THE ALTERNATING-CURRENT CIRCUIT

W. PERREN MAYCOCK, M.I.E.E.

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FOR ENGINEERS AND STUDENTS.

BY

W. PERREN MAYCOCK, M.I.E.E.

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PREFACE.

THIS little book is an attempt to convey some idea of the phenomena of the ordinary or single-phase alternating-current circuit to the minds of those new to the subject, by means of plainly worded and non-mathematical language.

The matter is, of course, a very important one to electrical students; and it also abounds in difficulties, many of which arise from the fact that authorities are by no means agreed as to the explanation of the various phenomena here dealt with.

In a work written from a practical or engineering standpoint, such as this is, it is almost absolutely necessary to look upon electricity as a something which flows along the conductor, as both explanation and comprehension are rendered much easier thereby. The student of advanced theories will consequently find little to interest him herein, except in a technical sense.

I have been greatly assisted by my friend Mr. C. H.

Yeaman (Chief Assistant Engineer at the Islington Electricity Works), in the preparation of this volume, and it is with great pleasure that I here acknowledge my indebtedness to him.

The book forms, in fact, the substance of a chapter in the forthcoming Vol. II. of my *Electric Lighting and Power Distribution*; it being thought expedient to publish it in advance, instead of delaying its appearance till the completion of the larger work.

Notwithstanding the smallness of the book, a very great amount of time and labour has been spent upon its evolution; with the result—it is hoped—that much additional information concerning alternating currents has been brought within the ken of the non-mathematical reader.

W. PERREN MAYCOCK.

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April, 1897.

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THE
ALTERNATING-CURRENT CIRCUIT.

1. **Theory of Electricity.**—To start with, it is necessary to adopt some theory of electricity. Now there are many theories for electrical action, but it is impossible to pick out any one and say that is the right one, though those in which electricity is looked upon as a movement or vibration of the ether are seemingly the most plausible. But to explain the phenomena with which we are about to deal, in the light of any of the advanced theories, would be extremely difficult, if not impossible, in a book of this character: and, moreover, it should be remembered that we are here concerned not so much with what is vaguely called 'electricity,' as with certain of its effects. Hence we must choose some simple practical theory, at the same time remembering that it is adopted to facilitate explanations, and keeping our minds ready for the reception or conception of some better one at a future time.

The theory advocated by the Author is that known as the ‘surplus and deficit theory,’ and it was first fully treated and extended by him in a series of articles in the *Electrical Engineer*, which articles were subsequently embodied in the Author's *First Book of Electricity and Magnetism.*[*]

It must here suffice to indicate the mere outlines of this theory. All things, conductors and insulators alike, are supposed to be imbued with electricity normally distributed—*i.e.* at even pressure or potential. Electrification is the act of heaping up electricity on one body or bodies, leaving a corresponding deficit on another body or bodies; the former is or are then said to be positively electrified, and the latter negatively electrified. A battery, or dynamo, or alternator is simply an electric pump, whose electro-motive (electro-pumping) force alters, or tends to alter, the even distribution of electricity in the circuit: these apparatus must consequently not be looked upon as ‘generators’ of electricity. In most cases where an uneven distribution of electricity exists, there will be a tendency for it to flow so as to regain a general level or distribution: when there is such a tendency, there is said to be a difference of pressure or potential, or a potential difference (abbreviated *P.D.*).

2. Alternating Current.—The simplest kind of current is that derived from a battery; this is a steady direct current, and its principal properties are presumed to be well known to the reader. A well-designed and properly-constructed direct-current dynamo gives a

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[*] Second Edition.

current which is very nearly similar in its effects to that of a battery; and for practical purposes, the laws which apply to the current from a battery may be equally well applied to that from a dynamo.

If a *reversing switch* R*, inserted in the circuit of a battery or direct-current dynamo, as shown in Fig. 1, be operated at regular intervals, alternating E.M.Fs. will be *impressed* on the outer circuit C, and an alternating

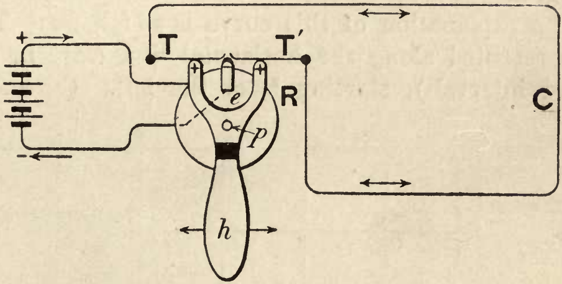

FIG. 1.

