, in fact, that the potential of the copper is about one volt higher than that of the zinc. If we connect these two plates through a galvanometer or ammeter we will find that this difference of potential sets up a current from the copper to the zinc, and while the current exists bubbles will rise from the copper, indicating that continuous chemical action is needed to maintain the difference of potential in spite of the equalizing current. On opening the circuit these bubbles will cease because there is now no current to relieve the pressure, which another test with the voltmeter shows to be still there. While battery types are legion, and the chemical reactions in them form almost a science of their own, the principle which is illustrated in this simple experiment forms the basis of them all.

If we move a wire quickly across a magnetic field the potential of one end of the wire will be raised and that of the other end lowered. If we wind the wire in a coil and provide means of rotating it, and of establishing a connection with its terminals, we have a dynamo—or generator, as it is more commonly called—and this difference of potential will set up a current through a circuit connecting its poles. There is one point of difference between the action of the dynamo and that of the battery, which is, however, more apparent than real; when the machine comes to rest the difference of potential ceases. The reason for this is that while in the battery this difference was maintained by chemical affinity; in the dynamo it was due to motion in the magnetic field and was free to discharge back through the winding, thus equalizing the pressure, when the motion ceased.

While the steam engine is a very inefficient machine, utilizing on an average less than one tenth of the actual energy latent in the coal; yet on account of the great difference in cost between coal and zinc, as well as in the attendance required and the larger and more convenient generating units available, the engine driven generator is, where water power is not available, the only commercially economical means of obtaining an electrical current on any considerable scale. The use of the primary battery is practically limited to isolated cases where the current required is small or intermittent. This economy explains, to a great extent, why the common battery system has rendered possible the great extension of telephone service and the equally great reduction in the average price for service which has constituted one of the greatest commercial and social revolutions in recent years.

The impelling force which, when the circuit is closed, sets up a current of electricity, is variously termed electrical pressure, electromotive force (abbreviated as e.m.f.), difference of potential (p.d.), and voltage; all, except the last, conveying the idea of a pressure tending to force an electrical charge to a lower level. The unit of measurement is the volt (whence the term "voltage"), which for practical use is legally defined as 1000/1434 of the e.m.f. of a standard Clark's cell, which is prepared according to certain fixed specifications. An approximation which is perhaps of more practical use to us is to consider its value as about one-half the voltage of a storage cell on discharge, about two-thirds of a new dry cell, or one-one hundred and tenth of that across our ordinary incandescent lighting leads.

Since there is some charge—or amount—of electricity in all substances, as shown by the fact that setting up a difference of potential will always, if the circuit is closed, develop it in the form of a current, it follows that there is nowhere in nature a point of actual zero potential. If there were, electricity would immediately flow to it from all directions, raising its potential until a balance was obtained. It is necessary, however, to have some definite standard, and so, just as with a thermometer we set an arbitrary point which we call zero, which is by no means a point of no heat, in computing electrical pressure we take the potential of the earth as our arbitrary zero and call all potentials above it positive (represented by +) and those below it negative (–). As, however, the potential of the earth is exceedingly variable, while we often deal with metallic circuits which have no connection with the ground and whose varying potentials are hence not comparable with that of the earth, the terms positive and negative lose their absolute meanings and become only relative. One point is positive or negative only as compared with another.

A theory—or more correctly, an hypothesis—of electricity which was suggested in the early days of electrical investigation considered all bodies at zero potential as containing equal charges of two different and opposing kinds of electricity, vitreous or positive and resinous or negative, which ordinarily neutralized each other so far as external effects were concerned. A charged body was considered as having more of one kind than of the other, and a current as representing the attraction of the two kinds for each other and their effort to neutralize each other. While discarded as a theory this hypothesis is much used in a limited class of cases, as it often symbolizes what is actually taking place more simply and conveniently than the pressure or stress theory which is now generally accepted as being nearer the actual truth. In this limited but entirely legitimate sense we will have frequent occasion to speak of electrical charges as being positive or negative in character, and as attracting, repelling, and neutralizing each other.

If we wish to investigate the cellular structure of plants, the physical composition of the blood, or the surface characteristics of the moon or of Mars, we must use a microscope or a telescope to magnify them sufficiently to be clearly visible. Similarly, in studying electrical phenomena it is often necessary or advisable to magnify the particular factors we are investigating. Reading the pointer of a voltmeter in preference to watching the smaller movement of the pivoted coil is a familiar example of this.

The earliest electrical experiment recorded was the attraction which amber, when rubbed, displayed for very light bodies. The test which we ordinarily use to determine the genuineness of the amber mouthpiece of a pipe is to rub it on the coat sleeve and pick up bits of paper with it. From the Greek word "electron," meaning amber, the word "electricity" is derived, and electricity was originally the science of the attractive power of rubbed bodies, particularly amber. We know now that it is not the rubbing itself which produces the effect but simply the close contact between dissimilar bodies which is most readily obtained by rubbing or striking them together.

If we fit a flannel cap to a stick of sealing wax, and provide the cap with a silk cord so that we can pull it off without touching it, we have a simple and instructive electrical machine. If we rub the sealing wax with the cap and then separate them, using care not to discharge the cap through the body or otherwise, we will find if we bring them near to two light pith balls suspended and insulated by silk threads, that they will both first attract the pith balls and then, after holding them for a short time, repel them. On then bringing the pith balls together they will first attract each other and then, after being in contact for a short time, will fall apart and become entirely indifferent.

This experiment opens a wide field of thought. It teaches us that by rubbing the sealing wax and flannel together we have set up electrical charges on both as shown by their attraction for the pith balls. After coming in contact the pith balls are repelled, indicating both that a charge is self-repulsive, spreading out over the pith balls in an effort to cover as much surface as possible, and, what is very much the same thing, that like charges repel. The attraction which the two pith balls thus charged display for each other teaches us both that the original charges are unlike, because the balls are not repelled as they would be if their charges were alike, and that these unlike charges attract until, when they come into contact, they neutralize each other.

Let us look at this experiment in a somewhat different light. If we assume that by rubbing them together we have raised the potential of the flannel, or made it positive to the sealing wax, and that we have lowered the potential of the sealing wax, making it negative to the flannel, then the increased electrical pressure on the first in its effort to find an outlet attracted the pith ball and raised its pressure to the same point, when the reaction between the two, both being at a relatively high pressure, naturally caused a repulsion. The action in the case of the sealing wax was the same, except that, being negative, it drew a portion of the normal charge from the pith ball, lowering its potential instead of raising it. The two pith balls then attracted each other because of the effort of the higher potential to discharge itself into the lower and restore the original equilibrium.

This experiment is simply an example of magnifying the factor under investigation—in this case electrical pressure—in order to observe it more closely.

Many of us have had the impression at some time that static and dynamic electricity, so-called, are two totally different things. The only difference between the electrical conditions of two pith balls, oppositely charged, and that of the terminals of a battery, are, first that the difference in the potential between the pith balls is much higher than that across the battery terminals, and, second, that the current produced on closing the circuit is very much smaller and consists only of a single impulse, perhaps oscillating for a small fraction of a second, not of a steady flow, as there is no means provided to maintain the difference of potential in spite of the equalizing current. The only general distinction which we can draw is that indicated by their names; static electricity being a charge or quantity of electricity under pressure, but at rest because the circuit is open and it cannot discharge itself; while dynamic electricity is the same charge flowing through a closed circuit in the form of a current. This distinction is not concerned with the question of whether the potential is high or low; and while it is true that the most conspicuous and spectacular manifestations of static electricity are at a high potential, such as the lightning flash, yet its most common and useful applications are at low voltages, as for example, in our telephone condensers, where the difference of potential is often below ten volts. Roughly speaking, an e.m.f. of about 100,000 volts is required to cause a spark one inch long.

Having discovered a method of magnifying the subject under investigation, we are now in a position to demonstrate the statement made earlier in this chapter, that a current is caused by "disturbing the equilibrium of the normal charge of electricity existing in all substances, raising its pressure or potential at one point and lowering it at another," and then connecting these two points. If we can set up a positive charge without at the same time setting up an exactly equal negative charge then our theory is wrong, for we have actually generated electricity, not simply altered its distribution or pressure. Let us see if this is possible.

If we rub a glass rod with a silk handkerchief held in the hand, and then test both the glass and silk for charge, using a suspended pith ball as before as an electroscope, we will find a strong positive charge on the glass and a weaker negative charge on the silk. If, however, we carefully insulate the silk instead of handling it, the two charges will be found to be exactly equal, and it becomes evident that the difference in the values of the two charges noted at first was caused by a portion of the negative charge on the silk leaking through the body to the ground. A much easier experiment to perform, and one which amounts to the same thing except that the polarities are reversed, is to rub the stick of sealing wax with the flannel cap and then, holding the cap in the hand, test both with the pith balls. We will find a strong negative charge on the sealing wax but none on the flannel. We found before, however, when the cap was held by the silk cord to prevent grounding it, that there was a positive charge on the flannel, and this positive charge has evidently, on account of its self repulsion, spread itself over the hand holding it, and thence over the body, the floor of the room, and the ground, its intensity being weakened to practically zero as it spread over the larger surface.

We have found, then, that in setting up a charge, either positive or negative, we necessarily set up an opposite charge, and the grounding of the opposite charge in the above experiments is the explanation of all cases where one polarity appears to exist alone.

We have, as yet, however, proved only half of our argument. Are these charges necessarily equal? Let us rub the sealing wax with the cap as before and then, leaving the cap on, test both together. The pith ball will show no evidence of any charge until we separate them, showing that the opposite charges neutralize each other when together, and are hence exactly equal, or that the potential of the sealing wax is lowered as much as that of the flannel is raised.

If a current is caused by a difference of potential between two points in a circuit then it is not necessary to have opposite polarities in order to produce it. If we connect two points, both of which are positive, but one at a higher potential than the other, a current will be established in an effort to equalize them, and in determining its energy, we do not need to know the absolute values of the two potentials, but only the difference between them. A familiar example of this is the charging of branch exchange batteries from the office battery. They are connected together through a charging lead and the ground in such a way as to oppose each other, but the office battery, having a larger number of cells and consequently being at a higher voltage, will set up a charging current through the branch battery in opposition to its e.m.f. For example, if the office battery has eleven cells and stands at twenty-two volts (two volts per cell) and the branch battery has seven cells and stands at fourteen volts, the difference between the two, or eight volts, is available to set up the charging current.

The charging of branch batteries, as well as all methods of grounded signalling, is often complicated by earth currents, caused usually by insufficient or defective return circuits of street railway systems. Remembering that our batteries, both central office and branch exchange, are always negative in polarity, their positive poles being grounded, it is evident that if a street railway system has disturbed the potential of the earth, making it eight volts more negative at the branch exchange than at the office, this neutralizes the difference between the two batteries, bringing both ends of the charging lead to the same actual potential, in which case there will be no current through it and the branch battery will receive no charge. If the difference of potential between the two grounds is still greater, the branch end of the charging lead becomes more negative than the office end and the branch battery will discharge back through the office battery. If, on the other hand, the branch ground is positive to the office ground, the effective difference of potential between the two ends of the charging lead will be greater than eight volts, and the branch battery will receive a heavier charge than is intended. Charging trouble due to earth current can be remedied only by either using a return wire instead of the branch exchange ground or by charging the branch battery from some other source, such as the local lighting system.

The recent heavy increase in earth currents has necessitated the abandonment of the system of grounded signalling formerly used on all trunks between our Chicago Exchanges and the adoption of a system of metallic signalling. Earth currents vary in value within wide limits at different hours of the day and it was found impossible effectively to compensate for these variations.

An e.m.f. in a circuit which opposes the original or "impressed" e.m.f. is called a "counter e.m.f." While earth current is perhaps the most obvious example of this in these days of rapid trolley development, it is by no means the only or even the principal one with which we have to deal. Every talking circuit, every circuit having capacity or retardation—and but few circuits used in electrical work are free from one or the other—has counter e.m.f. in some form which must be recognized and allowed for or utilized. This conception is indeed the key which, when understood and properly used, will unlock many baffling mysteries and seeming exceptions to established natural laws. In the charging circuit itself, of both the office and branch exchange batteries, the battery voltage is an e.m.f. " counter " or opposed to that of the charging machine or lead, which must be subtracted from the " impressed " e.m.f. to find the net or " effectual " e.m.f. which is available to force a current through the circuit.

Since the difference of potential between the terminals of a cell of battery depends on the relative affinities of the two plates or elements for the solution or electrolyte, it is entirely independent of the size of the cell. The small " B. T." storage cell having a surface of but a few square inches and a capacity of about six ampere-hours has the same e.m.f. as the immense cells used in our larger exchanges

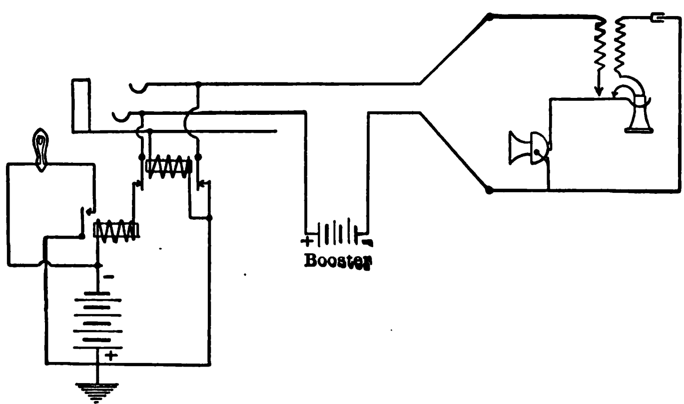

FIG. 3.

and in power houses, which may have a capacity of thousands of ampere-hours. Since, however, the chemical action required to maintain the initial difference of potential when a current exists depends directly upon the value of that current, the amount of current which can be safely drawn from a cell is directly proportional to the size of the cell or, providing that there is sufficient electrolyte, to the surface of the plates.

In the preceding chapter the necessity of " boosting " common battery lines, when the current is too small for satisfactory transmission or signalling, was noted. The simplest and, in general the most effective method, is by means of an additional battery cut into the line in such a way that its voltage is added to that of the office battery. Whether this battery should be made up of dry or storage cells, depends on the number of lines to be boosted. Where but few lines need this, dry cells are the cheaper, a sufficient number of them being looped in series with the battery side of each line to raise the total e.m.f. on the line to a point where it can maintain the desired value of current in the circuit. Since this simply amounts, so far as that particular line is concerned, to add-

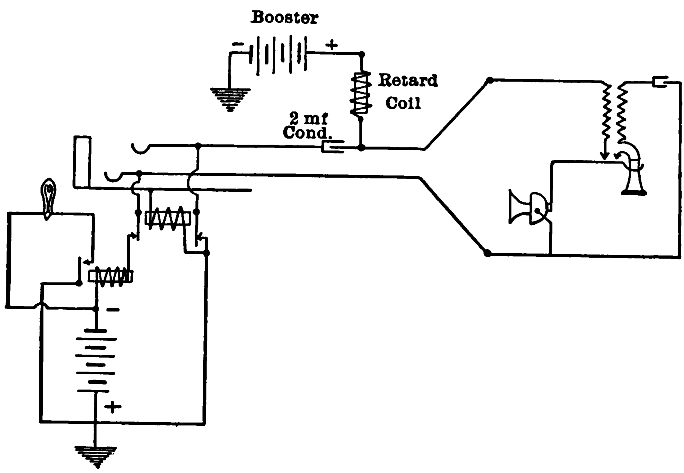

Fig. 4.

ing that number of cells to the office battery, the same rule should be followed as in all series battery connections, the positive side of the booster battery being connected to the negative side of the office battery, while the negative side of the booster goes to line. Fig. 3 shows the arrangement.

Since with this arrangement, each line requires its own booster battery, the dry cell method becomes expensive and unsatisfactory when there are a large number of lines to be boosted. The circuit of a storage battery booster is shown on Fig. 4. So far as the current through the line relay and instruments is concerned, the principle is exactly the same as in the former method, the office and booster batteries being directly in series to ground. The fact that the instrument is cut in between them is immaterial, being simply a matter of convenience in construction and operation. The combination of retardation coil and condenser in this circuit is worthy of special mention. It is desirable that one side of the booster be permanently grounded; admissible to signal grounded provided that the booster ground be so located as to prevent any trouble from earth current; but, for many reasons, highly undesirable to talk grounded.

Since its voltage is constant, a storage battery will, under uniform conditions, deliver a uniform, continuous, current. In a telephone circuit this continuous current is altered into fluctuating by the varying resistance of the transmitter. A fluctuating current acts in many respects as a combination of two separate currents, a continuous and an alternating. For most practical purposes we may consider that a condenser does not impede an alternating current, while it acts like an open circuit to a continuous current, and a retardation coil offers little resistance to a continuous current, while its impedance to an alternating current is very great.

In the storage battery booster circuit, when the more or less fluctuating current, which is increased in volume or amplitude by the two batteries being in series and assisting each other, reaches the junction of the retardation coil and condenser, it divides into its two component parts. The continuous portion, which controls the signalling, has its path through the retardation coil and the booster battery to ground, while the alternating portion has its path through the condenser, back to the tip of the jack, and is there available for transmission.

The retardation coil also serves to prevent cross-talk between the different lines connected to the same booster, as there is a retardation coil for each line.

A very serious class of trouble in telephone work is noisy lines, where the noise is caused by induction from neighboring wires. In order to observe it more closely, we will again resort to the plan of isolating and magnifying the disturbing electrical charge.

If we support a very light conducting body, such as a gilded egg shell, by a silk thread so that it is insulated but free to move, and bring near to it another body carrying a fairly strong positive charge, such as the disk of an electrophorus, the egg shell or light body will be attracted, although a previous test with a pith ball may have shown no charge on it. On removing the disk and again testing the egg, we will find that there is still no charge on it.

This phenomenon admits, on the face of it, of two possible explanations. Either the high positive potential of the disk attempted to relieve its pressure by spreading over the surface of the egg and attracted the egg in that

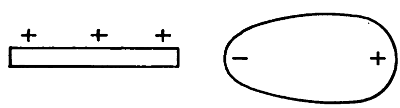

FIG. 5.

effort, or else it split up the equilibrium previously found on the egg, attracted a negative charge toward itself and repelled an equal positive charge to the farther end. Since the negative charge was the nearer its attraction for the disk overpowered the repulsion exerted by the more distant, although equal, positive charge on the other end, resulting in a movement of the egg toward the disk. Fig. 5 shows the distribution of the charges under this hypothesis.

If, while holding the disk near one end of the egg, we test the other end with a suspended pith ball, we will find a charge on it, and this charge may be shown to be positive by the fact that the pith ball, after receiving a portion of it by touching the farther end of the egg, will be repelled by the disk. We have, then, found a positive charge where previously there was none, and this change in conditions is evidently due to the proximity of the disk. If we touch the farther end, the induced positive charge in its effort to get as far away from the similar charge on the disk as possible, and also in an effort to discharge itself into the lower potential of the earth, flows through the body to the ground. On removing the disk we will find a negative charge on the egg as shown by the fact that a pith ball, after being attracted and allowed to touch it and thus receive a portion of its charge, is strongly attracted by the disk. The negative charge will be found over the entire surface of the egg because, although it was at first held at one end by the attraction of the disk, when the disk was removed its self-repulsion caused it to spread over as large a surface as possible.

Applying this principle of electrostatic induction to a noisy telephone line, we find a distribution of charges as

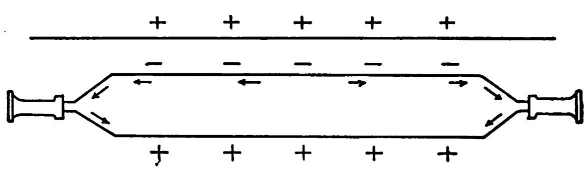

Fig. 6.

shown in Fig. 6, where the top line represents the disturbing wire, such as one side of an alternating electric lighting circuit, and the others, the two sides of a telephone circuit with a receiver at each end. As the current in the lighting circuit is produced by an alternating e.m.f. the polarity of the wire is constantly reversing. While it is positive, it acts as did the electrophorus disk in our last experiment, attracting a negative charge to the nearer side of the telephone circuit and repelling an equal positive charge to the farther side. At the next alternation the disturbing wire becomes negative, attracts the positive charge on the telephone circuit to the nearer side, and repels the negative charge to the other side. The only way in which these charges on the telephone circuit can exchange sides as required by the alternations of the lighting circuit is to pass through the receivers at each end, setting up an alternating current through them which will have the same frequency as that on the lighting circuit.

If we reverse the positions of the two sides of the telephone circuit—or " transpose " them—in the center of the zone of disturbance, the transposition offers another path for the charges as shown in Fig. 7, and as it has practically no resistance or impedance there will be a much larger alternating current through it than through the receivers. If we again divide these sections by a transposition in the center of each we will reduce the noise still further, and by a sufficient number of transpositions a line may be made reasonably quiet under almost any disturbing conditions. Aside from mechanical advantages,

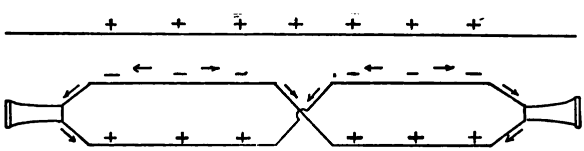

FIG. 7.

the use of twisted pairs in inside wire and cable conductors is generally advisable because each half twist acts as a transposition, preventing cross talk or other induction disturbances.

When we desire, as we often do, to represent pressure conditions graphically, we follow the same method as that illustrated in the previous chapter. The various curves shown in Fig. 2 would serve equally well as pressure curves.

To measure potential differences two methods are in general use. The purely pressure or electrostatic method, using an electrometer, is simply an elaboration of the pith ball electroscope to which we have referred in the preceding experiments, and depends for its operation on the attraction between opposite polarities. While fairly well suited to high potentials its action is weak and the delicacy of construction needed to make it sufficiently sensitive to measure potentials of only a few volts unfits it for practical use in low pressure work. The more usual method is by means of a voltmeter, which depends for its action on the force developed in a coil by the passage of a very small current. What it actually measures, then, is the current through its windings, but as this is proportional to the pressure or difference of potential across its terminals, it may be calibrated in volts. While an ammeter is connected in series with the circuit the current in which is to be measured, an electrometer or a voltmeter is bridged across a circuit or connected across the two points whose difference of potential we wish to know.

Questions.

1. What is the distinction between the " volt " and " ampere "?

2. If a generator simply sets up a difference of potential, why does it take three times as much power to drive it when lighting seventy-five lamps as when lighting twenty-five, the difference of potential being the same in both cases?

3. Of what terms are the following abbreviations—e.m.f.? p.d.?

4. State the distinction between static and dynamic electricity.

5. What is meant by the term " counter e.m.f."?

6. If an office battery of twenty-four volts meets an opposing earth potential of six volts, what pressure is available to force a current through the circuit?

7. What would be the answer to question (6) if the earth potential were reversed?

8. What is the principle of the booster battery?

9. Which side of a dry cell booster battery should be connected to the line? Why?

10. Describe the principle of line transposition.

CHAPTER IV.

RESISTANCE.

The three principal factors in electrical work are the current which performs the work and which is measured in amperes; the pressure which produces that current and is measured in volts, and the resistance or obstruction which every circuit, to a greater or less extent, offers to the current and which is measured in ohms. In considering the first two we have, in order to bring them under the broader and more familiar principles which underlie all experience, compared some of their phenomena with similar cases in ordinary mechanics. The very name of resistance indicates its nature as that which resists the passage of electricity. This definition is somewhat too broad because when alternating or fluctuating currents are considered we find that other factors besides simple resistance obstruct their passage, but for continuous current it is correct. It is analogous to friction to this extent: friction offers some obstruction to all mechanical movement and the energy consumed in overcoming friction is converted into heat. Resistance may be considered as a property—to a widely varying extent—of all substances, by which they oppose, either strongly or slightly according to the nature of the substance and its temperature, an electrical current; and by opposing it convert into heat the energy expended in maintaining it. We are accustomed to the idea that matter cannot be destroyed, and energy is equally indestructible. When we speak of the loss in a circuit, such as the "drop" in electric lighting leads, while some of the electrical energy has actually gotten away from us it has not been destroyed, but simply dissipated into space in the form of heat.

Unlike friction, the electrical resistance of a circuit is independent of its shape and can be readily computed if we know the length, material, size and temperature of the conductor. Coiling or bending a wire does not affect its resistance except as it may mechanically alter the cross-section. The temperature, if it is within reasonable limits, can for most practical purposes be neglected.

There is no substance in nature which is a perfect conductor, having no resistance, and none which is a perfect insulator, having infinite resistance; but there is a very wide range between silver, which, having the lowest resistance of any known substance, is taken as a standard, and a number of materials which, from their extremely high resistance, allow very little current through them at ordinary pressures, and hence are termed insulators. If we take a silver wire having a resistance of one ohm and a number of wires of other substances, having the same length and cross-section, we will find wide differences between their resistances; and the resistance of each sample, having the same length and diameter as the length and diameter of the silver wire taken as a standard, is termed the specific resistance of that substance; that is, its resistance as compared with silver. Published tables vary slightly on account of impurities in the samples tested, but the specific resistance of copper is about 1.063; of wrought iron, 6.46; of german silver, 13.92; and of mercury, 62.73.

Measurement of resistance is somewhat less simple than that of current or electromotive force, because it is a fixed property of a material substance, not of the current; and one which can be determined only by its effect upon a current, considered in connection with the pressure maintaining that current. Frequent reference has necessarily been made in preceding pages to the intimate relationship existing between the three elementary factors in electrical work, and in the introduction the ohm was defined as the amount of " resistance which requires a pressure of one volt to force a current of one ampere through it." Generally speaking, we are familiar with the fact that in every field of action the result achieved depends directly upon the intensity of the effort, and that the greater the difficulties to be overcome, the less the result, unless a correspondingly greater effort is made. Ohm's law, which by many students is supposed to be an abstruse mathematical formula, too deep and too obscure to grasp, is simply a definite statement of these two fundamental principles as applied to continuous current electricity. In any circuit, whatever the actual values may be, the value of current, expressed in amperes, is always equal to the electromotive force, expressed in volts, divided by the resistance in ohms. For convenience in use we may write it in the form of an equation, thus:

$$\text{" Current} = \frac{\text{Electromotive force "}}{\text{Resistance}}, \text{" Amperes} = \frac{\text{Volts "}}{\text{Ohms}}$$

or, for the sake of brevity, $I = \frac{E}{R}$, I standing for current, E for electromotive force, and R for resistance. There are two other ways of expressing the equation which amount to the same thing and are equally correct: $R = \frac{E}{I}$ and $E = I$ times R, or, as usually written, $E = I R$.

The incalculable value of this simple statement of relations is obvious, for if any two of the factors are known it is a simple matter of arithmetic to find the third by substituting the known values for the letters in the second term of whichever form of the equation fits the case.

Since the ohmic value of a resistance is equal to the difference of potential across its terminals, divided by the current through it, the most direct and obvious method of measuring it is to bridge a voltmeter across it, cut an ammeter in series with it, and divide the reading of the one instrument by that of the other, $R = \frac{E}{I}$. On the testing desks in many exchanges a milliammeter is normally in series with the test cord, and its reading, taken in connection with the voltage of the office battery, which is always approximately known, gives the tester a sufficiently close idea, for ordinary purposes, of the resistance of the circuit. When greater accuracy is desired the battery voltage is measured at the power board or busbar, an ammeter reading taken through the circuit, another taken through the office wiring alone, both readings reduced to ohms and the resistance of the office wiring subtracted from the total.

The calculation required for each measurement, although simple, renders this method too cumbersome for general use. In certain cases, however, where we wish to know the resistance of a circuit under actual working conditions, with a fairly heavy current, such as that of an arc or incandescent lamp when in operation, it is the only one available.

According to Ohm's law, the difference of potential required to produce a given current in a circuit, or the fall of potential through the circuit, is proportional to the resistance to be overcome. It follows from this that as electricity flows through a circuit its pressure falls in proportion to the resistance passed over. A similar case is found in the flow of water through a pipe, where its pressure decreases, as measured at different points along the pipe, in proportion to the friction and other obstructions overcome, until when it leaves the pipe its pressure is zero. If we have a ten-volt battery connected to a ten-ohm resistance the current will evidently be $\frac{10}{10}$ or one ampere ($I = \frac{E}{R}$), and this current will be the same in value, although not in pressure, at all points in the circuit. If we bridge a voltmeter across the resistance it will of course indicate the full battery voltage, or that the total fall of potential through the circuit is ten volts. If we bridge it across one-half of the resistance, or five ohms, then, since $E = I$ times R it will read 1 (ampere) times 5 (ohms) or five (volts); that is, we have used up one-half of our total difference of potential in forcing the current through one-half of the resistance. If we bridge it across eight tenths of the resistance, or eight ohms, it will read 1 (ampere) times 8 (ohms) or eight (volts).

If $I = \frac{E}{R}$ then the value of current through a given resistance is proportional to the difference of potential across its terminals. The action of a voltmeter depends upon this principle, and since its indications depend upon the value of current which the difference of potential across its terminals can maintain through it the scale can evidently be marked to indicate this difference of potential directly in volts.

If we connect a voltmeter, an unknown resistance, and a

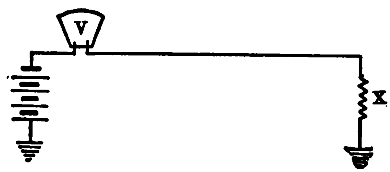

FIG. 8.

battery all in series as shown in Fig. 8, then, neglecting that of the battery, the total resistance of the circuit will be the resistance of the voltmeter added to the unknown resistance. Since the fall of potential throughout a circuit is proportional to the resistance passed over, the fall of potential through the unknown resistance will bear the same relation to the fall of potential through the voltmeter, which is indicated by its reading, that the value of the unknown resistance does to the resistance of the voltmeter. Since the fall of potential through the unknown resistance is equal to the total battery voltage minus the voltmeter reading, and the resistance of the voltmeter is always marked on either the instrument itself or the carrying case, the values of three of the factors are known, and it is a simple matter to calculate the fourth.

Let X = unknown resistance.
" V = resistance of voltmeter.
" E = total battery voltage.
and e = deflection of voltmeter or fall of potential through voltmeter.

Then $E - e$ = fall of potential through X

$$\text{and } \frac{X}{V} = \frac{E - e}{e}$$

Multiplying both sides of the equation by V, $X = V\,\frac{E - e}{e}$.

As an illustration of the use of this formula,
if $V = 3333$, $E = 24$, and $e = 8$,
then $E - e = 24 - 8 = 16$,

$$\frac{E - e}{e} = \frac{16}{8} = 2$$

and $V\,\frac{E - e}{e} = 3333$ times $2 = 6666$ for the value of X.

In actual practice on testing desks the readings are not usually reduced to ohms, but the tester knows by experience about what readings to expect under certain conditions, and diagnoses the case accordingly. Instead of specifying, for example, the ground as having a resistance of 6666 ohms he gives it to a repairman as an eight-volt ground, meaning that his voltmeter reads eight volts when connected to that ground.

To illustrate further, in testing a certain line with the test desk voltmeter, we get a reading of four volts with the instrument in series with battery and one side of the line to ground. We say there is a four-volt ground on the line meaning that the resistance of the ground on the line is 16,665 ohms.

$$\text{Since } V\left(\frac{E - e}{e}\right) = 3333\left(\frac{24 - 4}{4}\right) = 16{,}665 \text{ ohms.}$$

For fairly high resistances this forms a very convenient and accurate method of measurement, especially where the presence of earth current or other counter e.m.f. would cause serious errors in almost any other method. The actual value of the earth current cannot be accurately determined by any very simple method when X is unknown, but it can be readily approximated by a separate reading, and then added to or subtracted from the value of E, according to its polarity.

Since this test, which is deservedly popular among telephone men, is simply an indirect comparison between the resistance of X and that of the voltmeter, it is obvious that, when the reading is expressed in volts, as it usually is for convenience, the resistance of the voltmeter should be the same in all cases.

For resistances too high to be measured with a voltmeter a reflecting galvanometer may be used, either in the same manner or by comparing the reading through the unknown resistance with a similar reading taken through a known resistance.

For still higher resistances, such as high insulation values, the leakage method is the only one available, charging the opposite sides—for example, the inside and outside surfaces of glass insulators—to high opposite potentials and measuring the leakage through the insulation by the loss of charge. While somewhat out of the line of ordinary maintenance work, this method is of great commercial importance, and is interesting as an example of the remarkable refinement to which scientific measurements have been carried.

The methods so far described are commercially used only in special classes of work. For general resistance measurements over a range embracing all ordinary values the most convenient and accurate method is to arrange the unknown resistance and three known resistances in the form of a bridge, as shown in Fig. 9. The actual values of A and B need not be known, but only the ratio between them. R is a standard or known resistance with which X is compared. In the box type of bridge the battery is usually connected across a and c and the galvanometer across b and d, while in the slide wire type this arrangement is reversed. The reasons for this change are purely practical and do not affect the principle or method of reading.

The bridge depends for its operation on two fundamental principles; first, that a difference of potential between two points is necessary in order to set up a current; and second, that the fall of potential throughout a circuit is proportional to the resistance passed over. The current of course divides between the two paths $A+R$ and $B+X$, the relative amounts in each path depending on the ratio of their resistances. Suppose, for illustration, that the

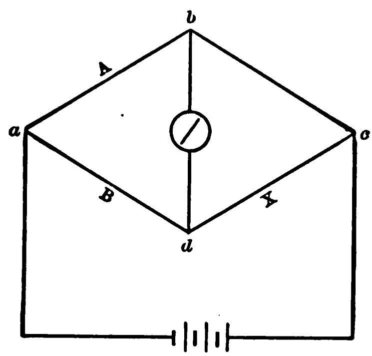

FIG. 9.

battery voltage is 10—which, by the way, is higher than is usually advisable or necessary—and that A, B, R and X are each 100 ohms. Starting at a, if the difference of potential between a and c is 10 volts, then on reaching b this difference will have fallen to one-half of 10, or 5 volts because one-half of the total difference of potential has been used up in maintaining the current through one-half of the resistance of the path $A+R$. For the same reason, the same fall will be found in the other path, $B+X$. Then if the potential of the current has fallen to the same extent in reaching d that it has in reaching b these two points will be at the same potential, and hence there will be no current through the galvanometer connected across them. If we alter the value of one of the arms of the bridge we destroy the balance and the galvanometer will be deflected. For example, make $X = 200$ ohms. Then if B is 100 ohms and X is 200 ohms, the resistance of B is one-third that of the path $B+X$ and the fall of potential through it will be only one-third of the total, or $3\frac{1}{3}$ volts. In this case the potential of the current has not fallen as much in reaching d as it has in reaching b, consequently the potential at d is higher than that at b and this difference of potential will send a current through the galvanometer, deflecting it. Leaving X at 200, we can restore the balance in two different ways. If we raise R to 200 the conditions in both paths will be the same, the potentials at b and d will be the same, the fall of potential in reaching both being $3\frac{1}{3}$ volts; and there will be no current through the galvanometer. If we leave R at 100 and raise B to 200, then as $B = X$ the fall of potential in reaching d will be one-half the total, or the potential at d is equal to that at b, and there will still be no current through the galvanometer.

We have found three different conditions under which the bridge is balanced, that is, where the potentials at b and d are equal as shown by no deflection of the galvanometer. Let us compare the figures and see if they suggest a formula which is true of all three:

	$A = 100$		$A = 100$		$A = 100$
	$B = 100$		$B = 100$		$B = 200$
(1)	$R = 100$	(2)	$R = 200$	(3)	$R = 100$
	$X = 100$		$X = 200$		$X = 200$

On examination we find that in each case A bears the same relation to B that R does to X, or $\frac{A}{B} = \frac{R}{X}$. Writing it as a working formula we have $X = R\frac{B}{A}$, covering all conditions where the bridge is balanced. As the value of R

and the ratio between B and A can be read directly in any bridge it is a very simple matter to calculate the value of X, multiplying R by the ratio $\frac{B}{A}$.

Two different types of commercial bridges have been mentioned, the slide wire and the box. While a knowledge of the skeleton circuit and its operation is all that is needed to enable one to use any ordinary bridge, a knowledge of the general forms which this apparatus assumes in practice is always helpful.

The slide wire type is justly popular among home students on account of the cheapness and simplicity of its

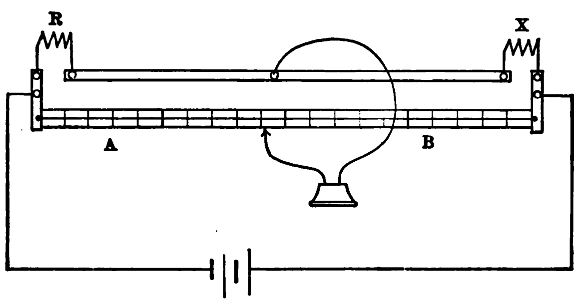

Fig. 10.

construction, while the accuracy possible to attain with it places it in the laboratories of the most advanced investigators. In its simplest form it consists of a scale of any convenient length—often one meter, whence the name "meter bridge"—divided into one hundred or one thousand equal parts, mounted on a board; of a heavy wire or strip of copper parallel to it and two or three inches away; of two short similar wires or strips placed across the ends of the scale, leaving an opening of convenient size between their ends and the ends of the longer strip; and of a bare German silver or platinoid wire, as small as possible without sacrificing the necessary mechanical strength, stretched over the scale and connected by clamps or by soldering to the short copper strips, *exactly* at the ends of the scale. The last point is important because if the connection is made, for example, one-eighth inch beyond the end of the scale a serious error will be introduced when taking readings near one end of the scale. Suitable binding posts are mounted on the copper strips for making the necessary connections. Fig. 10 shows the arrangement.

A resistance of any known value is connected across the left hand opening, and X, or the unknown, across the right hand. The battery is connected across the two short strips, one side of a head telephone is connected to the long strip and the other ends in a tip which is touched to the slide wire at different points until a balance is obtained as shown by the absence of a click. Applying the skeleton, A is the portion of the slide wire between the tip of the receiver cord and the left hand end of the scale, B is the portion between it and the right hand end, R is the known resistance, and X the unknown. As an illustration of its use:

$$\begin{aligned} \text{Let } R &= 100 \text{ ohms} \\ \text{and } A &= 450 \text{ (Scale divisions)} \\ \text{Then } B &= 1000 - 450 = 550. \end{aligned}$$

Applying the formula, $X = 100 \text{ times } \frac{550}{450} = 122.2 \text{ ohms.}$

The box type of bridge is made up in a multitude of widely varying designs. It consists essentially, however, of two sets of coils, usually of 10, 100 and 1000 ohms each, for the ratio arms A and B, and a rheostat consisting of either sixteen or forty coils which, by properly arranging the plugs, will give a resistance ranging from 1 to 11,110 ohms. The coils are mounted on the under side of a heavy sheet of hard rubber and connected to blocks on the top. These blocks are separated by small spaces and are connected together or to a common bar by slightly tapering plugs fitting in conical sockets cut in the adjacent faces of the blocks and bar, as shown in Fig. 11. The taper is shown considerably exaggerated in the drawing. The blocks are undercut to increase the clearance and consequently the insulation where they rest on the rubber. Fig. 12 shows the general scheme of the decade box bridge, where the rheostat is made up of forty coils arranged in groups of ten each. There is one plug to each ratio arm and one to each row of the rheostat. In the rheostat the units row is made up of ten coils of one ohm each, the tens row of ten coils of ten ohms each, and the hundreds and thousands rows in the same manner. Starting at the junction of *A* and *B* we can trace the four arms shown in the skeleton through the bar, through the plug which connects the bar with either the 10,100, or 1000 ohm block, through the coil

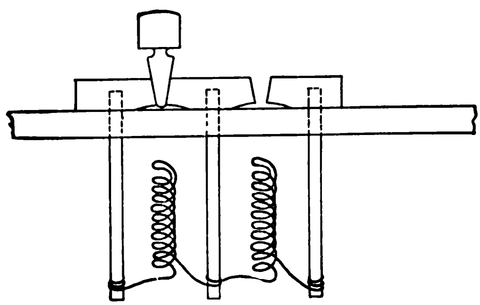

FIG. 11.

connected with that block to the first block in the units row of the rheostat, through the one-ohm coils in series until we reach the plug, through the plug to the bar, thence to the first block in the tens row, going through the rheostat in this way to the thousands bar, out through our unknown resistance and back to the *B* arm, and going through whichever coil is plugged to the bar, back to the starting point. The battery and galvanometer connections are the same in this as in the skeleton. The value of *R*, or the resistance of the rheostat, can be read at a glance from the positions of the plugs. With these as shown in the figure, the circuit is through six one-thousand, eight one-hundred, three ten, and nine one-ohm coils in series, giving a total resistance of 6839 ohms. The value of A is shown as 100 and of B as 1000 ohms. Since B is ten times A, X is evidently ten times R, or 68,390 ohms. In this lies the convenience of the box type of bridge, that X is always equal to R multiplied or divided by one, ten, or one hundred, according to the position of the plugs in the ratio arms A and B.

The only essential difference in the 16-coil type is in the method of cutting in resistance, all coils being con-

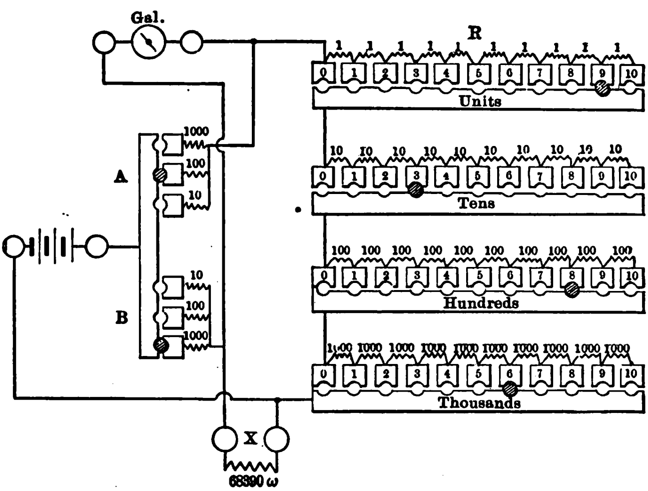

FIG. 12.

nected in series and short circuited by means of plugs. This involves the use of as many plugs as there are spaces between the blocks, or twenty-three in all, as against six with the decade bridge. On the other hand, it gives us the same range with a rheostat of 16 coils that we have in the decade type with 40, and also admits of a simpler, more compact and less expensive arrangement of the blocks, as shown in Fig. 13. The coils are usually arranged as follows: 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1000, 2000, 3000, 4000. With the plugs arranged as shown in the figure, counting the coils unplugged gives us values of 1000, 100 and 4589 for A, B and R respectively. Applying the formula, $X = 4589 \text{ times } \frac{100}{1000} = 458.9.$

While the range is the same in both, the decade type is somewhat more convenient in use and there is less liability to error in counting up the resistance in circuit, while as the number of plugs in circuit is always the same the possible error due to loose or dirty plugs is minimized. On the other hand the 16-coil type is much the cheaper and simpler in construction, while the fact that all the connec-

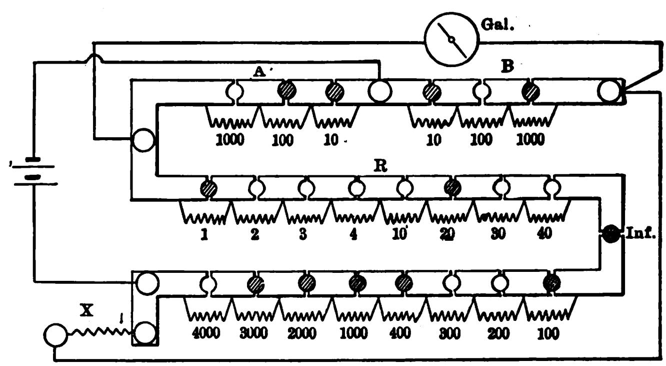

Fig. 13.

tions, except that from B to X, are in sight and made directly on the blocks is a very real advantage.