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* The construction and action of this form of reversing switch are as follows:—On an insulating base, e, pivoted at p, and provided with a handle, h, are mounted the U-shaped piece of metal, + +, and the straight piece, −, to which the + and − poles of the battery are respectively connected. When the switch handle is in the position shown, the metal tongues, $T\,T'$, connected with the extremities of the outer circuit, C, rest on + +, and no current flows from the battery. If the switch handle is moved to the right, the right-hand leg of the U-piece remains in contact with T', and the straight piece touches T, a current consequently flowing round C in a counter-clockwise direction. If the switch handle is moved to the left, the left-hand leg of the U-piece is in contact with T, and the straight piece with T', and a current flows round C in the opposite direction. Thus, if h is constantly worked to and fro, an alternating current will be set up in C.

current will be set up therein, as conveniently represented by the double-headed arrows ←→ ←→.

Supposing the circuit C had no inductance or other disturbing effect, the current or rate of flow of electricity in it would always be the same, but would be reversed in direction at regular intervals, as shown by the 'curve' in Fig. 2.

The explanation of this curve is as follows:—Time is represented along the horizontal line (say, in one-second intervals), starting from the left. Current in one direction is shown by vertical distances above this line, and current in the other direction by vertical distances below it. It is usual to style currents in one direction + (positive), and those in the opposite direction − (negative); but these terms are confusing to the beginner, who would probably assume that a '+ current' was different in its properties from a '− current.' We shall therefore refer to them as right- and left-hand currents respectively, these terms well conveying the idea that they flow in opposite directions round the circuit. Suppose at the time of commencing

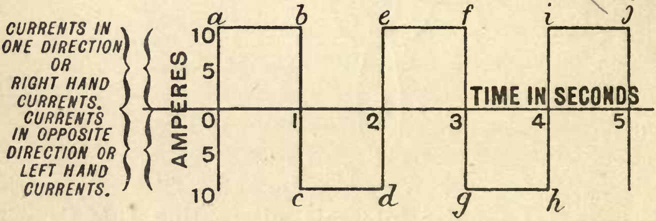

Fig. 2.

the 'curve,' a 'right-hand current' was flowing, and that its value was 10 amperes, and suppose also that the direction was reversed every second; our curve would then start at the point, *a*, and would run in a horizontal direction for 1 second—*i.e.* from *a* to *b*—when it would suddenly drop to *c*, the current having been reversed: the 'left-hand current,' *c d*, would continue for 1 second, as shown, and would then immediately change to the 'right-hand current,' *e f*. During the fourth second the current would be 'left-handed,' *g h*, during the fifth second 'right-handed,' *i j*, and so on.

The above is a purely imaginary condition of things, for a current cannot really change suddenly from one direction to another at its full value: but it is useful, as it gives the student a preliminary idea of an alternating current.

3. Alternating Current (cont.).—It is convenient to liken a steady direct current to a steady flow of water in one direction through a pipe: an alternating current may then be compared with the movement of water in the pipe when the direction of flow is changed more or less rapidly. Fig. 3 represents a pipe bent round so as to form a complete circuit, which includes a pump, *P*, the whole being filled with water. The water represents electricity, the pipe the conductor, and *P* the dynamo or alternator—according to its method of working. *P* is represented as a kind of small water-wheel, actuated by a pulley or handle outside. If *P* is rotated continuously in one direction, it represents the action of a battery or direct-current dynamo, the water

in the pipe (electricity in the conductor) being set flowing in one direction. If *P* rotates first in one direction and then in the other, at regular intervals, it represents the action of an alternator, for there will be a flow of water in the pipe (electricity in the conductor) first in one direction and then in the other. Now electricity—like water—may, for the purposes of this argument, be assumed to be incompressible ; so that with a given flow (current), the number of gallons of water or coulombs of electricity passing any point, *a*, in the pipe or circuit, is the same as the number passing any point, *b*. Thus, let the shaded part, *C*, represent one gallon of water or one coulomb of electricity: when *C* moves in either direction, all the water or electricity in front or behind it, *i.e.* all round the circuit, moves at exactly the same rate, irrespectively of the size of the pipe or conductor, which may vary at different parts of the circuit. In other words, the flow of electricity, in coulombs per second (amperes), is the same at all parts of a closed series circuit.*
When the circuit is not of this description, *i.e.* when it has branches, the current may vary in different parts.