There are three precautions which must be observed when using a bridge, in order to secure accurate results; first, to set all plugs in firmly, inserting them with a slight screwing motion; second, to close the battery about one second before the galvanometer; and third, to use no stronger battery than is actually necessary. The reason for the first is obvious, to avoid loose contacts with their varying and uncertain resistance; for the second, to allow time for the current to become steady in all four arms of the bridge before testing for a balance; for the third, to prevent altering the resistance of the coils by raising their temperature. It is also important that the contact ends of the plugs should never be touched with the hand; and that they, as well as all other contacts, should be kept scrupulously clean.

The heating effect of the current, or the conversion of its energy into heat by means of resistance, is well known and widely used. On it depends the operation of the electric soldering iron, of the street car heater, of the arc and incandescent lamps. The effect of temperature on resistance is less familiar, and for that reason often introduces

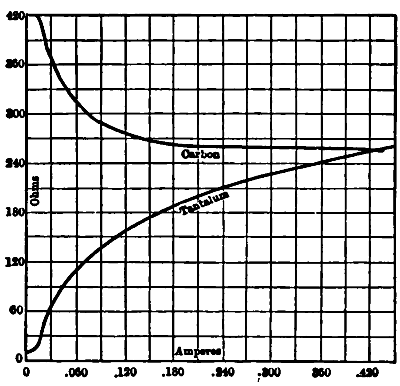

FIG. 14.

errors, the more serious because they are apt to be overlooked, in electrical measurements. The curves shown in Fig. 14 are plotted from measurements taken on two incandescent lamps, one having an ordinary carbon filament, the other a tantalum, through a wide range of current and consequent temperature up to full incandescence. They show a marked increase in the resistance of the tantalum and an equally marked decrease in that of the carbon. In general, the resistance of metals increases and that of carbon, of liquids and of gases, decreases with rise of temperature. With simple metals, such as silver, copper or iron, the increase is approximately uniform at about 0.4 per cent. for every rise of one degree centigrade, while with alloys, it varies widely. The resistance of German silver, which is the most widely used of resistance metals, increases only about 0.04 per cent. and that of platinoid, an alloy often used in the better grade of boxes, 0.02 per cent. for each degree. It is fortunate that the alloys best fitted for resistance work by virtue of their high specific resistance also have the lowest temperature coefficient.

In a shunt or divided circuit, where the current has a choice of two or more paths in parallel, it divides between them in inverse ratio to their respective resistances. The current in each path can be calculated in the same way as in a simple circuit, by dividing the difference of potential across its terminals by its resistance $\left(I = \frac{E}{R}\right)$. For example, if a four party line using the polarity system of ringing has two instruments on the battery side, one of them measuring 7000 ohms to ground and the other 13000 ohms, the current will divide between them, the first—with a 24 volt office battery—taking 0.0034 ampere and the other 0.0018. The total current in the circuit is evidently equal to all the separate currents through the parallel paths added together. In the case of the four-party line mentioned above this would be 0.0052 ampere.

It is often necessary to know the combined resistance of several paths in parallel. When they are equal it can be found by simply dividing the resistance of each path by the number of paths. For example, three equal paths will evidently allow three times as much current to pass as will one alone, and hence offer one third as much effective resistance. When they are unequal, an easily remembered although rather roundabout method is to find the total current flow at any convenient voltage, and calculate the combined resistance from this $\left(R = \frac{E}{I}\right)$. For example, the combined resistance of our four-party line to ground is $\frac{24}{0.0052} = 4615$ ohms. A simpler method, when only two paths are considered, is to divide the product of their resistances by the sum $\left(X = \frac{R_1 \text{ times } R_2}{R_1 \text{ plus } R_2}\right)$. This can be expanded to cover several paths by dividing them into groups of two each, figuring the combined resistance of each group, and then combining these results. A simpler method in actual practice, although rather formidable in appearance and phraseology, is to take the reciprocal of the sum of the reciprocals of the several resistances. The reciprocal of a number is the fraction having that number for its denominator and 1 for its numerator. The reciprocal of X is $\frac{1}{X}$. Following Ohm's law, the value of current in any circuit is, at a given voltage, inversely proportional to its resistance. For example: a circuit of 40 ohms resistance will allow one-half as much current through it at a given pressure as will one of 20 ohms, while its resistance is twice as great. $\frac{1}{2}$ is the reciprocal of 2. The relative current values in the two paths are called their relative conductivities. The conductivity in each case is the reciprocal of the resistance, and the total conductivity of the circuit is evidently the sum of the conductivities of the several parallel paths. The combined resistance, then, can be obtained by inverting this total, or taking its reciprocal.

For example:

$$\text{Let } R_1 = 2000,\ R_2 = 3000 \text{ and } R_3 = 4000.$$

The reciprocals are $\frac{1}{2000}$, $\frac{1}{3000}$, and $\frac{1}{4000}$ respectively. Adding the reciprocals $\frac{1}{2000} + \frac{1}{3000} + \frac{1}{4000} = \frac{6+4+3}{12000} = \frac{13}{12000}$

The reciprocal of $\frac{13}{12000}$ is $\frac{\frac{1}{13}}{12000} = \frac{12000}{13} = 923$. The combined resistance of the circuit, then, is 923 ohms.

Where it is necessary to regulate the value of the current in a circuit, and the e.m.f. is fixed, a variable resistance, or rheostat, is used. This is usually made up of resistance wire so arranged that the length in circuit can be varied by suitable switching devices. It may be made up of a number of accurately calibrated coils, as in our standard resistance boxes and the rheostat of a bridge, but since we are not ordinarily concerned with the actual resistance values, but only with the current strength, a rough approximation is usually sufficient. For temporary use, a water rheostat is often convenient. This consists simply of two metal or carbon plates dipping in slightly acidulated water. The resistance can be varied by varying the distance between the plates or the surface of the plates in contact with the water. Ordinary incandescent lamps are often used, as, for example, in charging leads, and the current varied by varying the number or size of the lamps in circuit.

A loose connection offers a familiar example of a varying resistance, but a resistance set up in this manner is too variable and too uncertain to be of any practical value, with one important exception. When the contact surfaces are carbon the resistance between them can be varied within wide limits by comparatively slight variations of pressure, and in a properly designed carbon rheostat this variation of resistance is fairly uniform.

While the invention of the magnetic hand telephone paved the way to successful telephony, the current set up by it when used as a transmitter was too small to make its use for that purpose commercially practicable. This difficulty was overcome by obtaining the current from a battery and by varying its strength in exact unison with the sound waves by means of a small carbon rheostat operated by a diaphragm, the diaphragm being set in vibration by the sound waves which it was desired to reproduce. A granular carbon transmitter, as usually constructed, consists of two carbon buttons, one fixed to a rigid metal support, the other mounted on the center of the diaphragm, with the space between them nearly filled with carbon in a granular or coarsely powdered form. As the diaphragm vibrates in unison with the sound waves the button—or electrode—attached to it alternately increases and decreases the pressure on the granular carbon, thus varying its resistance and consequently the value of the current through it from the battery. Simple and crude as this arrangement appears, we all know how marvelously accurate and faithful it is in its reproduction. The problem of telephone transmission to-day is not to improve the conversion of sound waves into electrical waves or their reconversion into sound—this is satisfactorily accomplished by the present transmitter and receiver—but to transmit these electrical waves with the least possible loss or deformation in the line or auxiliary apparatus.

QUESTIONS.

1. Name a perfect conductor, or one which has no resistance.
2. Name a perfect insulator.
3. What is the effect of resistance on a current?
4. What becomes of the energy used up in a resistance?
5. Why does a fuse wire melt when overloaded?
6. If 242 feet of No. 36 copper wire measures 100 ohms, about what length of No. 36 German silver wire would be required to make a 100-ohm coil?
7. State Ohm's law in your own words.
8. What is the total resistance of a telephone circuit if the milliameter reads 100 when the office battery is at 24 volts?
9. To what voltage must an office battery be boosted in order to send 0.035 amperes through a circuit measuring 1500 ohms?
10. If an office battery measures 24 volts, a branch exchange battery, 14 volts and the total resistance of the charging circuit is 100 ohms, how much charge will the branch battery receive?
11. At what rate does the potential fall there is a current through a resistance?

12. If the total resistance of a telephone circuit is 250 ohms, and of the transmitter included in that circuit 25 ohms, what is the difference of potential across the transmitter when the office battery is 25 volts?

13. What is the resistance of a ground which measures 10 volts on the low scale of a voltmeter having a resistance of 3333 ohms, when the office battery is 24 volts?

14. Will the ground in question 13 measure the same on the high scale, which has a resistance of 16666 ohms? Why?

15. In a bridge measurement, if $A = 100$, $B = 1000$ and $R = 758$, what is the value of X?

16. In a bridge measurement, if $A = 100$, $B = 10$ and $R = 687$, what is the value of X?

17. In a bridge measurement, should a high or low voltage battery be used? Why?

18. If two relays, one having a resistance of 500 ohms and the other 1000 ohms, are in parallel, with a difference of potential across them of 15 volts, what is the total current?

19. What is the combined resistance in the case given in question 18?

20. State in your own words the principle of the carbon transmitter.

CHAPTER V.

MAGNETISM.

One of the first of natural phenomena to attract the attention alike of the primitive philosopher and of our own childhood was that action of iron which we now term magnetism. The writer has watched with sympathetic enjoyment the triumph of a child who has discovered that by the use of a magnet he can distinguish between an iron screw and an enamelled brass one, thus partaking, in some degree, of the triumph which comes, in full measure, but rarely and to few of the more fortunate and gifted scientific investigators. While the attractive power of the lodestone, like that of rubbed amber, was known from almost the dawn of history, and we have a few isolated records of the early use of some form of the compass needle, no systematic investigation of the principles of magnetism or attempt to frame a coherent theory to guide us in its use was made, or was indeed possible, until comparatively very recent times.

If we mount two magnets, compass needles, for example, in such a way that they are free to turn; they will, unless affected by neighboring magnets or masses of iron, point very nearly north and south. For distinction we term the end which points to the north the north pole of the magnet and the other the south. If now we bring the magnets together we will find that their north poles repel each other, as do also their south poles, while the north pole of one attracts, and is attracted by the south pole of the other; giving us the first law of magnetism, that like polarities repel and unlike attract. This law is universally true and is the only condition of magnetic attraction or repulsion, although in practice we often find seeming exceptions which upset our calculations until properly analyzed.

Following out this experiment further, instead of two similar magnets let us take one fairly heavy bar magnet, resting on the table, and a small, light, magnetized needle, say about one-half inch long, suspended by a silk thread. If we approach the needle to one end of the magnet the law of polarities will place it in line with the magnet, pointing toward the nearest pole. As we move it over the magnet it will take up the positions shown in Fig. 15, indicating that there is a magnetic field set up in all the surrounding space by the magnet, which affects the exploring needle according to its position. We can most readily represent this field to ourselves by considering it as made up of lines of force streaming from the north pole of the magnet, curving out through space, and reentering it at the south

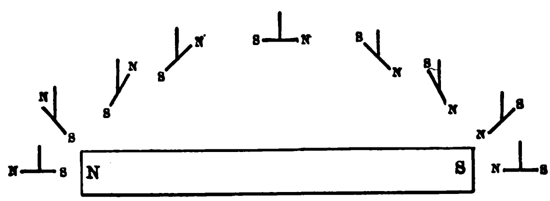

FIG. 15.

pole. This is the meaning of the term "lines of force," not that a field is actually made up of a number of separate lines, but that we can by the use of this expression most readily symbolize in our consciousness the conditions set up by a magnet or a magnetizing force. We are logically bound to assume, under this conception, that every line—or portion—of the magnetic flux which starts out from one pole of the magnet eventually returns, whatever its path may be, by way of the opposite pole of the same magnet; in other words, that we can no more have an open magnetic circuit than we can an open electrical one; and this assumption is correct, so far as we can determine experimentally.

The field around a magnet can also be mapped out in another way which, while not quite as sensitive, shows the general conditions at a glance. If we place a sheet of glass over a magnet and sprinkle iron filings on it, tapping the glass to assist the filings in finding their proper location, they will serve to make the lines of force visible by arranging themselves, through magnetic attraction, in the direction of the lines. Fig. 16 shows the field of a single bar

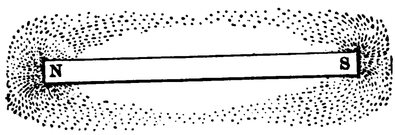

FIG. 16.

magnet as mapped out by this method, and confirms the indications of the exploring needle in Fig. 15. Since the lines of force extend from the north to the south pole the middle of the magnet is comparatively neutral, the field becoming stronger as we approach the poles. Fig. 17 shows, in a sense, the reason for the attraction between

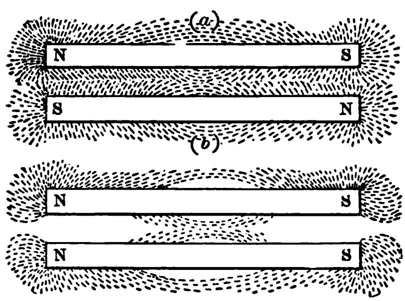

FIG. 17.

unlike polarities and the repulsion between like, which we found in our first experiment. In (a) the lines crowd in between the opposite polarities, taking the shortest path between them; while in (b) they crowd each other away. An examination of this figure will show the following laws as governing the general behavior of lines of force; first, that they tend to flow parallel and in the same direction;

second, that they tend to take the shortest possible path as offering the least resistance—or " reluctance "—; and third, that they never cross each other. A firm grasp on these three fundamental laws will throw a flood of light on the phenomena of magnetism and especially of electro-magnetism.

In Fig. 17 (a) the path of the lines is evidently from the north pole of one magnet into the south pole of the other, through its body to its north pole, across to the south pole of the first, and completing the circuit through the body of the first magnet. If we substitute a piece of soft iron for the second magnet the path of the lines will be essentially the same, although of course the total field will be only one-half as strong. If we define, as we have above, a north pole as the point from which the lines radiate, and a south pole as the one at which they enter, then the piece of iron has evidently become, for the time being, a magnet with definite north and south poles. That this is true can be readily shown by placing a piece of iron anywhere in a magnetic field and testing its polarity while in that position. The part farthest, for example, from the north pole, will be found in each case to have become also a north pole, whether the iron is in contact with the magnet or not. This phenomenon is called magnetic induction, and forms the basis on which depends the operation of all apparatus using a permanent magnet to produce a polarizing or selective effect. Familiar examples in telephone work are all ordinary types of ringers, and the coin collectors which employ opposite current polarities to collect and return.

Since the lines of force form always a closed circuit, they must exist throughout the body of a magnet as well as in the air between its poles. On this supposition, the neutral condition at the middle of the magnet which was indicated by the iron filings is, in a sense, illusory, and if we break a magnet in two at this point the lines will make themselves evident by developing north and south poles at the break. This is, in fact, the case; and no matter how minutely we may subdivide a magnet each portion will be found to be a magnet complete in itself, having equal north and south poles.

This fact has led to the formation of a theory of magnetism in which each molecule, the smallest particle of iron which can exist as iron, is supposed to be a tiny permanent magnet. In soft iron and unmagnetized steel the molecules are supposed to lie in such a position that their poles form closed magnetic circuits among themselves. On subjecting the iron to the stress of a magnetic field the molecules will turn wholly or partly in line with the field, their north poles facing in the direction of the lines of force or toward the south pole of the field. Fig. 18 shows the way in which the molecules are supposed to line up under these conditions, the dark ends representing the north poles of the molecules and the light the south. An inspec-

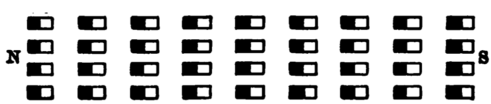

FIG. 18.

tion of the figure will show that the magnetic effects of all the molecules are added together, and develop a north pole at one end of the mass and a south pole at the other, while in the middle they neutralize each other so far as any external effects are concerned.

We would naturally expect that the softer the iron the easier the molecules could be turned in this way, and also the less their tendency would be to retain this strained position when the magnetizing force was removed. This is apparently the case, for soft iron can be magnetized much more readily and strongly than hard iron or steel; while it retains comparatively little, as contrasted with the "residual" or "permanent" magnetism found in hard iron or steel. There is a partial exception to this rule when the magnetic circuit consists wholly of iron. In that case the molecular magnets can complete their circuit as readily through the entire mass of iron as they can by resuming their normal positions. On opening the iron circuit they will of course fall back and form closed circuits among themselves. This is the explanation of the familiar "freezing" of a relay or ringer armature when the air gap is too small to form an effective break in the circuit.

It requires a certain amount of energy to turn the molecules out of their normal positions, and this energy is not all returned to the circuit when the magnetizing action ceases. A certain amount of it is used up in overcoming what appears to be some kind of molecular friction, and consequently appears as heat in the iron. When the magnetism is rapidly reversed, as in the armatures of all motors and generators and the fields of alternating current motors, the heat developed in this way is often serious. This phenomenon is termed "hysteresis."

We can readily see, now, why the law that like polarities repel has many seeming exceptions. If one magnet is placed in the field of another much stronger than itself with the like poles adjacent, the stronger magnet will overpower the weaker and reverse its polarity, and this holds true with both permanent and electromagnetism. The result will, of course, be an attraction where we may have expected a repulsion. This may, perhaps, be made clearer by considering the similarity of action between magnetism and electricity. In electricity, according to Ohm's law, "Current $= \frac{\text{Electromotive force}}{\text{Resistance}}$." The corresponding formula in magnetism, based on the same principle, is "Magnetic flux $= \frac{\text{Magnetomotive force}}{\text{Reluctance}}$." In a circuit having two opposing electromotive forces the direction and volume of the current depends on their relative strengths. Similarly, in a circuit having two opposing fields the direction and strength of the resultant field depends on the relative strengths of the two fields of which it is composed. This similarity cannot, however, be followed too far in practice; because air, although offering a comparatively high reluctance, by no means insulates magnetism as it does electricity. In practice, unless the difference between the two fields is considerable, the actual result will be the formation of intermediate poles in the circuit, the lines from them completing their circuit through the air.

If we dip a wire carrying a current of several amperes into a pile of iron filings it attracts them, and lifts them on raising it. If we cut off the current the filings drop. This action is apparently magnetic; but the wire is not a magnet, because there is no indication of the opposite polarities. We can obtain a section of this field by passing the wire vertically through a piece of cardboard and sprinkling iron filings on the cardboard. The filings will map out a field consisting of concentric circles rotating around the wire as a center and at a right angle to it. As the current increases in value this field becomes stronger and the circles expand to a greater distance from the wire; as it decreases they contract or fall in toward it until when the current dies to zero the lines are all absorbed by the wire. These circles act in all respects like the lines of force set up by a permanent magnet; they attract and repel each other, they tend to flow parallel and in the same direction and to take the shortest available path, they never cross each other, and their direction can be mapped out by a magnetic exploring needle.

If we suspend two wires close together and free to move, with their lower ends dipping into mercury to form a conducting path, they will tend to draw together on passing through them a fairly heavy current, if the current is in the same direction in both; and will repel each other if it is in opposite directions. Each wire will set up a field of its own, and if they are close enough together these fields will distort each other. When they are in the same direction the lines can complete their circuit most readily by uniting and rotating around both wires as a common center, and their effort to make their paths as short as possible will tend to pull the wires together. When they are in opposite directions they will oppose each other and tend to push the wires apart. Carrying this idea somewhat farther, if we suspend an open coil or spiral of No. 22 bare copper wire by one end, with the other end touching a surface of mercury, it will set up a decided vibration when there is a current of two or three amperes through it. The lines of force set up by the several turns unite in this case and rotate around all the turns together as in the preceding experiment. In their effort to make their paths as short as possible they will pull the turns together until the end is lifted out of the mercury, breaking the circuit and destroying the field.

If in a coil through which there is a current we find lines of force passing from one end out into space and returning at the other end, forming a complete magnetic circuit, we have evidently the same conditions as in a permanent magnet. In fact, if we arrange a light coil on a pivot, so that it is free to turn, and provide some means which will not resist turning, such as mercury cups, to complete the circuit through it, we will find that it tends to stand in a north and south direction, that it develops a north pole at one end and a south pole at the other as shown by attraction and repulsion when approached by a permanent magnet or a similar coil; in short, that it acts in all respects as a magnet, although there is not a particle of iron about it.

A little consideration will show that the space inside the coil forms a little less than one-half of the total circuit of the lines of force. If we insert in this space some substance which conducts the lines of force more readily, or has a higher " permeability," than air, we will evidently, in accordance with the modification of Ohm's law which applies to magnetic flux, increase the strength of the field set up by a given magnetizing force. Iron has been found experimentally to have a permeability which, while varying widely in different samples, is in many cases 10,000 times that of air. We would expect, then, that the addition of an iron core to our pivoted coil would nearly double the strength of the field. In practice we find that it considerably more than doubles it. The probable explanation is two fold: first, that the stray fields escaping between the turns are, by the greater permeability of the iron, brought into line with the effective field; and second, that the lines of force through the iron turn the molecules in line with the direction of their flow, by the same action that we found in the case of magnetic induction from a permanent magnet. On the latter supposition the natural magnetism residing in the several molecules is the principal factor in producing the field, the lines set up by the coil acting chiefly as a directing force.

Carrying this idea somewhat farther, if we extend one end of the iron core to a point near the other and on the extension pivot an armature, we have evidently reduced the air gap in the magnetic circuit to the small space between the face of the armature and the adjacent end of the core; increasing the magnetic flux, or the strength of the field, correspondingly. Since the armature is of the opposite polarity to the adjacent end of the core it will be attracted when a current is sent through the winding, and if we arrange contacts so that they are opened or closed by its motion we have a relay which will control a second circuit in accordance with the current changes in the first. Other things being equal, the strength of pull on the armature of a relay depends on the amount of current, as affecting the " ampere-turns " or " magnetomotive force;" and on the size of the air gap, as affecting the " reluctance " or resistance of the magnetic circuit.

The ringer movement universally used in telephone instruments is an interesting example of reaction between two magnetic fields. Fig. 19 shows the skeleton arrangement, where *N* - *S* is the polarizing permanent magnet mounted on a soft iron yoke, with a coil mounted on each end of the yoke and a soft iron armature pivoted in front of the coils and free to swing toward one coil or the other. The inside ends of the two windings are connected together and the outside ends go to line, so that the current around the coils is in opposite directions and tends to magnetize them oppositely. The short dotted lines . . . . . > and the arrows on them show the path of the magnetic flux set up by the permanent magnet and the long ones - - - - > that due to a current through the windings in the direction indicated. On inspection of the figure we note that while with one coil the two fields are in the same direction and assist each other, with the other coil they are in opposite directions and oppose each other. The armature of course moves toward the stronger coil. Reversing the current reverses the field set up by it, reverses the relative strengths of the two coils, and pulls the armature over to the other side. In practice

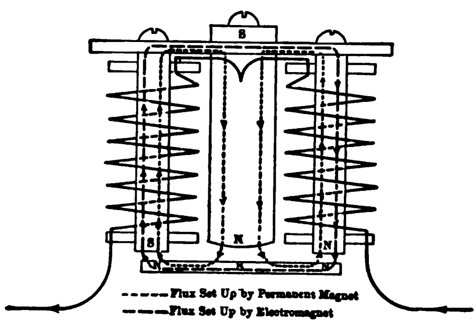

FIG. 19.

this mechanism is operated by an alternating current, the frequency most usually employed being about twenty cycles or forty reversals of direction per second.

The polarity of the field set up by the " idle " coil depends upon the relative strengths of the two opposing fields; that due to the permanent magnet and that caused by the current. With no current the armature is magnetized by induction, its center becoming south and both ends north. The statement is often made that in operation one coil attracts the armature while the other repels it. This is true only when the magnetomotive force of the winding on the " idle " coil is the proper strength to set up a flux through its core approximately equal to and opposing that which the permanent magnet tends to set up through the same core. Below this point the original field, although weakened, is still the stronger of the two and is effective in attracting the armature; above it the coil overpowers the permanent magnet and sets up a flux through itself, the armature, the core of the other coil, and the yoke in series. In either case we have in the core of one coil—and in the air gap between it and the armature—the sum of the two fields, and in the other the difference. This develops a stronger attraction for the armature in the one case than in the other, and the stronger attraction pulls it over.

A somewhat different and perhaps more simple example of reaction between two fields is found in the case of a telephone receiver. In its ordinary commercial form this instrument consists of a horseshoe permanent magnet, each pole carrying a soft iron extension on which is wound sufficient magnet wire to give from 10 to 60 ohms resistance. Facing the ends of these soft iron pole pieces is mounted a thin soft iron diaphragm which is firmly supported at the edges but free to vibrate in the center. The diaphragm is set as close to the pole pieces as possible without touching them, reducing the air gap in the magnetic circuit to a very small space. The center of the diaphragm, which almost closes this circuit, is strongly attracted and is "buckled" toward the magnet. By being put under this tension due to the magnetic field the diaphragm becomes exceedingly sensitive to slight changes in the strength of the field. The inside ends of the two windings are connected together, the outside ends going to line, so that a current through the coils tends to magnetize their cores oppositely. As these cores are already magnetized oppositely by the permanent magnet on which they are mounted, a current in one direction will assist the action of the permanent magnet and pull the diaphragm closer; while in the opposite direction it will oppose and weaken this action, allowing the diaphragm to spring away.

In sensitiveness and accuracy of action, with a mechanical construction absurdly simple when the results obtained are considered; this instrument, which first made telephony possible—being used by Bell as both transmitter and receiver, whence the term "hand telephone" often applied to it—is perhaps the most remarkable piece of apparatus in use to-day. The vibrations of the diaphragm—and consequently the sounds produced by it—are, within reasonable limits, almost exactly proportional to the variations in the current, resulting in practically perfect reproduction; while its extreme sensitiveness enables it to detect a current as small as 0.000 000 000-000 6 ampere, or six ten-thousand-millionths of a milliampere, classing it with the most sensitive galvanometers as a current detector.

By experimenting with a pivoted coil through which there was a current we found that it became, while the current existed, a magnet having distinct north and south poles. From this we developed the electromagnet, which is so important a foundation-stone in our modern industrial edifice. If we examine it closely, tracing the path of the electricity through it, we find that if we face the end of the coil which a test shows to be the north pole the current is directed around it left handedly, or in the opposite direction to the hands of a clock, while at the other end, or south pole, the conditions are of course reversed. Remembering that by convention the north pole of a magnet is assumed to be the one from which the lines of force leave it, to reenter at the south, a little consideration will show that if we look along the wire in the direction of the current the field is rotating around it right handedly, or clockwise. A convenient simile by which to remember this is that if we drive a screw into a board we force it from us by turning it to the right, and draw it toward us by turning it to the left. Similarly, if a current is directed from us the lines of force rotate to the right, while if the current is toward us their direction is reversed.

If lines of force can never cross, but tend to flow parallel and in the same direction, two adjacent wires through which there are currents, will tend to place themselves in such positions, relatively to each other, that the two currents will be parallel and in the same direction. This deduction is confirmed by holding a wire carrying a current above or below the pivoted coil. The coil will turn until the current through its winding is flowing parallel to and in the same direction with that in the wire, bringing the axis of the coil at a right angle to the wire.

Following the same principle, a compass needle, which is simply a pivoted bar magnet, will tend to place itself at a right angle to the wire; the lines flowing from its north to south pole turning it in an effort to place themselves parallel to and in the same direction with those set up by the wire.

This phenomenon suggests the simplest and, in fact, the most sensitive type of galvanometer. If we make a complete turn of the wire around the compass needle, above and below, we double the deflecting force because both portions of the wire tend to turn the needle in the same direction. Two complete turns will give twice the deflecting force of one because, the current remaining the same, we have doubled the ampere-turns; and we can increase the sensitiveness of the galvanometer by adding turns until either the coil becomes so large that the wire is too far from the needle to affect it materially, or the resistance becomes too high.

While the magnetic flux set up by the coil is, within certain limits, approximately proportional to the ampere-turns, the deflection of the needle is not. The angular deflection depends on the relative effects on the needle of two fields; the one, due to the earth's magnetism, tending to keep it in a north and south direction; and the other, set up by the coil, tending to turn it at a right angle to this. With the needle at zero it is in line with the field of the earth and at a right angle to that of the coil; as it turns it swings across the former and the controlling force becomes more effective, while the deflecting force, working at a smaller angle, is less effective. In practice, instruments of this type are used only for very small deflections, where the deflection is nearly proportional to the current.

On account of its sluggishness and sensitiveness to external magnetic influences the needle galvanometer is not suited to general work, and has been replaced, for all except the most delicate laboratory measurements, by a later type usually known, from the name of its originator, as the D'Arsonval galvanometer.

If we send a current through a light coil suspended between the poles of a permanent magnet, the coil becomes

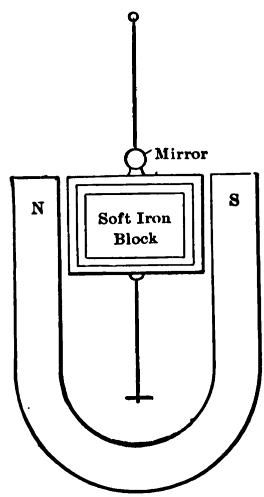

FIG 20.

an electromagnet and tends to turn until its north pole faces the south pole of the permanent magnet, and *vice versa*. If we arrange the leading-in wires as top and bottom suspension, and adjust them so that they tend to keep the coil normally in a position where its axis is at a right angle to the field of the permanent magnet, and mount on the coil either a pointer or a mirror, as shown in Fig. 20, we have a galvanometer which can be made almost as sensitive as the most delicate needle instrument, or can be made easily portable and mechanically strong. As the air gap in which the coil swings is made very small, either by placing a soft iron block inside the coil or by making both the coil and the distance between the pole pieces small, the field set up by the permanent magnet has so much more effect on the coil than does any ordinary external field that the instrument is practically shielded from disturbing magnetic influences.

The turning action of the coil can also be explained in another way which, while it amounts ultimately to the same thing, is perhaps more complete. Fig. 21 shows the reaction between the field of a single wire and that set up by a magnet. The current is supposed to be directed from us and consequently setting up a field which rotates around it right handedly, while the lines set up by the magnet are directed from left to right. Since lines of force can never

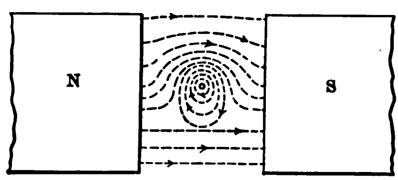

FIG. 21.

cross each other those set up by the magnet are pushed out of place and can reach the south pole only by going around the wire in the same direction as the lines set up by the wire. In their effort to shorten up their path and regain their original shape these lines will evidently pull the wire in a downward direction. Since the strength of the field set up by the wire depends on the value of the current through it, the power of the reaction depends on the strength of this current, as well as on the strength of the fixed field. The effect due to the former we can increase only to a limited extent by increasing the number of turns of wire on the coil; the latter we may make almost as large as we please.

In a commercial ammeter or voltmeter it is highly desirable that the scale be proportional; that is, that a given variation in the current through it shall move the needle the same distance over the scale at all readings. With the D'Arsonval galvanometer the controlling force, being caused by a spring (either torsion or spiral), is proportional to the angle of deflection. If we curve the pole pieces and soft iron core to a circular shape as shown in Fig. 22 the magnetic flux through the coil is the same in all positions, and the deflection becomes directly proportional to the current. To make the instrument portable it is necessary to swing the coil on pivots instead of suspension wires, and to coil up the leading-in wires in the form of flat spiral springs, usually placed one at each end of the coil.

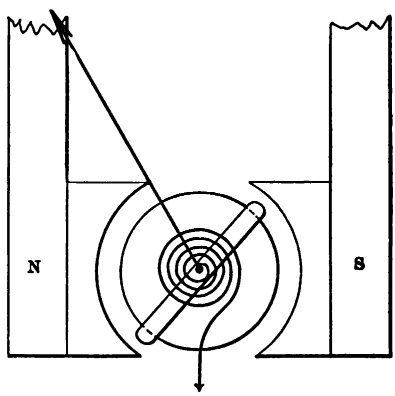

FIG. 22.

Since an ammeter is connected in series with a circuit to measure the value of the current in that circuit; it is essential, in order that inserting it shall not alter the value of the current, that its resistance shall be negligibly small. This is accomplished in practice by using a D'Arsonval galvanometer modified as shown in the figure, and shunting it with a very low resistance, usually a small fraction of an ohm. The current of course divides between the galvanometer and the shunt in inverse ratio to their respective resistances, very much the larger part going through the shunt.

In order accurately to measure the difference of potential between two points it is essential that the voltmeter which we connect across them shall not appreciably lower the resistance between them, or its resistance must be high as compared with that of the rest of the circuit. We accomplish this in practice by using the same sensitive galvanometer as in the ammeter, but instead of shunting it we connect a high resistance—50 ohms or more for each volt to be measured—in series with it. For use simply in measuring voltage the galvanometer should be as sensitive and the resistance in series with it as great as possible, while for use in measuring resistance by the voltmeter method described in the preceding chapter they must be proportioned to suit the special conditions under which the instrument is to be used. For general telephone work about one hundred ohms per volt, or 3000 ohms for a 30 volt scale, is a convenient resistance.

If we arrange the pivoted coil of a D'Arsonval galvanometer so that it can make a complete revolution, by using sliding contacts instead of leading-in wires, and either removing the iron core or fixing it to the coil so that it will turn with the coil instead of being supported on a bracket; the coil will, on sending a current through it, turn until its poles face the opposite poles of the permanent magnet. If we reverse the current at that instant, making the adjacent poles alike, the poles of the coil will be repelled instead of attracted and the coil will make a half revolution, again bringing the unlike poles together. A similar reversal at this point will produce a similar result and complete the revolution. We have now produced a direct current motor, at the same stage of development as the primitive steam engine which required the services of a boy to reverse the valves at the completion of a stroke. If instead of using simple sliding contacts we mount on the shaft the two halves of a split ring, connect the ends of the coil one to each segment, and adjust two brushes touching the split ring at opposite points so that they reverse the connections between themselves and the segments at the instant the unlike poles come together, the rotation will be continuous. While differing widely in design, direct current motors are all built on this principle, and consist essentially of the three pieces of apparatus; field magnet, armature (coil), and commutator with brushes.

QUESTIONS.

1. What is meant by the term " lines of force?"

2. Name the two most common methods of mapping out a magnetic field.

3. On what fundamental law of magnetism does the action of an exploring needle depend?

4. From which pole of a magnet, north or south, are the lines of force assumed to go out into space?

5. In a straight bar magnet, what proportion of the lines sent out from one pole returns at the other?

6. What is meant by the term " magnetic induction"?

7. What is residual magnetism?

8. What causes a relay or ringer armature to " freeze"?

9. What is an electromagnet?

10. Describe the principle of a relay.

11. In what way does increasing the air gap affect the adjustment of a relay or pair of ringers? Why?

12. How many blows per minute does the clapper of a bell give when ringing on ordinary 20 cycle current?

13. If the diaphragm of a receiver touches the pole piece what is the result? Why?

14. If the permanent magnet in a receiver loses it magnetism what is the result? Why?

15. What is the relation between the direction of current through a coil and the location of its north pole? Why?

16. Why does a compass needle turn at a right angle to an adjacent wire through which there is a current?

17. What effect on the deflection of a D'Arsonval galvanometer does reversing the current have? Why?

18. What is meant by a " proportional scale"?

19. Why is the scale of a Weston voltmeter proportional?

20. Name the essential parts of a direct current motor.

CHAPTER VI.

ELECTROMAGNETIC INDUCTION.

While the fact that a current sets up a magnetic field around the wire which carries it, has furnished us with commercially practical electrical measuring instruments, as well as with motors, telephones, and in fact nearly all the apparatus for utilizing that current; its converse, that setting up a field around a wire generates an e.m.f. in that wire, is equally important, since upon this fact depends the operation of the dynamo and induction coil, the former furnishing us with the current and the latter transforming it.

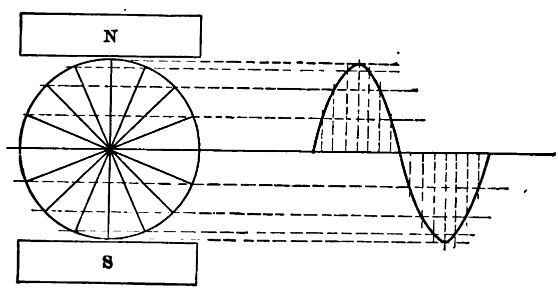

FIG. 23.

A steady field around a wire does not affect it in this respect, but any alteration in the intensity of the field or motion of the wire across it, will set up an e.m.f. in the wire, the value of this e.m.f. being proportional to the rate at which the lines are cut by the wire. Fig. 23 shows several successive positions of a coil rotating in a uniform magnetic field. Starting with the coil in a horizontal position, as we turn it to the right it cuts more and more of the lines of force each instant until it completes one quarter of a revolution, or turns through an angle of 90 degrees. Since the e.m.f. is proportional to the rate at which the lines are cut it rises during this quarter revolution from zero to a maximum. During the second quarter revolution the number of lines cut each instant diminishes, and the e.m.f. falls with it, until both reach zero at the end of the half revolution or a turn of 180 degrees, as the wire is now sliding along the lines of force instead of cutting them. During the second half revolution this process is repeated, except that, as the same wire is now cutting the same lines of force in the opposite direction, the e.m.f. is also in the opposite direction. This suggests a simple method of representing the electrical conditions in the coil, or of plotting the pressure curve. Let us extend a line through the center of the coil at a right angle to the lines of force, and lay off on it any convenient distance to represent a complete turn of 360 degrees. Then one half of this distance will be 180 degrees, one quarter will be 90 degrees, and so on. Since the line connects the two points in the revolution where the e.m.f. is zero it forms a zero or base line for the curve. When the field is uniform the value of the e.m.f. is at all times proportional to the distance of the wire above or below the line. Laying off on the base line one-eighth of the distance representing a complete revolution, the curve will at this point be the same distance above the line that the wire is when the coil has completed one-eighth revolution. At one-quarter the distance it will be at the same height that the wire is at the end of a quarter turn, or will indicate the maximum potential, which we have found to be reached at this point. At three-eighths it has fallen to the same point that it reached at one-eighth and at one-half or 180 degrees the curve crosses the zero line, building up the opposite or negative impulse in the same way below the line and returning to zero at 360 degrees. This is mathematically known as a sine curve, and represents the pressure changes in a coil revolving at a uniform speed in a uniform magnetic field. It is the ideal which is aimed at in designing all electrical generators, and which is, as we shall find in the next chapter, where curves are shown taken from a working machine, very closely approximated in some telephone ringing sets.

While we have considered the conditions in one side only of the coil, similar changes, of course, take place in the other side, but in the opposite direction, because it is cutting the same lines of force as the first but in the opposite direction. These two impulses, in flowing around the coil, unite to give a single stronger impulse.

The current set up in the armature coil—or winding—of every generator is, then, alternating in character. If we want a current of that type for ringing telephone bells or for electric lighting or power distribution over extended territory we terminate the ends of the coil on two solid rings mounted on the shaft, with a brush bearing on each ring, forming sliding contacts. The external circuit con-

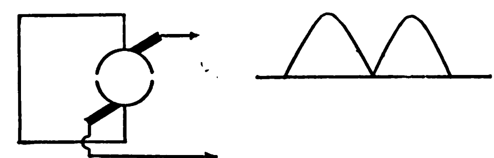

FIG. 24.

nected to the brushes is thus a direct continuation of the coil, and its changes of e.m.f. follow those of the coil.

We may change this alternating current into direct by substituting for the two solid collector rings the two halves of a split ring, forming a two-segment commutator, and by so adjusting the brushes, which are set opposite each other, that they reverse the connections between the coil and the external circuit at the instant that the e.m.f. in the coil reverses. This double reversal, by keeping the current always in the same direction, brings the second impulse above the line and gives the curve shown in Fig. 24. It will be noted that this generator design is identical with that developed in the preceding chapter for a simple motor, and almost any dynamo may be used for either purpose.

This current, while direct, is far from being continuous, as it dies to zero twice during every revolution. If we mount on the shaft a second coil at a right angle to the first its changes of e.m.f. will take place at a right angle to those of the first, and the two curves, by overlapping 90 degrees, will give the resultant shown in Fig. 25. The fluctuations are now much less marked, and by increasing the number of coils sufficiently the curve may be made almost a straight line, and the generator will give a practically continuous current.

It would carry us far beyond the limits of this discussion to consider the multitudinous designs of direct current armatures, but the general principles underlying them all are those developed above.

A modification of the simple two-part commutator which

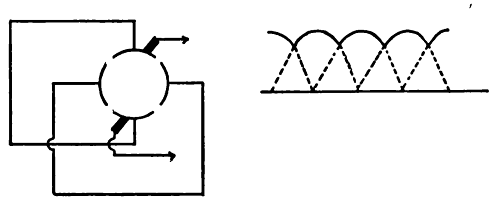

FIG. 25.

is often used on telephone ringing generators consists in permanently grounding one segment. This segment—and the end of the armature winding connected to it—is thus always at zero potential, while the other is alternately positive and negative. The brushes are so set that while the active segment is positive the positive brush is in contact with it; when it reverses and becomes negative the positive brush passes to the grounded segment and the negative brush to the active segment. This virtually splits up the alternating current into its two elements and delivers the positive impulse to one brush and the negative to the other. The curves are shown in Fig. 26. This arrangement is used in connection with a polarity system of ringing four-party lines, the impulse pulling over the armature of a biased bell, while the dead interval allows time for the biasing spring to pull it back. An impulse in the opposite direction pulls the armature in the same direction as the spring and consequently produces no result.