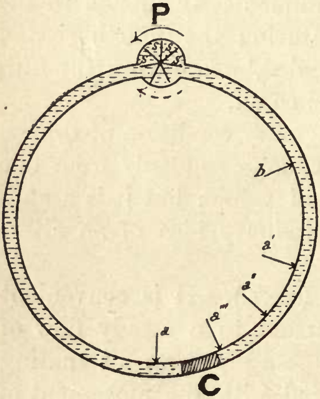

FIG. 3.

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* Provided it has negligible capacity (§§ 6, 7, etc.).

Referring still to Fig. 3, let us consider the action of alternating flow at different *frequencies*—*i.e.* at different rates of alternation (§ 16). The faster *P* works the greater its water-motive force, and the more rapid will be the flow with a given length and size of pipe (circuit conductor); it being presumed that there is very little waste of energy in the useless carrying round of water in the spaces *s s s s*: this water-motive force is clearly analogous to the electro-motive force of an alternator. The frequency of the flow (of water or electricity) does not depend on the value of water-motive or electro-motive force, but on the rate at which the latter change their direction. Thus, if *P* rotates in the direction of the top arrow for half a minute, and then in the direction of the dotted arrow for half a minute, the current will change its direction twice a minute. Now, with a given length and size of pipe (circuit conductor), any particular gallon or coulomb, *C*, may make 10, 20, 30, or more 'laps' (journeys round the circuit) before the reversal of flow takes place: if the direction of flow is changed at lesser intervals, *i.e.* if the frequency is increased, our gallon or coulomb may only succeed in making two or three journeys round in one direction before the reversal of flow occurs. It is thus conceivable that, with a high frequency, our unit of water or electricity may only traverse a part of the circuit (say, from *a* to *b*) before it has to turn back, and that the greater the frequency the less the distance actually travelled over. Thus this path may decrease, as the frequency increases, to a–a', a–a'', or a–a''', it being remembered that there is a similar movement in the other parts of the circuit. The motion of water or electricity in the circuit depicted in Fig. 3, may, when the water- or electro-motive force has medium frequency, be compared with that of the balance-wheel of a watch. The current in a given circuit is thus proportional to the distance traversed at each alternation by any given coulomb, *C*, multiplied by the number of alternations per second: so that if the current is kept constant, when the frequency is doubled, the path traversed by any given coulomb will be halved, and *vice versâ*. It will be remembered that current is defined as the number of coulombs passing any given point in a circuit per second: and in the case of alternating current we consider the actual number of coulombs passing by, irrespective of their direction of flow. Thus, with a very high frequency, it is conceivable that the coulomb *C* (Fig. 3) will merely oscillate in front of the point a''', the number of times it passes this point in one second being a measure of the current.

The greater the frequency the sharper the to-and-fro movement of electricity; and the comparatively non-dangerous character of extremely high frequency currents, such as are sometimes used in experimental work, may be roughly accounted for by supposing that the electricity in the circuit moves over so minute a path that the current is indefinitely small, certain retarding effects increasing with the frequency (§§ 21, 22, 27, 29).

The hydraulic analogue of an alternating-current circuit is often illustrated as in Fig. 4; the pulley, *p*, representing the rotating part of the alternator; the force of the pump piston, *P*, the electro-motive force; and the up-and-down movement of the piston, the reversals in the direction of the electro-motive force. Good as this analogy is in some respects, it is rather a faulty one, inasmuch as there is no actual passage of water through the pump; and the student might from this infer that there was no passage of electricity through the alternator: and we assume that the electricity flows through the alternator, or dynamo, or battery, just as it does through the other parts of the circuit.

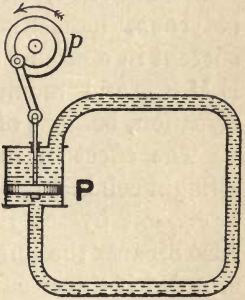

Fig. 4.