Since the e.m.f. of a generator armature is proportional

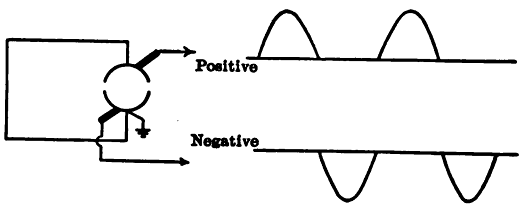

FIG. 26.

to the rate at which the lines of force are cut it can be increased by any one of three distinct methods: first, increasing the length of wire cutting the lines by increasing the number of turns in the winding; second, increasing the speed of rotation; and third, increasing the strength of the field. The first is limited by the space available and

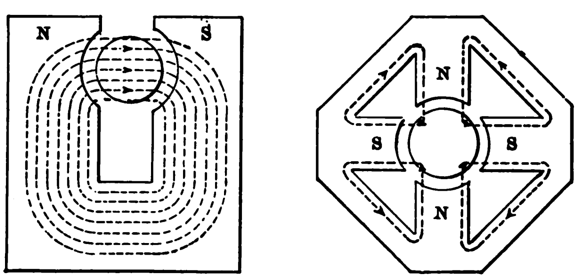

FIG. 27

by the carrying capacity of the wire; the second by mechanical considerations affecting the bearings and the centrifugal force; the third admits of almost indefinite increase either by using larger field magnets or by increasing their number. Referring to Fig. 27, doubling the number of poles evidently has the same effect as doubling the speed of the armature, giving two complete cycles for each revolution. For many reasons the multipolar plan is becoming increasingly popular, particularly where a current as nearly continuous as possible is desired as, for example, in machines designed for charging the storage batteries in telephone exchanges.

A common frequency for alternating current lighting is 60 cycles per second. It would obviously be impossible, from a mechanical standpoint, to run a large armature at a speed of sixty revolutions per second, but by increasing the number of poles we can obtain this frequency at a moderate rotative speed. For example, a machine having twelve poles gives six cycles per revolution, and would hence require a speed of only ten revolutions per second or 600 per minute to furnish a 60-cycle current.

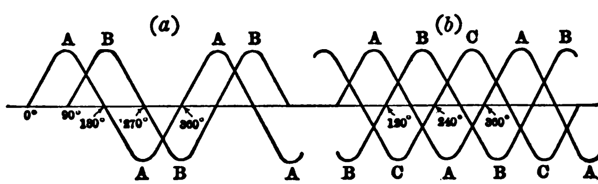

FIG. 28.

On account of the size of wire required to carry a large current, direct-current transmission is not practicable except in small amounts or for short distances. Alternating current can be stepped up or down by means of transformers, which we will consider later, and hence can be transmitted economically for considerable distances. It has proved to be a difficult problem, however, to design a thoroughly satisfactory motor to operate on the simple alternating current which we have described, and the development of power transmission was slow until the invention of the "polyphase" or "multiphase" method.

If to a simple single coil alternator we add a second coil set at a right angle to the first, the e.m.f. changes in it will evidently take place 90 degrees behind those in the first. Drawing the two curves together, we get Fig. 28

(a). If we mount three coils on the shaft, spaced equal distances apart, or at angles of 120 degrees to each other, we get three currents with a phase difference of 120 degrees between them, as shown in Fig. 28 (b). The latter arrangement is the one most commonly used and is known

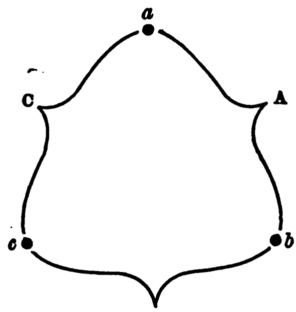

FIG. 29.

as the three-phase system. The angle between the phases is such that the three currents can be carried by three wires. Referring to Fig. 29, if the three dots *a*, *b*, and *c* represent the three wires, *a* and *b* form the two sides of the circuit which carries current *A*, *b*, and *c* carry current *B*,

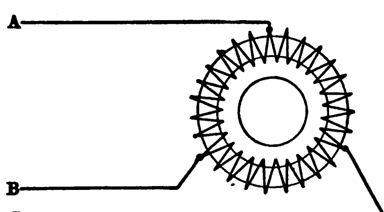

FIG. 30.

and *c* and *a* carry current *C*. If we wind wire in a closed circuit around an iron ring and connect the three line wires to it at points equal distances apart, as shown in Fig. 30, the phase differences will cause the maximum points of the three currents to follow each other around the ring, and the magnetic fields set up by them will pull an armature placed inside the ring around after them. The armature usually used is a simple closed circuit or " squirrel cage " affair and depends for its action on currents induced in its winding by the " rotating " field.

From a mechanical standpoint the three phase motor is almost ideal in its simplicity. It eliminates the most serious sources of trouble found in other motors by having no commutator or brushes, and by using an armature so simple and strong that it can hardly break down. It has rendered possible that extension of long distance power transmission which, perhaps next to that of the telephone, has been the most remarkable and useful development in the electrical field in recent years.

An ingenious and, within reasonable limits, a fairly efficient generator is the ordinary telephone receiver. Referring to the description given of it in the preceding chapter, it is evident that setting the diaphragm into vibration by talking against it will vary the reluctance of the magnetic circuit by varying the amount of air gap between the diaphragm and the pole pieces. This varies the strength of the field in which the coils are located, and thus sets up an e.m.f. in them in one direction while the diaphragm is moving toward the pole pieces and in the opposite direction as it moves away. Although this e.m.f. is necessarily weak, it follows with almost perfect exactness the complex variations of the sound waves, except when these are so strong as to interfere with the exceedingly rapid and delicate vibrations of the diaphragm. The Bell invention which marked the beginning of practical telephony covered the use of two essentially identical instruments of this kind as transmitter and receiver. The only actual difficulty in the use of a receiver—or hand telephone—as a transmitter lies in the fact that it is impossible to increase the volume of transmission from it to a commercial point without sacrificing distinctness. The writer has, however, talked over one from a pole near Fort Sheridan to Joliet, a distance of about 65 miles, including perhaps ten miles of unloaded cable through Chicago, without any difficulty in being understood.

As a current increases in value the circular field surrounding it spreads out like the ripples set up by dropping a stone into water. As it decreases the lines contract toward the wire as a center. An alternating current first sends out circles whirling in one direction, then draws them back to itself, reverses their direction of rotation, and sends them out again. Since lines of force when cutting through a wire generate in it an e.m.f. proportional to the rate of cutting, it is evident that a second wire placed parallel and close to the first will have generated in it an e.m.f. varying in synchronism with the exciting current. If the primary current is alternating the secondary will reproduce it exactly as to frequency and form; if the primary is pulsating or fluctuating the secondary will

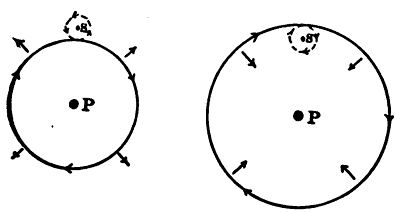

FIG. 31.

still be alternating, in one direction as the primary increases and the field expands and in the opposite direction as it decreases and the field contracts.

In Fig. 31, where *P* is a cross section of the primary wire and *S* the secondary, the primary current is supposed to be flowing from us and consequently setting up a circular field which rotates to the right. In case (a) the current is increasing in value and the circle expanding, as shown by the arrows. As it approaches *S* each point in the circle passes under *S* to the right, or in the same direction that it would if considered as being, for an instant, a point in a circle rotating around *S* left handedly. But this would involve a current in *S* toward us, or in the opposite direction to that in *P*. Accordingly we find by experiment that while the primary current is increasing in value the secondary is in the opposite direction to it. In case (b) the primary current is decreasing, and consequently, while the circle still rotates in the same direction as before, it is contracting, and in returning to *P* it cuts through *S*. As it approaches *S* each point in its circumference passes above *S* in the same direction as if it were a point in a circle rotating around *S* as a center, to the right, corresponding to a current directed from us in *S*, or in the same direction as that in *P*. This gives us the second rule, that while the primary or exciting current is decreasing in value the secondary current produced by it is in the same direction as the primary.

This conception of the relations between a line of force and the secondary wire it is about to cut furnishes us with a convenient and simple method of ascertaining the direction of any induced impulse.

It is evident from an inspection of the figure that if the secondary wire, instead of being parallel to the primary, is at a right angle to it, the circle will not cut across the secondary and no impulse will be induced in the direction of its length, although local eddy currents will be set up in its cross section.

If we wind the two parallel wires in a coil we not only obtain the necessary length in a small compass but utilize a larger proportion of the circumference of the circular field. Remembering our experience with the electromagnet, we would expect that the addition of an iron core would greatly increase the strength of the inducing field and consequently of the induced impulse, and this we find to be the case.

In practice it is not necessary to wind the two wires side by side, provided that they are wound on the same iron core, and are so arranged that all the lines of force set up by the primary shall cut through the secondary.

In any induction coil—using the term in its broadest sense to designate a coil in which an impulse is set up or "induced" in one winding by the electromagnetic action of another—the primary and secondary e.m.fs. bear the same ratio to each other as the number of turns in their respective windings. As in a telephone repeating coil we do not, except in special cases, wish to alter the form of an impulse in any way, but simply to " repeat " it from one circuit to another, the windings in these coils usually have the same number of turns. In the induction coil used in a telephone instrument it is usually considered desirable that the e.m.f. of the secondary impulse shall be higher than that of the primary, and this is accomplished by increasing the number of turns in the secondary winding. In the majority of electric light and power transformers, on the contrary, it is necessary that the secondary be " stepped down." If, for example, the line pressure is 1100 volts, and the desired building pressure 110, then the number of turns in the secondary will be one-tenth of that in the primary. To allow for the inevitable losses in transformation it is of course necessary in practice to make the number of turns in the secondary slightly greater than the ratio would indicate. For convenience in description it is customary in electric lighting and power work, as well as with some telephone companies, to arbitrarily designate the low resistance winding as the secondary, irrespective of its actual function. The unit of electrical power is the volt-ampere or " watt," and is found in any circuit by multiplying the current at a given instant by the pressure which maintains it. Since we can never obtain from any apparatus more power than we put into it it is obvious that if we step the voltage up or down by means of an induction coil, in doing this we necessarily decrease or increase proportionately the value of the current. For example, in the case of the transformer instanced above, if we step the voltage down in a ratio of ten to one, the available current in the secondary will be ten times that in the primary.

The reason for the enormous increase in the practical application of electricity which has been made possible by the use of the alternating current is two-fold. First, the quantity of current required to transmit a given amount of energy in a given time is decreased as the voltage increases—the product of the two remaining constant—; second, the current which can be forced through the resistance of a line varies directly with the pressure. Combining these two factors; if, for example, we double the voltage, we will need only one quarter as much copper in the line to transmit a given amount of energy in a given time.

In practice an alternating current is generated at either the desired line pressure and the machine switched directly to the line, or at a lower voltage and raised to the desired pressure by step-up transformers. At the receiving end of the transmission line it is stepped down by means of another set of transformers to whatever pressure is best suited to the purpose for which it is to be employed. Alternating current, then, is not only economical in transmission, especially at the exceedingly high voltages—between fifty and one hundred thousand—which are becoming increasingly common on long distance lines, but offers a flexibility in handling and an efficiency of transformation which places it in a class by itself as an agent for the transmission of energy.

A single-phase transformer is essentially a simple induction coil, and would be represented by the same symbol as the coil used in a telephone set. A three-phase transformer is made up of three single-phase transformers with their primary—and secondary—windings connected according to one of the methods shown in Fig. 32. These are known respectively as the delta and star methods of connection.

Referring again to Fig. 31; if, instead of being sections of wires in adjacent windings, *P* and *S* are sections of adjacent turns in a single winding, the same causes will tend to produce the same effects as in the former case. That is, as an impulse starts in the first turn of a coil, represented by *P* it produces an impulse in the opposite direction, or generates a " counter e.m.f. of self-induction," in the adjacent turn represented by *S*. After this counter e.m.f. has been overcome—a portion of the original pressure having of course been used up in the process—and the impulse begins to die away its circles of force, in contracting, cut through the adjacent turn again but in the opposite direction, and generate an e.m.f. which tends to maintain the original impulse or to maintain the current after the stoppage or reduction of the original e.m.f. The e.m.f. of self-induction, then opposes either an increase or a decrease in the current through such a coil.

The action of self-induction can be analyzed very simply by keeping in mind the fundamental principles of electromagnetism with which we are now familiar. It differs in no way from the case of simple induction between two separate windings; except that both impulses, inducing

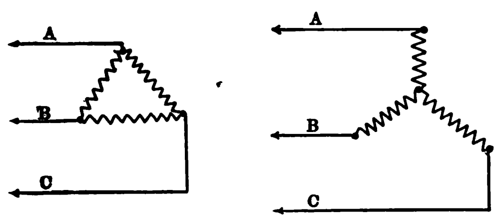

FIG. 32.

and induced, exist in the same wire at the same time, and hence react directly upon each other in a way which makes this an exceedingly interesting and important object of study.

Since the e.m.f. of self-induction is set up by the cutting of the wire in a coil by the lines of force set up by the current through the wire, it can exist only while these lines are expanding or contracting, or while the value of the current is changing. The fact that a certain coil is wound inductively interests us, only so far as its effect upon the current is concerned, when considered in connection with the nature of that current. Perfectly continuous current is affected not at all; a slightly fluctuating one has its variations smoothed out—a familiar example of this is the use of a retardation coil in the charging circuit of an exchange battery to eliminate machine noise—while an alternating current, which is constantly changing in value from one extreme to the other, is affected constantly and to the greatest extent. These three cases are illustrated by the dotted lines in Fig. 33, where the continuous current, although delayed in its rise when the circuit is first closed, quickly reaches its normal value and maintains it; the fluctuating current is smoothed out into

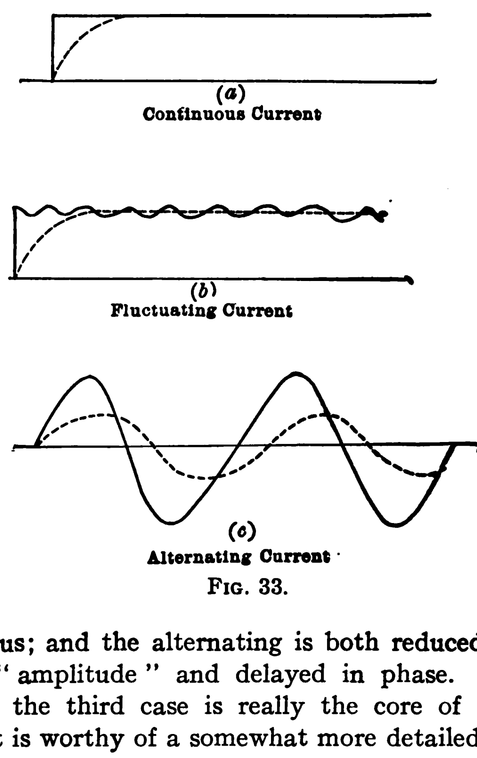

Fig. 33.

continuous; and the alternating is both reduced in quantity or "amplitude" and delayed in phase. Since the effect in the third case is really the core of the whole matter it is worthy of a somewhat more detailed examination.

Since in all cases of electromagnetic induction the value of a generated e.m.f. is proportional to the rate at which the lines of force are cutting through the wire, the e.m.f. of self-induction, which is simply a special case, is, disregarding the modifying influence of an iron core, proportional to the rate at which the current is changing. Starting with the current at its negative maximum, at that instant the circles of force have reached their limit of extension and are neither expanding nor contracting. Consequently they are not cutting through the wire at any point and the e.m.f. of self-induction is zero, as shown in Fig. 34. As the current falls toward zero the circles of force contract, generating an e.m.f. of self-induction which assists the current, and the curve starts down below the line to show that the two impulses are now in the same direction. Supposing the current curve to be a sine, it becomes steeper as it approaches the line, and the e.m.f.

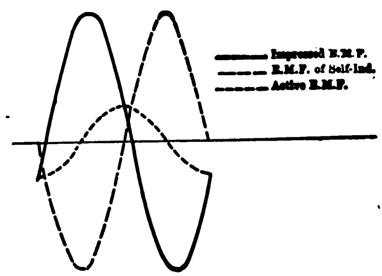

FIG. 34.

of self-induction, being proportional to the rate of change, increases in value until it reaches a maximum as the other crosses the line. As the current increases in a positive direction the circles of force expand, rotating in the opposite direction. This double reversal of magnetic conditions keeps the e.m.f. of self-induction in the same direction as before, but now opposing the current. As the rate of increase in the value of the current becomes less and its curve flattens out toward the positive maximum the generated e.m.f. becomes less, falling to zero as the current reaches its highest point. Coming down the current curve during the next half cycle the same conditions are set up, but now in the opposite direction. The e.m.f. of self-induction comes above the line, assisting the current, reaches its positive maximum as the current curve crosses the line, and falls to zero again when the current reaches its negative maximum. The e.m.f. of self-induction is thus always one-quarter cycle or 90 degrees behind the current, or, employing the usual terminology, the e.m.f. of self-induction lags 90 degrees behind the " active " e.m.f. which is in phase with the current and is maintaining it through the circuit.

Since the current has been retarded in both rise and fall by the e.m.f. of self-induction, the active e.m.f. is evidently the resultant of two factors; the original or " impressed " e.m.f. and the e.m.f. of self-induction; now opposing, now assisting, each other; and is at all times equal to their algebraic sum. We can, in a sense, step backwards; and trace the curve representing the impressed e.m.f. by locating each point in it at a distance above or below the line equal to the algebraic difference between the other two at that instant. On completing the figure in this way we find that the active e.m.f.—or the current—lags behind the impressed e.m.f. to an extent depending on the comparative value of the e.m.f. of self-induction, and this lag is the one referred to when the " lagging effect " of self-induction on alternating current is considered. The extent of the lag ranges from zero in a circuit having no self-induction to 90 degrees in one where this factor is infinite. In practice it can never reach 90 degrees because in that case the power returned to the circuit by the inductance would be equal to the work done upon it; an electrical impossibility. From this lagging or retarding effect comes the term " retardation coil " as applied to a coil designed to utilize this principle.

Closely related to the lag is the reduction in current amplitude suffered by an alternating current in a self-inductive circuit. A further inspection of Fig. 34 will show that as the e.m.f. of self-induction—and consequently the angle of lag—increases the value of the active e.m.f. and of the current must decrease. This is evident both from the mathematical relations between the three curves and from the fact that as the angle of lag increases a larger portion of the e.m.f. of self-induction becomes counter or opposed to the impressed e.m.f., at the same time that it increases in value.

In dealing with alternating current values it is necessary to be especially exact in the use of terms. What, for example, do we mean by the voltage of a current, when that voltage is in a state of perpetual transition? We evidently do not mean the maximum values in such cases because if the curve is a very peaked one the total energy may be small while the maximum is large. An alternating current voltmeter is most simply calibrated by comparison with a direct current instrument, using direct current, and is equally correct for either type of current. If, however, we connect the two instruments to a pulsating generator—such as that used in polarity systems of telephone ringing—their readings will be totally different, the alternating current instrument reading perhaps sixty per cent. higher than the other. This type of pulsating current, it will be remembered, is simply the positive or negative half of an alternating current.

Since the amount of chemical action produced in a voltameter depends simply upon the total amount of electricity in coulombs which has passed through it, irrespective—within wide limits—of the rate, it is evident that it will indicate the average value of the current; and a direct current ammeter or voltmeter does the same. When the heating or power effect of the current is considered we find that it is not at all proportional to this average value; or that the " effective " current or pressure, as indicated by properly designed alternating current instruments, is not the " average " current or pressure.

The unit of power is the watt or volt-ampere.

$$\text{Power} = I \text{ times } E \text{ (or } I\,E).$$

But according to Ohm's law

$$E = I \text{ times } R \text{ (or } I\,R).$$

Substituting this value of E in the first equation:

$$\text{Power} = I \text{ times } I\,R$$
$$= I^2 R.$$

The power in a circuit, then, at any instant is equal to the square of the current at that instant multiplied by the resistance of the circuit, and the average power is equal to the average of all the instantaneous power values. The unit of current may in this way be defined as that which, when squared and multiplied by a given resistance, is equal to a unit of power. In the case of continuous current the instantaneous values are all the same and the square root of the average of the squares of the instantaneous values is evidently equal to any one of the instantaneous values. In the case of alternating current the instantaneous values vary constantly and widely, and since the squares of numbers increase in value very much faster than do the numbers themselves the square root of the average of the squares of the instantaneous values is greater than the average of the values. As the basis of power, therefore, the effective current in any circuit is equal to the square root of the average of the squares of all the instantaneous values of the current, often spoken of as "the square root of the mean square." If

$$\text{Power} = I\,E$$

and acording to Ohm's law—

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

then substituting as before:

$$\text{Power} = E \text{ times} \frac{E}{R} = \frac{E^2}{R}$$

or the power in a circuit at any instant is equal to the square of the e.m.f. at that instant divided by the resistance. This leads to a rule similar to the preceding; that the effective pressure in a circuit is equal to the square root of the average of the squares of all the instantaneous values of the pressure.

With these revised definitions of current and pressure—which, for continuous current work, do not conflict with the older and simpler ideas merely because they are in that case identical with them—we are prepared to glance at the interesting and important subject of power in an alternating circuit. With direct current we can find the power very simply by measuring the current and the voltage and then multiplying the two readings to find the watts. Where there is no self-induction the same rule applies to alternating current. The power at any instant is equal to the product of the current and pressure at that instant, and the average power to the average of all the instantaneous values. We found that self-induction causes the current to lag behind the e.m.f., so that where it is present the product of either the " average " or the " effective " current and pressure—or the " apparent " watts—is greater than the average of the products of the instantaneous values, or the " true " watts. An examination of Fig. 34, where the current is out of phase with the e.m.f. and at times actually opposed to it, may make this clearer.

Aside from its power application this revised conception of current and pressure is all-important to the student of telephone work in connection with the apparent resistance of a circuit. A definition was given in an earlier chapter of resistance, which was purposely limited in its scope to continuous current; because we have here a factor which, under certain conditions, resists the passage of an electrical current and reduces its volume, and is yet entirely distinct from simple resistance. The fundamental differences between resistance and self-induction in application are two; first, resistance affects all currents, irrespective of their form, while self-induction affects them only as they vary in value and is non-existent for continuous current; second, resistance reduces the value of a current by converting a portion of its energy into heat and thus wasting it, while self-induction accomplishes the same object by setting up a counter e.m.f. which virtually lowers the net pressure in the circuit and thus reduces the current without waste of energy. There is, in fact, no loss in a retardation coil except that due to the resistance of the winding and the inevitable iron losses in the core caused by eddy currents and hysteresis. This peculiarity has given rise to the very apt term of "choke" coil, calling attention to the fact that it acts as a reducing valve, reducing or "choking back" the pressure directly. The term "reactance" coil is derived from the fact that its operation depends, first, upon the action of the current in setting up a counter e.m.f., and then on the reaction between this counter e.m.f. and the original pressure.

To cover the apparent resistance of a circuit under all conditions the term "impedance" has been generally adopted. This includes its simple resistance, the opposition due to self-induction, and the apparent resistance which a condenser offers to a varying current; and may evidently be expressed in ohms. Ohm's law, then, as covering all conditions, becomes

$$\text{Effective current} = \frac{\text{Effective e.m.f.}}{\text{Impedance}}.$$

In the case of continuous current these three factors are equivalent to the three simpler terms previously considered; to determine their values under other conditions is the problem of alternating current study. Effective current and pressure may be measured directly by properly designed instruments; impedance is somewhat less simple in its content but may be calculated from the other two.

Since the action of a retardation coil depends primarily on the intensity of its magnetic field this is ordinarily made as great as possible by a liberal use of copper and iron. To make the number of ampere-turns very large while keeping within resistance limits a comparatively large wire is used, while the reluctance of the magnetic circuit is made as low as possible by using a closed circuit, with no air gaps or external poles, and by using a comparatively large amount of very soft iron. As in most induction coils, eddy currents are minimized by laminating the iron core, building it up of a number of small iron wires which are rusted sufficiently to insulate them from each other.

Where it is necessary, as in resistance standards, to wind wires in coils but without self-induction, a non-inductive arrangement is used; doubling the wire in the middle, fastening the doubled portion to the frame, and winding the two halves side by side, bringing the ends out together. A little consideration will show that the mangetic effects of the two halves of such a winding are equal and opposite, and will therefore neutralize each other.

Where it is necessary, as in the case of a relay which is included in a talking circuit, to preserve the magnetic effect but at the same time to avoid the distortion and attenuation caused by self-induction, an ordinary magnetizing winding is placed on the core to operate the relay, and a higher resistance non-inductive winding shunted around it to provide a by-path for the speech fluctuations. As an instance, the writer recalls a number of 20-ohm tubular relays which had caused transmission complaints on account of their high impedance. To remedy this a thirty ohm non-inductive winding was added, giving a combined resistance of twelve ohms. The non-inductive shunt of course weakened their action, but improved their talking qualities very materially. Where it is not admissible to weaken the relay action in this way a condenser may be used instead of the non-inductive shunt, and serves the same purpose so far as transmission is concerned, while not diverting any of the signalling current.

While perhaps outside of the proper scope of this book, a brief outline of the three fundamental electrical units as affected by alternating conditions may be of interest.

In order to accurately measure effective current or pressure an instrument must be used whose indications are proportional to the average of the squares of the instantaneous values of the current passing through it. The instrument most generally used for this purpose is some type of the electrodynamometer. This consists essentially of two coils; one fixed, the other pivoted or suspended inside it but normally held at a right angle to it by a torsion spring. On establishing a current through the two coils in series the reaction between their fields tends to turn the movable coil in an effort to place it in line with the fixed coil. Since the intensity of the field set up by each coil is proportional to the current through it, while the deflecting force is the product of the two, the deflecting force is evidently proportional to the square of the current. The same plan is followed in these as in direct current instruments, shunting the dynamometer for use as an ammeter and cutting a dead resistance in series with it for use as a voltmeter. Caution is necessary in doing this, however, as the self-induction of the fixed and movable coils is apt to introduce an uncertain impedance and affect the reading.

Disregarding electrostatic capacity, the impedance of a circuit depends upon its simple resistance, its inductance

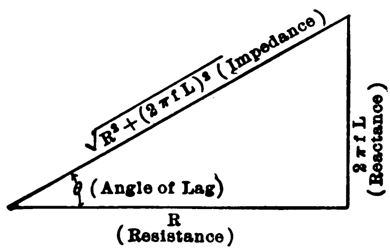

FIG. 35.

(or coefficient of self-induction), and the frequency of the current through it. A coil is said to have an inductance of one " henry " when a change of one ampere per second in the current generates an e.m.f. of one volt. As practical illustrations, a bipolar telephone receiver has an inductance of about one-third henry, while that of a pair of 1000 ohm ringers is from ten to thirty. These values, of course, vary widely with design and adjustment; but, within reasonable limits, are not very materially affected by the frequency.

Since the value of a generated e.m.f. is proportional to the rate at which the lines of force cut through the wire it is evident that increasing the frequency of an alternating current through a self-inductive coil will, by increasing this rate, increase the e.m.f. of self induction; although not in proportion, since the current will be somewhat smaller. This in turn increases both the angle of lag and the impedance. The mathematical relations between impedance, reactance, resistance, and lag may be very conveniently expressed by the right triangle shown in Fig. 35. If one of the acute angles is made equal to the angle of lag, the adjacent side to the simple resistance, and the opposite side to the value $2\pi f L$ ($\pi = 3.1416$, f is the frequency in cycles per second, and L the inductance in henrys), then the hypothenuse will equal the impedance. By the application of the simpler rules of geometry and trigonometry to this triangle many of the elementary problems of alternating current can be readily worked out.

Questions.

1. What is the cause of the current set up by a generator?

2. What is the difference between a direct and an alternating current generator?

3. What is the principle of the polarity system of four-party ringing?

4. What is the effect on transmission from a hand telephone used as a transmitter if the diaphragm touches the pole pieces? Why? If it is too far away? Why?

5. Why is the current in the secondary winding of an induction coil always alternating?

6. If the primary of an induction coil has 500 turns and the secondary 1250 what is the value of the e.m.f. generated by opening and closing a ten volt primary circuit?

7. What is the difference in principle (not in construction) between an induction coil and a retardation coil?

8. On which type of current does a retardation coil have the greater effect, continuous or alternating? Why?

9. What are the two effects on alternating current of self-induction?

10. What is meant by the " lag " in an alternating circuit?

11. What is the meaning of "impedance"?

12. What is a "watt"?

13. Should a retardation coil have an open or closed magnetic circuit? Why?

14. Describe a non-inductive winding. Why is it non-inductive?

15. Will a retardation coil offer more or less impedance to a current of 100 cycles per second than to one of 200 cycles? Why?

CHAPTER VII.

CAPACITY.

When investigating the subject of electrical pressure we found that what we know as a charge of electricity was produced on raising or lowering the potential of a body, and that this charge, being apparently a definite amount of electricity under a greater or less pressure than normal, tended to discharge itself in the form of a current unless thoroughly insulated. By examining the distribution of the charges on an egg shell when approached by a charged body, we found that by means of electrostatic induction one charge will, if close enough, set up or affect another, even though the two bodies may be insulated from each other. In the experiment referred to, let us suppose that the original charge is positive and that the induced positive charge on the eggshell has been removed by touching it with the finger. The corresponding negative charge remained on the egg instead of discharging through the hand because it was held there by the attraction of the positive charge on the electrophorus disk. On removing the disk it spread over the surface of the egg and was free to discharge when offered a conducting path. We have here an illustration of the phenomena of " bound " and " free " charges, or charges which, in the one case, are prevented from discharging by the attraction of an adjacent charge of the opposite polarity, and in the other exist, to most intents and purposes, alone, and may be considered as being simply conditions of abnormal pressure which naturally tend to become normal by means of a discharge.

If we insulate a sheet of tinfoil and charge it by an electrophorus disk we will evidently be able to force into it only enough electricity to bring it to the same potential as the disk. This charge will be free, that is, it can be drawn away by grounding it. If we paste the tinfoil to one side of a sheet of glass the conditions will still be the same. If we paste a similar sheet to the other side of the glass it will be acted upon in precisely the same way that the eggshell was in the former experiment, by electrostatic induction through the insulating glass from the other sheet of tinfoil, an induced negative charge being drawn to the side next to the glass and an equal positive charge repelled to the outer surface. The induced positive charge can now be drawn away to ground, leaving the negative charge bound by the attraction of the positive on the other sheet. It is, however, impossible to conceive of one charge as binding another without being itself bound, at least to some extent, by the other, and accordingly we find that the larger portion of our original positive charge cannot now be drawn away by grounding it; it has ceased to be free and is bound by the attraction of the negative charge which it has itself set up. Also, it is evident that this attraction will allow us to force more electricity into the first sheet of tinfoil from the electrophorus disk than before, at the same potential. The electrostatic capacity of a body, or the quantity of electricity which it will hold on its surface at a certain potential depends largely, then, on its position relatively to other bodies, and also on their condition, and from its ability to condense or concentrate a larger quantity of electricity on one of its tinfoil layers than it would otherwise hold at the same potential comes the term condenser as applied to a piece of apparatus depending on the principle we have developed. A condenser consists essentially of two insulated conducting bodies, close enough together to act upon each other by electrostatic induction, but separated by some insulating substance. The insulating layer, which may be air, glass, mica, paraffined paper, or any other suitable insulator, is called the dielectric, and the conducting bodies the coatings or plates.

Strictly speaking, since the charges on the two plates are equal and opposite, a condenser as ordinarily used stores, not electricity, but electric energy; because in order to make the charges equal and opposite as much electricity must be drawn from the negative plate as is forced into the positive. This can be proved by charging a condenser in any convenient way, then discharging it by connecting the two plates together, and then testing each plate separately. They will both be found at zero potential, showing that the excess quantity of electricity on the positive or high pressure plate exactly neutralized the deficiency on the negative or low pressure plate.

The unit of capacity is the farad. In a condenser of one farad capacity a difference of potential of one volt across its terminals set up, for example, by a one volt battery connected across them, will transfer one coulomb of electricity from its negative to its positive plate. This unit would be extremely unwieldy for practical use, and is for that reason usually divided into millionths, or microfarads, (abbreviated mf.) just as we often divide the ampere into thousandths, or milliamperes.

Since a charge is self-repulsive, its different portions, if we may use that expression, tending to force each other as far apart as possible, no portion of a static charge is ever found inside of a conductor, but only on its surface. For the same reason, when the surface is uniform a charge spreads over it uniformly. The capacity of a condenser, then, is independent of the thickness of the plates, but varies directly with their surface.

Since the charge on the electrophorus disk did not noticeably affect the eggshell until it was brought fairly close to it, it is evident that electrostatic induction, which is so important a factor in the operation of a condenser, is dependent largely on the distance between the two bodies. It can be proved experimentally that the capacity of a plate condenser is inversely proportional to the distance between the plates.

If in the eggshell experiment we had filled the space between the disk and the egg with various insulating substances we would have found marked differences in the intensity of the inductive effect. The effect produced by electrostatic induction, and consequently the capacity of a condenser, depends then, not only on the thickness of the dielectric but also on the material of which the dielectric is composed. The readiness with which a dielectric will allow electrostatic induction to act through it, as compared with air, is termed its specific inductive capacity. The specific inductive capacity of paraffine is about two; of shellac, about three; of glass, from six and one half to ten. A condenser using paraffine—or, what is almost the same thing, paraffined paper—as a dielectric has about twice the capacity of a similar condenser using air, provided, of course, that the surface of the plates and the distance between them is the same in both cases.

Summing up, the capacity of a condenser, or the amount of charge which it will hold at a potential difference of one volt between its terminals, varies directly with the surface of its plates, and inversely with the distance between them, and also depends on the nature of the dielectric.

The volume of a quantity of air is measured in cubic feet, and the capacity of a tank is also expressed in the same terms, much as a quantity of electricity is measured in coulombs and the capacity of a condenser in farads. It by no means follows, however, that we can put only ten cubic feet of air into a tank having a ten foot capacity, or that a one farad condenser will hold only one coulomb. In both cases it is a matter simply of pressure, and by doubling the pressure we can double the quantity held in either the tank or condenser.

If we suspend a weight by a string, forming a pendulum, and strike it sharply, the length of the resultant swing is a reliable indication of the amount of energy in the blow. Since the actual quantity of charge in an ordinary condenser is very small in comparison with the potential difference across its terminals—in a 2 mf. condenser there is only 0.000002 of a coulomb per volt—the current produced on closing the circuit is, unless the resistance of the circuit is very high, practically an instantaneous impulse. If a galvanometer or voltmeter be included in the circuit this impulse has the effect of a blow, producing the familiar " condenser kick " of the needle, and the extent of this kick is an accurate indication of the amount of the discharge. The same is true of the charge, and condenser charges and capacities can be readily compared with a good voltmeter. With a given condenser the swing of the needle is nearly proportional to the amount of the charge, and it can be readily shown, for example, that 220 volts will impart twice as heavy a charge to a 2 mf. condenser as will 110 volts. Since with a given potential difference the volume of the charge is proportional to the capacity we can readily compare the capacities of two condensers by charging or discharging them through a voltmeter.

Since the opposite charges on the plates of a condenser are held by their mutual attraction the dielectric is under a constant stress in holding them apart. In addition to ordinary leakage, which, since no insulator is perfect, always exists to some extent and will in time discharge the condenser, there is an actual deformation of the dielectric, its particles being apparently turned in the direction of the lines of induction. As the potential difference increases this deformation also increases until the dielectric breaks down and the condenser discharges through. This is precisely what happens to the condenser in an unprotected telephone in case of a lightning discharge or high tension cross. The same principle is utilized in carbon plate arresters, where two plates of carbon are separated by a small air gap, one plate being connected to ground, the other to line.

When a condenser is discharged the particles of the dielectric do not, except in the case of air, at once resume their normal position. It is a familiar fact that on charging or discharging a condenser through a head telephone by tapping it, we get a succession of gradually diminishing clicks in both cases. This " soaking-in " effect, as it is called in the one case, and " residual charge " in the other, is due to the deformation of the dielectric, the particles being gradually displaced on the charge and as gradually returning to their normal position on the discharge.

Since the two sides of a telephone circuit are conductors, separated by insulation of some kind, they form the two plates of a condenser, having usually a very appreciable capacity. Like all others, the capacity of this condenser depends upon the amount of surface, the distance between the plates—in this case the wires—and the nature of the dielectric. All open wire tests depend upon this fact, since it is evident that, other things being equal, the capacity of a line or conductor is directly proportional to its length. The test usually made on a testing disk is to charge and discharge the line, considered as one plate of a condenser with the ground as the other, through a voltmeter, and estimating its capacity, and consequently the distance to the fault, by the kick of the voltmeter. In cable testing the capacity of the open conductor is compared directly with that of a good one in the same cable by means of a bridge. The sound test used by every repairman depends on the same principle; putting a head telephone between line and ground and comparing the noise on the two sides of the line. This test utilizes the constantly varying earth potential, and probably in some cases that of the air, to charge and discharge the line through the head telephone. Testing desks are frequently equipped with a ground key which connects the telephone in the same way and affords a test much quicker and more sensitive than the more common test with a voltmeter.

Since the two plates of a condenser are separated by insulation it is obvious that when cut in series with a circuit it opens the circuit so far as continuous current is concerned. Its ability to receive and give out a charge, however, sets up an entirely different set of conditions where alternating or fluctuating currents are concerned, and investigation along this line opens up a wide and fascinating field of study.

If a generator which sets up an alternating e.m.f., having the form of the sine curve which we found in the case of the ideal generator discussed in the preceding chapter, is connected to the two sides of a short open line, the difference of potential across the ends of the wires forming the line will evidently be the same at any instant as that across the terminals of the machine, because, the circuit being open, there can be no current through it. Raising the potential of any body, however, requires the transfer of some quantity of electricity to that body, just as raising the pressure of air in a pipe involves forcing some additional air into the pipe. There is, then, some current in the circuit, but as the capacity of two short wires, and consequently the amount of electricity which they will hold at ordinary pressures, is inappreciable, this current is too small to be detected. If we connect the wires to the terminals of a condenser the circuit is still open, but the capacity of its two sides is no longer negligible, and the current required to transfer enough electricity through

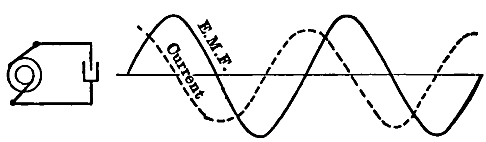

FIG. 36.

the circuit to keep up the difference of potential across its ends increases in proportion to the capacity. As the potential of the machine rises there is a current into the condenser, charging it; and raising its potential in step with that of the machine. The value of this current will depend on the rapidity with which the potential is rising. When the potential of the machine is at a maximum that at the ends of the wires, or at the terminals of the condenser, has reached the same point. Since there is no further rise there is no occasion for any further flow of electricity, and the current accordingly dies to zero. Referring to Fig. 36, which shows the connections and also the pressure and current curves, when the pressure curve has reached its highest point the current curve has fallen to the zero line. As the potential of the machine falls, that across the terminals of the condenser, being connected to it, falls with it. But the charge which a condenser, or any other charged body, will hold, depends directly upon the pressure. The condenser cannot, then, now hold all of its original charge, and since, if it did hold it, the condenser would be at a higher potential than the machine, the excess charge flows out of the condenser and back through the machine. Its direction is opposed to the e.m.f. of the machine and is consequently in the opposite direction to what it was before, and the current curve falls below the line. Considering the change in the potential of the machine from the positive maximum to the negative maximum as simply a fall of pressure from the highest to the lowest point, this reversed current will evidently continue until the point of lowest potential is reached, and will then cease. The current curve, then, falls back to the zero line at the instant when the potential of the machine reaches its negative maximum. As the potential of the machine begins to rise from this point, in order that the potential of the condenser may rise with it electricity must flow from the machine to the condenser, charging it, and this current will exist until the potential of both reaches the positive maximum and the condenser is fully charged. As the value of current required to keep the potential of the condenser in step with that of the machine depends on the rate of change in that potential, the current reaches its maximum value in either direction when the potential is changing most rapidly, which, in the case of the sine wave, is when the curve crosses the line. The current is in one direction, then, when the potential of the machine is on the up grade, and in the opposite direction when it is on the down grade, reaching a maximum value in both cases when the potential is crossing the line. An inspection of the curves will show that this results in the current changes taking place exactly one quarter of a cycle, or 90 degrees, before the corresponding pressure changes, or that the current "leads" the pressure by this amount. For the sake of simplicity we have considered only one side of the circuit—and the condenser plate connected to it—but since the total quantity of electricity in the circuit is the same at all times (we can neither create nor destroy electricity, but only alter its pressure and distribution) it necessarily follows that similar changes have taken place in the other side, but in the opposite direction. For the same reason it has been supposed that the pressure curve is a pure sine, and that resistance, self-induction, armature reactions in the machine, and other factors which complicate the problem in actual practice, can be neglected.

Telephone ringing generators are built to approximate these conditions as closely as possible. When ringing through a condenser, then, the curve of the current through the circuit—and consequently through the ringers—to and from the condenser terminals is, although differing in phase, very nearly the same in shape as it would be were the condenser left out. There is one peculiarity which should be noted here. The self induction of a pair of ringers is necessarily very high, and causes the current through them to lag considerably behind the e.m.f. The leading effect of the condenser, being opposite in direction to this lagging effect, partially neutralizes it and brings the current more nearly in phase with the e.m.f. In some cases a noticeable improvement in ringing has been found on cutting a condenser into the circuit, and it can be shown that with a pair of 1000 ohm ringers operating on an ordinary 20 cycle generator current the impedance of the combination can be reduced to the simple resistance of the ringers by raising the capacity of the condenser to from two to eight microfarads, according to the inductance of the ringers. While the popular statement that a condenser allows alternating current through it is not, strictly speaking, correct, it represents the to and fro motion of the electricity closely enough for most practical purposes.