An alternating current might be described as a 'continual oscillation' of electricity in the circuit, just as the movement of the balance-wheel of a watch is a 'continual oscillation.' It must be borne in mind, however, that the use of the term 'electrical oscillation' is applied to the movement of electricity when a condenser is discharged, a rapid to-and-fro movement *in an incomplete circuit*, which dies away to nothing: this movement is similar to that of the prong of a tuning-fork, or of one end of a compass-needle coming to rest in a strong magnetic field. The term oscillation should therefore be confined to the case of condensers, to prevent confusion.

4. Inductance or Self-Induction.—When a direct current begins to flow along a circuit, it sets up a

magnetic field around the conductor. This magnetic field, in being set up, reacts upon or cuts the conductor, and induces a momentary reverse E.M.F. therein. When the current flowing along a conductor is stopped, the magnetic field collapses, and in collapsing cuts the conductor, and in consequence another momentary E.M.F. is induced in the conductor, which is 'direct,' *i.e.* in the same direction as the inducing current.

This action, which is due to *inductance* or *self-induction*, momentarily opposes the setting up of a current in a circuit by reason of the opposing 'reverse' E.M.F., and momentarily retards its 'breaking' or cessation, because of the momentary 'direct' E.M.F.

The effect of inductance is not very noticeable in straight conductors, as the conductor cannot be so effectively cut by the lines as when it is coiled up (§ 26). Also because the lines of force set up in a circuit are more crowded if the circuit is coiled up, and are increased in number if the coils have iron cores; inductance is always greatest in circuits containing electro-magnetic apparatus such as magnets, transformers, and the like.

The effects of inductance are noticeable in a circuit not only when a current is set up or stopped, but also when it is increased, or diminished, or reversed; such increase, or diminution, or reversal, altering the number of lines of force passing through or interlinked with the circuit, and their direction, and therefore giving rise to momentary induced E.M.Fs.

5. ALTERNATING CURRENT (CONT.).—From what was said in the preceding paragraph, it should be clear

that it is impossible to suddenly start a current at its full value, and equally impossible to suddenly stop it; because of the effects of inductance or self-induction, etc., the current taking time to 'grow' and time to die away. It is thus even more out of the question to suddenly *reverse* a current in a circuit.

Although it is possible to arrange a simple circuit or to wind a coil so that it shall have little or no inductance, as shown in Fig. 5, where each half of the circuit or coil neutralises the other's magnetic effect, the conductor will still have *capacity*,* and this also exercises a disturbing effect on the current. Moreover, a coil such as that shown in Fig. 5 would be useless for solenoids or electro-magnets, as it would have no magnetic field. It therefore follows that every working circuit exercises more or less disturbing effect, and also that, in the case of an alternating current, this disturbing effect is continuous. Consequently, the 'curve' in Fig. 2 does not represent a real alternating current, for such not only varies in direction, but is also constantly varying in strength. With a given circuit, the changes in direction and strength take place at regular intervals, and an alternating current is thus often called a *periodic*, *harmonic*,

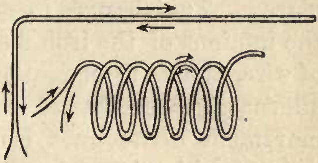

FIG. 5.

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* See the Author's *First Book of Electricity and Magnetism*, Second Edition, § 159: or his *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 37.

or *wave current*. In fact, the curve of a real alternating current is a series of waves, which may be roughly likened to those set up in a rope which is fixed at one end, while its other end is rapidly moved up and down (Figs. 31, 34, and 36).

The simplest case in which an alternating current is set up is when two Bell telephones are used as transmitter and receiver respectively. The iron plate or diaphragm of the telephone used as transmitter, is caused by the voice to perform motions to and fro in front of a magnet, on the end of which a coil of wire is placed. The changes in the strength of field caused by the motions of the iron disk, induce E.M.Fs. in the coil of wire, and as these motions are to and fro, the field is alternately strengthened and weakened, the result of the movement of its lines being an alternating E.M.F. in the coil, which is cut by those lines. As the transmitter is in this case connected to an exactly similar telephone by a couple of wires forming the circuit, a current alternates in the circuit and coils of both instruments, and the magnet of the second telephone (or receiver), being correspondingly strengthened and weakened, its diaphragm is caused to perform movements of a similar character to those of the transmitter diaphragm, and it sets up sound waves in the air in front of it. The transmitter and receiver thus really act as a miniature alternating-current dynamo and motor respectively.