When fluctuating or pulsating e.m.fs., which, although they are in one direction only, are constantly changing in value, are considered, the question becomes somewhat more complicated. In examining the operation of the common battery booster circuit outlined in Chapter III, we found that a fluctuating current can often be considered as made up of two separate currents, a continuous and an alternating, combined in one circuit. We can see somewhat more clearly now why, in that circuit, we talk metallic—through the condenser—although signalling grounded.

The effect of cutting a condenser in series with a pulsating ringing current, which consists of uniform impulses in one direction with dead intervals of equal length between, is somewhat peculiar. It is a well known fact that the result is to convert it into some kind of an alternating current, and on analysis the conditions appear as shown in Fig. 37. During the dead interval the generator brush

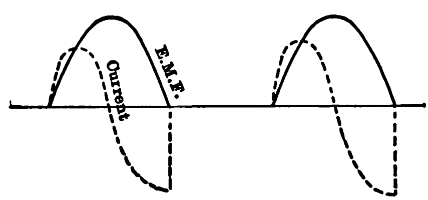

FIG. 37.

is on the grounded segment of the split collector ring; both the machine and the condenser are at zero potential, and there is no current. When the brush strikes the active segment and its potential begins to rise electricity must flow from the machine to the condenser in order to keep the potential of both at the same point. As the potential is rising the most rapidly at the beginning of the impulse, the current curve will be a maximum at this point, falling as the pressure curve flattens out, and dying to zero when the potential of both machine and condenser reaches a maximum. As the total rise of potential has been only one half that found in the case of the alternating e.m.f. (from zero to positive maximum instead of from negative maximum to positive maximum) the quantity of electricity required to raise the potential of the condenser to this point, or the positive current impulse, is only one half that in the former case. As the potential begins to fall the charge flows out of the condenser and brings the current curve below the line in the same way as in the case of alternating e.m.f. The current increases in value as the potential falls more rapidly, and tends to build up a negative impulse of the same form as in Fig. 36, but at the instant that the pressure curve reaches the zero line the generator brush strikes the dead segment, and pressure and current stop together. Since the positive impulse consists of the charge, and the negative impulse of the discharge, of the condenser, they must evidently be equal in quantity, while the area bounded by the negative curve,

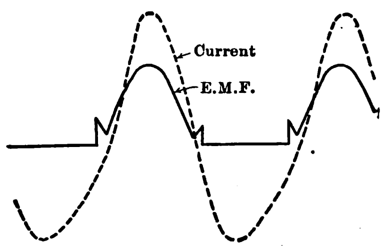

FIG. 38.

which represents this quantity, in Fig. 37, is evidently only one half as great as in Fig. 36.

We have here, then, a true alternating current consisting of two equal impulses succeeding each other in opposite directions, completing a cycle while the e.m.f. completes one half cycle, and then followed by a dead interval of equal length.

This analysis, like the former, assumes that there is no self-induction or other disturbing factor in the circuit to complicate the problem. The actual conditions in telephone ringing are of course very different on account of the high self-induction of the ringers or relays. Fig. 38 is a curve taken on ordinary twenty cycle pulsating generator when ringing a 1000 ohm bell through a 2-mf. condenser. The current starts up with the pressure at the beginning of an impulse as before, but the counter e.m.f. of self-induction, by opposing this rise, causes it to be more gradual, and delays its peak to about the same point as the peak of the pressure curve. It retards the fall in the same way, bringing the current curve back to the line at about the same time as the pressure. While the pressure has now reached zero, still the condenser is fully charged, and tends to discharge in a sudden rush of current, which, however, is retarded in the same way as the charge until it covers practically all the dead interval in an approximate sine wave. While the total amount of energy conveyed by the current is still only one half as great as when the full alternating e.m.f. is used, the two current curves are now very similar and produce almost the same effect, except, of course, in the strength of the ring.

In practice, however, we find a noticeable difference in the magnetic effect of the two impulses, and this is accounted for by their difference in shape. As an illustration of this, the biased bell used in polarity systems of four-party ringing can be readily adjusted to ring through a condenser without interference, although the opposite impulses going through it are actually equal in quantity. This adjustment is, of course, too delicate for commercial use.

We have considered so far only the effects of a condenser cut in series with the line. The question of distributed capacity, where the two sides of the line itself act as the plates of a condenser, with the capacity distributed throughout its entire length, is considerably more complex. Since the distance between the wires is so much less in a cable than on an aerial line the capacity of comparatively short lengths of cable conductors is more serious in its effects on telephone transmission than that of fairly long aerial wires. Standard transmission, as defined in Chicago practice, does not admit of a greater loss than that due to the equivalent of eighteen miles of No. 19 gage cable having a mutual capacity of 0.060 microfarads and a loop resistance of about 88 ohms per mile. Simple resistance is in itself, within reasonable limits, comparatively unimportant as a cause of transmission loss, except where it cuts down the current to the transmitter—it is perfectly possible to talk through a lead pencil mark on a piece of paper—but in connection with distributed capacity it becomes a serious element.

For the purpose of analysis the problem is made simpler by considering the capacity as due to a number of separate small condensers bridged across the line at intervals, as shown in Fig. 39, the principle and result being essentially the same as in actual practice. As an impulse set up by the transmitter flows over the line a portion of it is absorbed by each condenser, charging it until it reaches the same potential as the point of the line to which it is connected. We cannot now neglect the line resistance as we did when first analyzing the simple case of a condenser

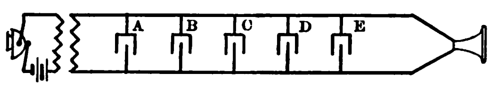

Fig. 39.

connected directly to a generator, because there is a fall of potential through the resistance of every closed circuit, and in this case the fall is aggravated by the shunting effect of the condensers. Condenser *A*, then, receives the heaviest charge; condenser *B* a somewhat lighter one; and so on through the circuit until, if there is any of the impulse left after charging all of the condensers, it produces sound in the receiver. As an impulse reaches a condenser it must charge the condenser to its own potential before it can pass on, using up a quantity of electricity depending on the capacity of the condenser and the difference of potential across its terminals. The quantity of electricity flowing past any point in a circuit during a given time depends on the originating e.m.f. and on the resistance of the circuit. Combining these two facts, it will evidently take a definite, although very small, interval of time to draw enough electricity through the circuit to charge the condenser to the potential of the impulse, and the length of time required will depend, other things being equal, on the resistance of the circuit and the capacity of the condenser. This is the $C R$ law as applied to transmission, both telegraphic and telephonic, and in practice we find that the transmission loss in a circuit is approximately proportional to the product of the capacity in microfarads and the resistance in ohms. If the impulse does not last long enough to overcome all of the resistance in the circuit and charge all of the condensers it is evident that none of it will reach the receiver.

During the rise of the impulse we have found a certain shunting effect, but if the impulse lasts long enough the current will eventually reach its full value at the end of the line. As the impulse dies away the differences of potential across the terminals of the condensers fall, causing them to discharge back into the line. So far as the flow of electricity into and out of each condenser is concerned, the action is, except as it is slowed up by the line resistance, essentially the same as in the case of the series condenser previously considered. The time interval loss due to the combined resistance and capacity will cause a uniform displacement in phase and the shunting effect will cause a reduction in the value of the current at the farther end of the line.

The charge and discharge of the condenser may produce simply a virtual shunting effect, as shown by a reduction in the amplitude of the wave or the volume of the sound, or it may produce an actual distortion of the wave and muffling of the sound, according to circumstances. In practice, both effects unite to limit telephone transmission. Assuming the capacity of each of our bridged condensers to be small as compared with the amount of electricity flowing, as an impulse reaches each condenser it divides; a portion of it flowing into the condenser and charging it while the potential of the impulse is rising, and the remainder flowing on through the circuit and keeping in phase. As the potential of the impulse falls the condenser discharges back into the line, causing the portion of the original impulse which had been used to charge it to lag 90 degrees behind the other portion. This charge will divide on reaching the point where the condenser is connected to the line, a portion of it flowing after the original portion which is still in phase and distorting it by the 90 degree lag, while the other portion flows back toward the source of e.m.f., opposing and distorting any succeeding impulse.

The form of the current used in telephone transmission is exceedingly complex, but it can be considered as a combination of simple sine waves of widely varying fre-

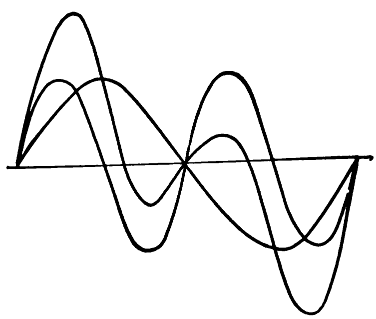

FIG. 40.

quencies as shown in Fig. 40. We have found that since under certain conditions the counter e.m.f. of self-induction is proportional to the rate of change of the current the higher frequencies are retarded in phase and reduced in amplitude or volume more than the lower, causing a distortion of the complex speech wave. Comparison between this and the result produced by capacity leads to interesting and important results.

Referring to Fig. 41, where the second curve has twice the frequency or half the time length of the first, it is evident that an angular lead of 90 degrees due to capacity will produce only half the lead in point of time on the higher frequency that it will on the lower. A little consideration will also show that in rapidly charging and discharging a condenser its impedance or apparent resistance will be less for the higher frequencies than for the lower, because, the e.m.f. being the same, the quantity of electricity conveyed is dependent on the length of time the current exists, while the capacity of the condenser is fixed.

Referring to Fig. 42, let us investigate the action of bridged or distributed capacity and series inductance

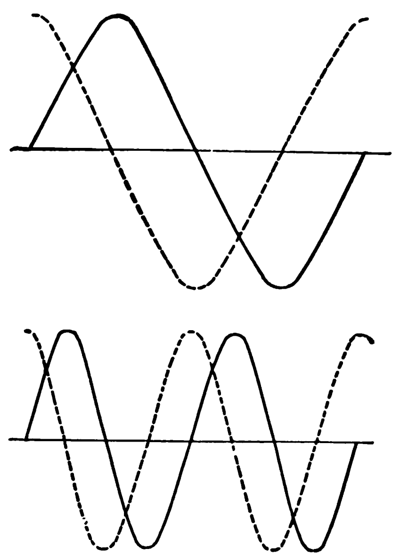

FIG. 41.

when combined in a telephone circuit. We found a reduction in amplitude of each impulse when passing a condenser, due to a portion of it being absorbed in charging the condenser. We also found that this charge was returned to the line 90 degrees behind the original impulse, and that on reaching the line it divided, causing a distortion of both the original and a succeeding impulse. By the insertion of inductance on both sides of the condenser we retard it from flowing back toward the source of e.m.f. and avoid the distortion by it of the succeeding impulse, and also—since the e.m.f. of self-induction opposes both the rise and fall of a current through it—we retard the passage of the original impulse until the lagging discharge from the condenser comes into phase with it, restoring its original form. The potential of the impulse having reached a maximum the e.m.f. of self-induction no longer opposes its passage but rather assists it, drawing it completely from the condenser and assisting the action of the other inductance in preventing interference with a succeeding impulse.

Divested of mathematical formulas, this is essentially the action in loaded cables or lines. There is of course a delay in phase throughout the circuit, but, since the original wave form and frequency are retained by the combination of the two opposing factors, this is imma-

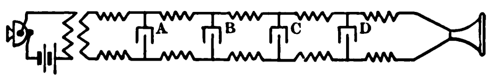

FIG. 42.

terial. An interesting side light on this delay is that while the normal speed of the electric current is probably the same as that of light, 186,000 miles per second, in a heavily loaded cable it may be brought down to a few hundred miles, and in some of Professor Pupin's experimental apparatus it was reduced to a velocity of only a few feet per second.

While inductance coils at or near the ends of the line are essential to balance its capacity they interfere with the transmission of impulses from that end by retarding and distorting them, causing what is known as the "reflection loss." This necessitates "tapering off" the inductance of the loading coils as we approach the ends of the cable, each coil having a lower self-induction than the preceding one, until the end of the cable or its junction with an unloaded cable or route is reached.

The invention of the loading coil, which marks an epoch in the development of telephony, is a striking example of the practical value of the theory, and of the unvarying reasonableness and obedience to fixed, logical laws, of the universe.

Questions.

1. What is meant by a " charge " of electricity?
2. Why will a condenser plate hold a greater charge than a single conductor of equal surface?
3. What is meant by the " capacity " of a condenser?
4. What quantity of electricity will one plate of a 2 mf. condenser hold at a p.d. of 110 volts?
5. What is the meaning of the term " dielectric"?
6. If dry porous paper, giving practically an air insulation, were substituted for the paraffined paper used in a 2 mf. condenser, what would be its capacity?
7. What is the result of cutting a condenser in series with (*a*) continuous current (*b*) alternating current (*c*) pulsating current?
8. Why is the transmission loss in a cable greater than on an aerial line of equal resistance?
9. How may this be remedied?

CHAPTER VIII.

BATTERIES.

When considering electrical pressure, we found that we could set up a difference of potential by placing two dissimilar metals in an electrolyte which attacks one of them more readily than the other, and that the plate, or element, for which the electrolyte has less affinity, becomes positive to the one more readily attacked. We also found that since the difference of potential between the two elements depends upon their relative affinities for the electrolyte it is independent of the size of the cell; while since the chemical action required depends upon the value of the current, the current capacity of a cell is proportional to its size, or, more correctly, to the surface of the elements exposed to the electrolyte.

Batteries are classed under two general headings, primary and secondary or storage; so called because the first furnishes a current by direct consumption of one of the elements—usually zinc—in the electrolyte; while the second must be " formed " by a charging current before a difference of potential is set up between its plates, and in this way it stores, not electricity, but the energy of the charging current.

As a primary battery the simple copper-zinc cell previously described, while it illustrates the principle of operation, perhaps better than any other type, is not commercially satisfactory; chiefly because the chemical reaction liberates hydrogen gas at the copper plate. This quickly reduces the current, both by partly insulating the copper and by setting up a counter e.m.f. A considerable amount of inventive ingenuity has been employed in endeavoring to reduce or prevent this " polarization," as well as in an attempt to increase the difference of potential by using different combinations of elements and electrolytes.

A certain amount of waste is caused in every primary battery by "local action." This is due to variations in the composition or density of either the zinc plate or the electrolyte. If there are particles of other metals or of carbon in the zinc plate, or if one portion is harder than another, a local difference of potential will be set up and both zinc and electrolyte will be consumed in maintaining the resultant current. Similarly, if the density of the electrolyte is greater at one place than at another, or if its composition has been made non-uniform by the chemical reactions in the cell, it will display a greater affinity for the zinc in one place than in another. This difficulty may be minimized by either alloying the zinc with a small proportion of mercury or by amalgamating its surface.

The simplest, and, for intermittent work, perhaps the most generally satisfactory cell, except as to portability, is a carbon-zinc couple in an electrolyte consisting of a saturated solution of ammonium chloride, commonly known as salammoniac. There is no attempt made to prevent polarization, but its effects are minimized by using a large surface of carbon, usually made up in the form of a cylinder which surrounds a pencil zinc. This type is generally known as a carbon cell.

The Léclanché cell represents a partially successful attempt to overcome the polarization of the carbon cell by placing the carbon plate in a cup of porous earthenware and loosely filling the cup with a mixture of carbon lumps and manganese peroxide. The latter unites with the liberated hydrogen to form manganese sesqui-oxide and water. The depolarizing action is not sufficiently strong, however, to enable the cell to furnish a considerable current for any length of time, and it is therefore classed with the carbon type as an "open circuit" cell, suitable for intermittent work only.

From the standpoint of convenience, cleanliness, and portability, the development of the so-called "dry" cell has marked a decided advance in battery work. It consists in general of a zinc cylinder which forms both the containing case and the negative element, with the carbon plate surrounded by a mixture of granulated carbon and manganese peroxide, while the electrolyte—which is principally a solution of salammoniac—is made into a paste with some inert substance. The top of the cell is tightly sealed to prevent evaporation or spilling.

While the local action and consequent deterioration of the dry cell appears to be somewhat greater than that of the older types of salammoniac battery, its manifest advantages have enabled it largely to displace the liquid cells for intermittent work, especially in telephone service; as well as to open up a new field for itself in pocket lamps, etc. Its current capacity and endurance are, when its construction is considered, rather surprising, being superior to those of the average carbon or Léclanché cell.

Where a steady current is required for a considerable time, as in supplying switchboard transmitters or in operating the vibrator of a Warner pole changer, a "closed circuit" cell must be used. In these, as a rule, high voltage is sacrificed in the effort to secure perfect depolarization. There are two types in general use in local battery exchanges known as the "gravity" or "Callaud" and the "Edison-Lalande."

In the gravity cell a plate of copper, so shaped as to offer a large surface, is placed at the bottom of a glass jar and covered with crystals of copper sulphate. Near the top of the jar is placed a plate or "crowfoot"—so called from its shape—of zinc. The cell is filled with water and a small amount of zinc sulphate added to lower its resistance. In action, the copper sulphate is decomposed and the copper deposited on the copper plate, while the zinc plate is dissolved as zinc sulphate. The solution of copper sulphate, being heavy, remains at the bottom of the jar, with the lighter and weaker solution of zinc sulphate floating above it. The name of the cell is derived from this use of gravity to keep the depolarizing solution and the electrolyte separate.

Polarization, the bane of other cells, is here actually turned to a slight advantage, as the copper, which is liberated instead of hydrogen, decreases the resistance of the cell somewhat by increasing the surface of the copper plate. The gravity cell is therefore perfectly fitted for constant, closed circuit, service. It is not fitted for intermittent work because the two solutions tend to mix by gradual diffusion except when there is some current flowing. While its field is thus limited, it has been an invaluable factor in the development of telegraph and telephone work; and is undoubtedly, in that field, the most generally satisfactory type of primary cell which has been devised.

The Edison-Lalande cell consists of a plate of copper oxide and one or, more commonly, two of zinc, in a saturated solution of caustic potash or soda. The copper oxide is held in a frame of copper and serves as both the positive plate and the depolarizer. It unites with the inevitable hydrogen, forming water and depositing metallic copper.

Since in this cell the depolarizing action is perfect, while there is only one solution and very little local action, it is fitted equally well for either open or closed circuit work. Although the electrolyte is unpleasant stuff to handle, and the positive plate gradually decreases in efficiency owing to the reduction of the oxide and deposition of metallic copper in its pores, the cell is reliable and requires very little attention.

The voltage of the salammoniac cells is about one and one-half; of the gravity and Edison-Lalande, about one.

An exhausted gravity cell may, to a certain extent, be reformed by sending a charging current through it in a reverse direction. This exactly reverses the primary action, deposits metallic zinc on the zinc plate and attacks the copper plate, forming copper sulphate. This action is typical of the behavior of secondary or storage cells in general, although cells designed for this work must first be formed by a charging current; their initial condition being practically that of an exhausted cell.

At present, the " lead-lead " is the only type of storage cell in general use. Commercial cells are differentiated sharply into two distinct classes, the " soft lead " and " hard lead " types. The chemical reactions are the same in both, the difference being in their construction.

The original storage cell, invented by Planté, consists of two plates of lead in dilute sulphuric acid. On establishing a current through the cell peroxide is formed on the surface of the positive plate, while the negative is not affected. On removing the charge and closing the circuit of the cell there is established a current from positive to negative, reducing the peroxide partly to a lower oxide and partly to a sulphate, while a sulphate of lead is formed on the surface of the negative plate, to be reduced again to metallic lead on the next charge.

As the film of peroxide shields the lead beneath it, the amount of chemical action per unit of surface is comparatively small, and the most serious problem of storage battery design is to provide a large surface without sacrificing the necessary mechanical strength or unduly increasing the weight. The method followed by Planté was to charge and discharge the cell a number of times, reversing its polarity each time. This produced the desired result by making the plates porous or spongy, but the plates were mechanically weak and the expense prohibitive. The method used at present in the manufacture of all soft lead plates is to groove or spin the surface of the plates, in this way increasing the surface in some makes as much as twenty times. They are then formed by a charging current, after in some cases, receiving an oxidizing bath.

Another method of shortening Planté's forming process is the pasting method invented by Faure, which was the precursor of the modern " hard lead " plate. In this a grid is cast of lead alloyed with antimony to stiffen or harden it—whence the name—and the active material consists of buttons set in the grid and made of some oxide or other salt of lead, which is altered by the usual forming current to peroxide on the positive plate and spongy lead on the negative. The chloride or Manchester positive is peculiar, in that, while it uses a hard lead grid, the buttons are made of lead ribbon rolled up and crimped to increase the surface, and formed by the Planté process.

The electrolyte used in all types is dilute sulphuric acid, having a specific gravity of about 1200, or 1.2 heavier than water. This gravity corresponds to about one part by volume of acid to five of water. Purity of both is essentially necessary, as any impurity, either vegetable or mineral, will materially shorten the life of the plates.

Both to increase its current capacity and to decrease its internal resistance a storage cell is, except in the smallest sizes, made up of a number of plates set as closely together as possible without serious danger of touching. They are set alternately negative and positive, and there is always one more negative than positive. To minimize the liability to accidental short circuits some type of separator is used between the plates, of either rubber, glass, or wood. Present practice is tending toward the use of very thin sheets of porous wood, stiffened by heavier strips of wood, as affording the most perfect protection.