The magneto-machine and bell so much used in telephone and other work afford another example. The magneto-machine (sometimes called the 'ringer' or 'generator,') is a simple form of alternating-current dynamo, the alternating current being induced by the rotation of a coil of wire in a two-pole magnetic field (§ 15): while the magneto bell may be likened to an alternating-current motor, for its hammer will only move continuously when an alternating current is passed through its coils.*

6. CAPACITY IN ALTERNATING-CURRENT CIRCUITS.—One very and increasingly important difference between the action of direct and alternating currents is shown by the experiments illustrated in Figs. 6 and 7. Here two circuits are depicted, each containing a source of E.M.F., a glow-lamp *L*, and two condensers *C C*; but in the one the E.M.F. is due to a direct-current dynamo *D*, and in the other to an alternator *A*. Now, in Fig. 6 it is clear that no current can flow through the lamp, even if one of the condensers be removed, for each interposes a break in the continuity of the circuit.

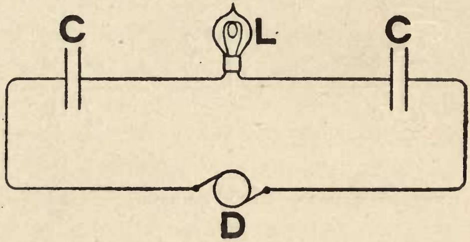

FIG. 6.

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* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 84.

In Fig. 7, if the condensers are suitable in capacity, the lamp *L* will light up, and at first sight this result seems most inexplicable; but when we consider the action of the condenser,* and the fact that the alternator is keeping up a constant surging of electricity backwards and forwards between the plates *a* and *b*, it becomes evident that there must also be a corresponding flow of electricity in the lamp circuit, between the plates *c* and *d*. The results would be precisely the same if one condenser only were employed in each experiment; but the use of two makes the effect in Fig. 7 all the more remarkable.

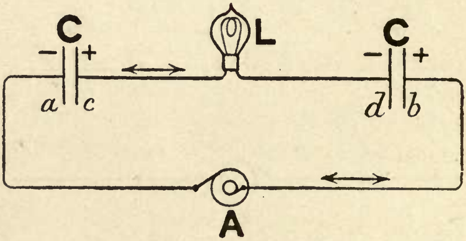

Fig. 7.

It will be noticed that in the experiments above described the capacity is in series with the circuit—*i.e.* there is no through conducting path. This state of things effectually prevents the continual flow of a direct current, but does not stop the 'action' of an alternating one.

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[*] See the Author's *First Book of Electricity and Magnetism*, Second Edition, § 166.

A fuller explanation of the second experiment (Fig. 7) is as follows. Before the alternator is working, the whole circuit is filled with electricity evenly distributed, and at zero potential or pressure (§ 1). Now suppose the alternator to work. During the first alternation, *i.e.* while its E.M.F. is in one direction (§ 16), it pumps electricity from *a* to *b*, causing a P.D. between *a* and *b* about equal to its own E.M.F. *b* is consequently +ly. electrified and *a* −ly. electrified, as indicated by the signs + and −. Influence (electrostatic induction) takes place across the condenser dielectrics, causing a rush of electricity through the lamp from right to left, so that *c* is + and *d* −. During the second alternation, that is when the reversal of the alternator E.M.F. occurs, electricity is pumped from *b* to *a*, so that *a* becomes + and *b* − ; a rush consequently takes place at the same time from *c* to *d*, *c* becoming − and *d* +, and so on ; the reversal and flow of electricity in the alternator circuit causing a corresponding reversal and flow in the lamp circuit.