Perhaps the most serious difficulty experienced with a storage cell is " buckling " or bending of the plates under the pressure set up in the active material by the chemical reactions. While aggravated by an excessive charge or discharge this takes place to some extent under the most favorable conditions and eventually short circuits the cell. The soft lead plate is especially prone to this trouble and often has to be actually blocked in place by plates of glass or other insulation. Aside from the pasting feature, the hard lead plate represents an attempt to overcome this difficulty by using a grid stiff enough to hold its shape; an attempt which has been only partially successful, because while a hard lead plate buckles much slower than a soft one, it is harder to straighten and more apt to be broken in the process.

While less subject to buckling, the hard lead plates are more liable to disintegration of the active material, not only lessening the capacity of the cell but occasionally short circuiting it by pieces lodging between the plates. Disintegration is also a source of danger in forming sediment at the bottom of the jar, short circuiting the cell when it reaches the plates.

Since water evaporates while sulphuric acid does not, the level of the electrolyte gradually lowers and its specific gravity rises during service. This should be cared for by the addition of *pure* water at frequent intervals, because it is important both to keep the gravity uniform and to avoid exposing the plates to the air.

A portion of the acid is taken up on discharge in forming lead sulphate, lowering the specific gravity. It is, of course, returned to the electrolyte during a charge, and the variation in gravity between charge and discharge is about thirty-five points in a cell which has a full equipment of plates. In practice, this extreme variation is seldom found, both because the majority of cells have less than the full equipment of plates, and because a cell should not be habitually pushed too close to the danger line on discharge.

The e.m.f. of a storage cell on discharge is usually about two volts, rising on charge to about 2.5 and falling when near the safe limit of discharge to about 1.9.

The capacity of a cell is given in ampere-hours, and the normal discharge rate is usually given as that which will discharge the battery in eight hours; or, expressed in amperes, it is equal to the ampere-hour capacity divided by eight. If this rate is exceeded in practice, the life of the cell will be materially shortened. The charging rate is the same as the discharge, but on account of the inevitable loss in transformation it will, if the cell has been entirely discharged, have to be continued for something over eight hours. If a cell is discharged or charged below the normal rate, the time will be correspondingly extended.

Aside from buckling and disintegration, the most serious source of trouble in a storage cell is that known as "sulphating." During discharge, a sulphate is formed on both plates, but is readily reduced by the succeeding charge. If the cell is allowed to stand discharged, or if its work is exceedingly irregular, this sulphate becomes converted into another form which is extremely dangerous to the cell and should be removed at once. It may show up as white patches or may lighten the entire surface of the plate. Being insoluble and insulating, it tends to shield the active material behind it from the action of the acid and current, and reduces the capacity of the cell to an extent depending on the extent of the surface thus shielded. It may usually be removed by a prolonged overcharge at about one-half the normal rate.

As the storage battery, in addition to being an expensive item in the equipment of a telephone exchange, is the immediate source of the current on which the operation of all the rest depends, too much emphasis can hardly be placed on the importance of giving it proper attention and care. Frequent readings of the voltage and specific gravity should be taken on both charge and discharge; and periodical inspections made to determine the distance between the plates as affected by possible buckling or shifting, the amount of disintegration, the liability to short circuits from any cause, the distance between the sediment and the bottoms of the plates, the presence of any foreign material—especially metal—which may have accidentally fallen in, and the color of the plates. The positives should be a chocolate brown; the negatives a clear light gray or lead color. When the charge is nearly completed and the most of the active material formed up, the current begins to decompose the water of the electrolyte, causing the familiar phenomenon of "gassing" or "boiling." On the uniformity of gassing and the color of the plates an experienced battery man depends almost as much as on the voltage and specific gravity readings.

It is of the utmost importance that a battery should never be reversed; and before connecting to it the polarity of the charging lead must invariably be tested, either with a voltmeter or by dipping it and a ground or return wire into acidulated or salty water, when bubbles will be given off freely from the negative pole and few, if any, from the positive.

Since a cell acts, in a sense, as a pump, setting up electrical pressure, a little consideration will show that if we connect to the positive or high pressure side of one cell, the negative or low pressure side of another, the potential of the charge, which has already been raised by the first cell, will be raised still further by the second; or the voltage of the two cells will be added together. If we connect the two cells in parallel, the voltage will not be raised, but the surface which is available to supply the current is increased, or we have increased the current capacity in proportion to the added plate area. A number of cells connected either in series or in parallel constitute a battery; a term which is often used, although incorrectly, to designate a single cell.

For many reasons, it is not practicable to supply the current for a telephone exchange, as we do for an electric lighting circuit, directly from a generator. Where a few instruments only are concerned, the simplest and most effective method is to use a few primary cells—from one to four—in each set. In an exchange large enough to warrant the initial expense, the common battery or central energy system is far more satisfactory, using a single battery of storage cells located in the office to supply all current for both talking and signalling. A few of the manifold advantages of this arrangement are: elimination of battery trouble at the subscriber's station—often the most inaccessible portion of the plant—; uniformity of current supply (a primary cell decreases in effectiveness from the day it is installed, while by proper maintenance the storage battery may readily be kept up to its original standard, or nearly so); greater economy, both because the energy is derived from the consumption of coal in air instead of zinc in acid and because of the greater attendance economy of a few large units in one battery room as contrasted with a large number of small ones scattered over a large district; and the possibility of automatic signalling; which has raised our service standards so far above those of " ring-down " days. While it is undoubtedly true that it is possible, under perfect battery conditions, to obtain slightly better transmission from a local battery instrument than from a common battery set, yet under commercial conditions the reverse is true, on account of the variation in effectiveness of the primary cell.

A small battery may be most conveniently charged from a direct current lighting circuit, using a rheostat or bank of lamps to keep the current down to its proper value. As the larger part—usually about 75 per cent—of the energy is by this method wasted in the dead resistance, a charging machine is more economical and should be used where the current required is large enough to warrant the outlay.

A charging machine is a specially designed generator—either motor or engine driven—which has a large number of commutator segments and is usually multipolar. The object of this design is to make the current from the machine as uniform as possible to avoid putting noise on the battery busbars to which it is connected, and consequently on all the lines in the exchange. In order to cut down this machine noise to a negligible point it is also usually necessary to insert a retardation coil in the charging circuit to smooth out the fluctuations which careful design of the machine has not been able entirely to eliminate.

The simplest method of all is that often followed in the case of small branch exchange batteries, connecting them through a charging lead direct to the office battery. The only actual disadvantage to this method is that the voltage of the branch battery is necessarily somewhat low, and transmission from the branch exchange board is of course not quite as good as it would be with a higher voltage battery.

Questions.

1. What causes the difference of potential between the terminals of a battery?

2. If the e.m.f. of a cell having an active surface of five square inches is two volts what is it in the case of a similar cell which has a surface of one hundred square inches?

3. What is the ratio between the current capacities of the two cells mentioned in Question 2?

4. What is the difference between a "primary" and a "secondary" or "storage" cell?

5. What is meant by "polarization" of a cell?

6. What is "local action"?

7. What is the electrolyte in a Léclanché cell?

8. What is the depolarizer in a gravity cell?

9. What is the distinctive feature of the "dry" cell?

10. What is the distinction between "open" and "closed circuit" cells?

11. Describe a "hard lead" storage battery element.

12. Describe a "soft lead" storage battery element.

13. Why is large surface area important in a storage cell?

14. Why is a separator necessary in a storage cell?

15. What is meant by "buckling"?

16. Why does the addition of antimony to a grid lessen buckling?

17. Name two common causes of short circuits in a storage cell.

18. What is meant by "sulphating"?

19. Why is it important to add water to a storage cell at frequent intervals?

20. What is the effect on the specific gravity of the electrolyte of charging the battery?

21. If a storage battery has a capacity of 800 ampere-hours, at what rate should it be charged?

22. What should be the color of the positive plate? Of the negative?

23. How can you most quickly tell, on looking at a battery, when it is nearly charged?

24. Name three methods in common use in telephone work for charging storage batteries.

25. If you have no voltmeter what test would you make to determine the polarity of a charging lead?

CHAPTER IX.

CIRCUIT DRAWING.

In the evolution of the human race, the step which, beyond all others, marked the dawning of conscious intelligence, and rendered the present man possible, was the development of language. Each vocal sound acquired a definite meaning; it became a symbol, which represented a certain feeling, emotion or impression. These symbols served a double purpose. They enabled our primitive ancestors to communicate with each other, just as money, which is the symbol of performed labor, facilitates the exchange of the fruits of our labor; and the combination of symbolic sounds rendered possible the formation of connected ideas and thus of what we know as the process of thinking or reasoning, just as the combination of pennies gives us dollars.

The next important step was to represent, by recognizable marks, both these ideas and the more familiar objects in nature. Writing was thus at first practically drawing, and the origin of the alphabet was the hieroglyph, a crude drawing which illustrated enough of the object to convey the impression desired.

Our present language, then, both spoken and written, is simply a crystallized system of symbols which enables us both to combine our ideas—to reason connectedly—and to communicate those ideas to others. Language alone, however, can never cover the ground, and it is frequently necessary to supplement it by more flexible or exact symbols.

To design a circuit or to trace its operation, the first essential is to have a clear idea of the apparatus which constitutes it, or of the object sought. We are not concerned primarily with mechanical details but with principles of operation. Having given a blue print, the first question is not " What is the actual appearance and arrangement of its parts? " but " How does it work? " The symbol, then, which in a blue print represents a certain piece of apparatus should show, not its mechanical construction, but its principle of operation, the "way it works ", and should show this in as simple and as clear a manner as possible. It should be, if we may use the expression, a picture of an idea rather than of an object.

The origin of the larger number of the symbols in common use in our blue prints is evident at a glance, especially if we keep in mind that they represent ideas and principles. It might be interesting however, to examine some of them to bring out this point.

A resistance coil is symbolized by drawing the line which represents a wire in a zig-zag form, to indicate that there is a considerable length of wire in a small space. A retardation coil is shown by the same symbol, with the addition of a rectangle representing the iron core on which so much of the self-inductive effect depends. Since electromagnetic induction between two wires takes place only when they are parallel and close together, the two windings of an induction coil or repeating coil which form an inductive pair are shown facing each other to call attention to the inductive effect between them. They are drawn zig-zag to show that they are wound in coils. Our representation of a relay is perhaps the most perfect and complete symbol in the list. The zig-zag lines around the rectangle indicate that we have a winding around an iron core, which will set up a magnetic field in the core, when there is a current through it. Facing the end of the core, we draw another shorter rectangle, or a heavy line, representing the armature, which, when attracted by the core, pulls up towards it, swinging on a pivot at one end and opening or closing a contact at the other. This cares for one set of contacts, both front and back; a second set would be represented in the same way at the other end of the core, and a third set by another armature and set of contacts placed out beyond one of the others, but in line with it. The position of each contact, in front or back of the armature, shows clearly whether it is opened or closed when the armature is pulled up toward the core. A condenser consists essentially of two metallic plates parallel and close together, but insulated from each other, to admit of electrostatic induction between them. These essentials are clearly shown in the symbol, where one set of parallel lines encloses another but is not directly connected to it. A key or a jack is represented in such a manner as to indicate how the different contacts are made or broken.

One of the most interesting symbols, and one which is not appreciated at its full value and is consequently often used wrongly, is that representing battery. In a primary battery, the negative or zinc plate is dissolved in the electrolyte while the cell is in action and must be made comparatively heavy to ensure reasonably long life. The positive plate, whether of copper or carbon, is liable to polarization and must have a large surface to minimize this. The symbol is a representation of these two plates the negative being indicated by a short heavy line, referring to the amount of material in the zinc plate, and the positive by a long thin one, alluding to the larger surface of the copper or carbon. It is often a matter of importance to know the polarity of the battery shown in a blue print, and were the origin and meaning of this symbol always kept in mind, a glance would tell it. Unfortunately this has not been done, and we are compelled to rely on the markings, + and −, which are often omitted.

While it is impossible to draw a line of sharp distinction between them, because all blue print symbols are really more or less idealized representations of actual apparatus, there is another class which approach more nearly the ancient hieroglyphs and are merely outline drawings designed to suggest to the mind certain pieces of apparatus, the principles or actions of which are either immaterial to the circuit or are so uniform and so well known as not to require a closer definition. Examples of this are the com-

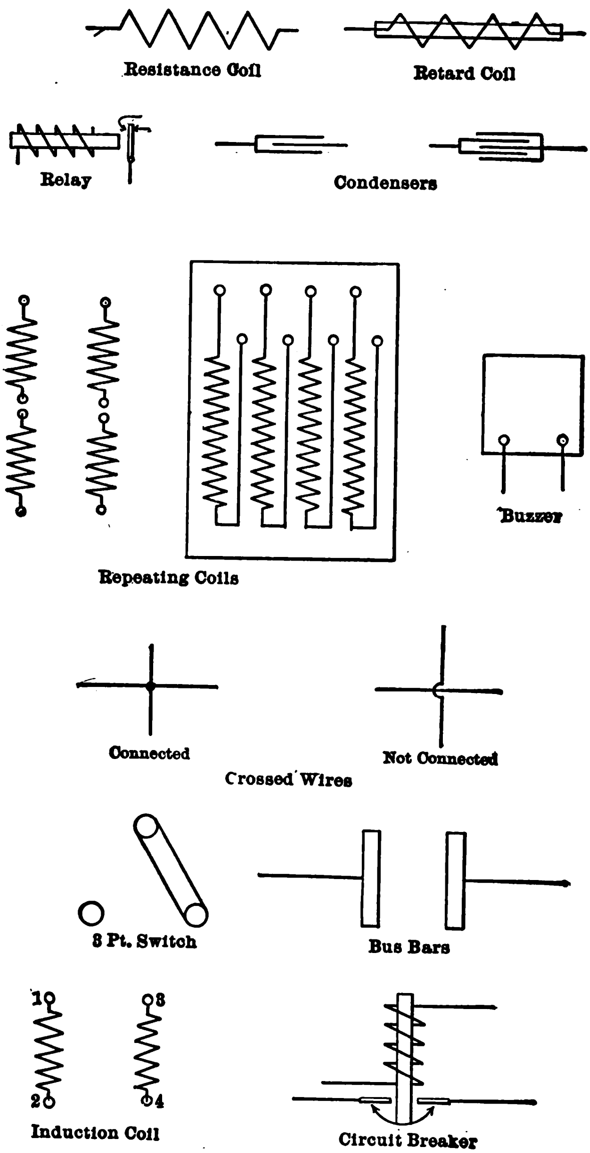
Resistance Coil
Retard Coil
Relay
Condensers
Repeating Coils
Buzzer
Connected
Not Connected
Crossed Wires
8 Pt. Switch
Bus Bars
1
3
2
4
Induction Coil
Circuit Breaker

FIG. 43.

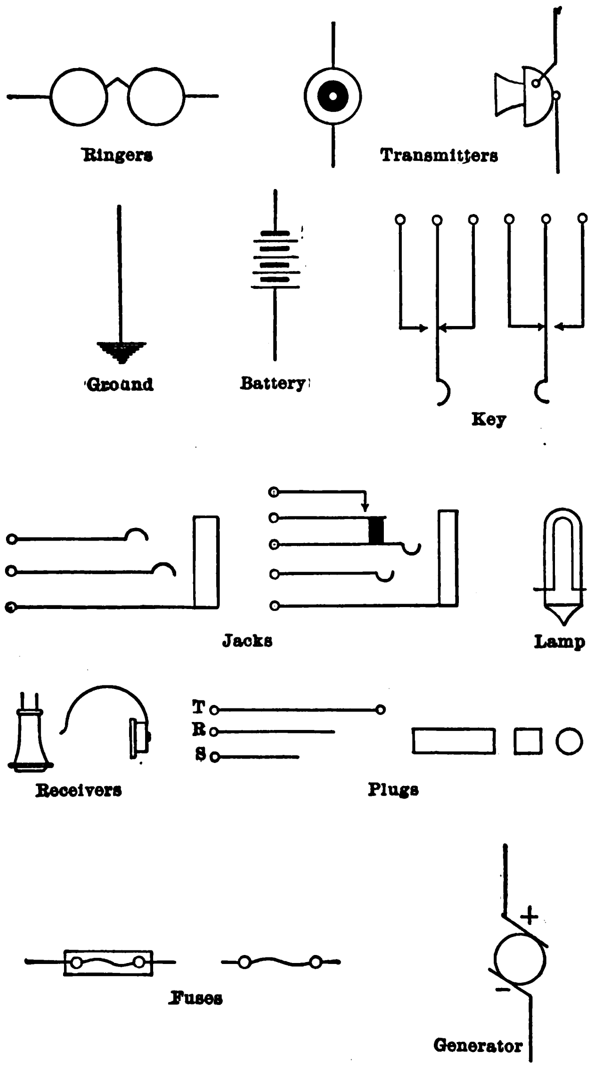
Ringers
Transmitters
Ground
Battery
Key
Jacks
Lamp
T
R
S
Receivers
Plugs
+
−
Fuses
Generator

FIG. 43.

mon symbols for the receiver, the transmitter, and a paii of ringers (Fig. 43).

Just as the combination of simple sounds or characters led to connected reasoning, so the combination of apparatus symbols enables us to construct a circuit, which is simply an association of the principles and actions of its separate parts, interacting and reacting upon each other in such a way as to produce the desired result. We could not expect to understand a mathematical demonstration or a connected argument by glancing at the middle of it or at the conclusion, but would find it necessary to start at the beginning and trace it through in a logical manner, one step at a time. A blue print or drawing of a telephone circuit follows the same laws of reasoning and must be traced through in precisely the same way. Practice

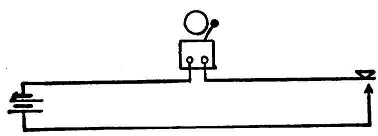

FIG. 44.

shortens the process, not by changing the method, but by giving a quicker comprehension. We must first learn the language by finding the meanings of the various symbols employed, and then read it as we would a sentence, one character at a time.

In a simple door bell circuit, we find three, or more correctly, four, symbols, representing the bell, the battery, the push button, and the wires connecting them. To trace the circuit, we start where the e.m.f. originates, at the positive pole of the battery, trace the circuit through the push button—which is shown open because that is its normal condition—through the bell and back to the battery. We know that connecting the bell to battery will cause it to ring, and this is accomplished at will by pressing the push (Fig. 44).

The standard subscribers' line circuit will serve to carry us a step farther. It is shown in Fig. 45. The purpose of the circuit is to enable the subscriber to pull up a line relay—which in turn signals the operator by lighting a lamp at the answering jack—by taking his receiver off the hook. Substituting a relay for the bell, and an upper contact of the switch hook for the push button, we have the same basic principle as in the door bell circuit. It is also necessary to so arrange the circuit that when the operator plugs in she will automatically cut off all the line signalling apparatus. Starting, as before, at the battery, we may trace the circuit through the line relay, through a back

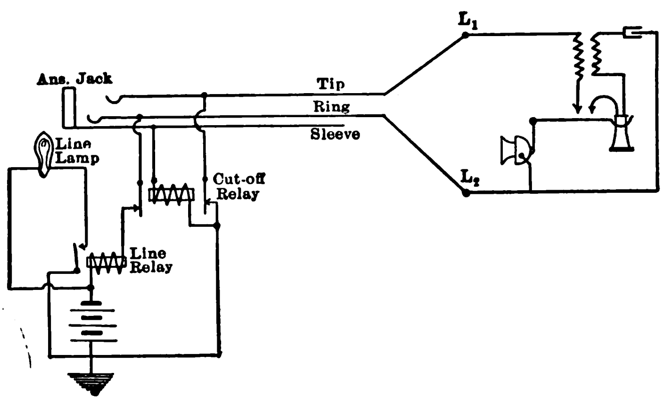

FIG. 45.

contact of the cut-off relay—which is shown closed because that is its normal condition—out over the ring side of the line to binding post L_2 of the instrument, through the transmitter to the body of the switch hook, through the upper contact—so called because it is shown above the hook to indicate that it is closed only when the receiver is off—through one winding of the induction coil to L_1, back over the tip of the line and through the other back contact of the cut-off relay to ground or the other side of the battery. Taking off the receiver closes the circuit of the line relay at the upper contact of the hook, allowing a current through the relay which energizes it, pulling its armature up against the front contact. A current is then established through the line lamp, lighting it, and through the front contact of the relay to ground. The operator answers by inserting in the answering jack a plug having talking battery through a repeating coil on the ring and tip, and supervisory battery on the sleeve. As the winding of the cut-off relay is connected between the sleeve of the jack and ground, the battery on the sleeve of the plug will be grounded through it and pull it up, opening the back contacts and cutting off the line battery and ground, thus leaving aclear line for the cord talking battery. This releases the line relay by opening its circuit, and its armature, by falling back, opens the lamp circuit and extinguishes the lamp.

These two simple examples illustrate the general method of tracing a circuit; the method which must be followed in all cases and which, if followed carefully, will unravel the most intricate circuits.

Questions.

1. What is the reason for drawing a circuit instead of simply describing it?

2. Describe in your own language the objects of a blue print symbol.

3. On the symbol for a key, why are the inside contacts always drawn closed and the outside open?

4. What is meant by the " back " contact of a relay?

5. What idea does the circuit breaker symbol shown on Fig. 43 convey to the mind?

6. In Fig. 45 which side of the battery is shown grounded, positive or negative?

7. Why is it not sufficient to represent a repeating coil in the same manner as a buzzer?

8. Draw the skeleton circuit of a common battery instrument, including the ringers.

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