It has been stated that the same results would have been obtained with one condenser only in circuit ; and this will be understood from what follows. In Fig. 8, *A* is an alternator, with two wires joined to its terminals ; one of the wires being severed and a lamp, *L*, inserted. The ends of the wires approach very closely, as at *a* and *b*, but are not in contact, a sheet of glass or other dielectric, *d*, being interposed to prevent sparking across : the alternator circuit is consequently not complete. Now the ends of the wires *a* and *b*, and the dielectric *d*, virtually form a condenser of extremely small capacity, and the alternator pumps electricity backwards and forwards between *a* and *b*. But in this case very little electricity passes at each reversal of the E.M.F., owing to the small capacity of the ends of the circuit, and an ordinary lamp will consequently show no indication of a current.*

When the alternator is pumping in one direction, say from *a* to *b*, a quantity of electricity will pass sufficient to make the P.D. between *a* and *b* equal to the E.M.F. of the alternator; or, in other words, the condenser *a b* will be charged to the potential of the alternator. Now, the smaller the capacity of a condenser, the less is the displacement of electricity necessary to raise the P.D. between its coatings to a given amount: in the present case, because of the extremely small capacity of the ends of the circuit, only a very minute quantity of electricity

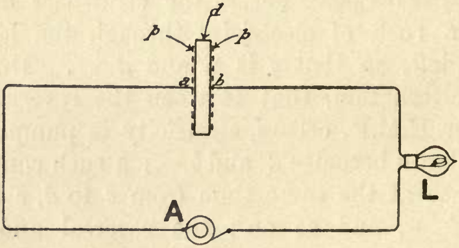

FIG. 8.

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* The wires are supposed to be suspended in mid-air, and not running side by side or near other bodies, as we wish to consider the circuit as only having appreciable capacity at its ends.

will pass from *a* to *b*. When the alternator reverses its E.M.F., another small quantity of electricity will be pumped from *b* to *a*, and so on backwards and forwards with every alternation of the E.M.F.

By putting metal plates on each side of the dielectric, *d*, as shown by the dotted lines *p p*, the capacity of the adjacent ends of the circuit (*i.e.* of the condenser) will be greatly increased, and a much greater quantity of electricity will pass to and fro through the lamp; but the current will still be insufficient to light it with a simple two-plate condenser such as this, unless of very unwieldy dimensions, or unless an enormously high E.M.F. is employed. It will be seen, however, that by using a large or multiple-plate condenser of sufficient capacity, an ordinary E.M.F. will cause enough electricity to pass to and fro to light a lamp, or, if need be, a number of lamps.

It has been explained how what is practically an alternating current can be kept up all round the circuit, even if one or two condensers be inserted therein (Figs. 7 and 8); and the reader should now be able to understand that the fanciful arrangement of things depicted in Fig. 9 is possible; any number of lamps, *L*, and condensers, *C*, being joined consecutively in the circuit of an alternator, *A*; the lamps burning brilliantly if the condensers are of sufficient capacity, and the E.M.F. high enough.

As will be presently pointed out, every electric lighting circuit possesses more or less capacity, owing to the proximity of the conductors to each other and to the Earth. Whether capacity can be extensively made use of in ordinary methods of alternating-current electric lighting and power supply, is an open question, though Mr. James Swinburne has maintained that it can, and has constructed tinfoil condensers with thick paper dielectric compressed between metal plates, and placed in a solid air-tight iron box filled with special insulating material of an oily nature to maintain the insulation. We cannot enter into the consideration of the circumstances under which condensers have been or are being applied, as they are used only in isolated cases at present (§ 32). At all events, the results depicted in Figs. 8 and 9 are closely related to many beautiful experiments with alternating currents of extra high pressure and frequency, which certainly seem to foreshadow great advances on the methods of electrical distribution and lighting as at present carried out.

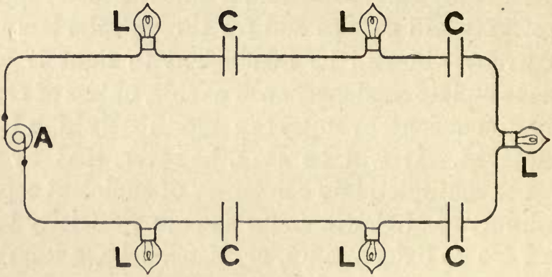

FIG. 9.

7. CAPACITY IN ALTERNATING-CURRENT CIRCUITS (CONT.).—The reader will probably have been puzzled by

the statement made at the end of the preceding paragraph, to the effect that every ordinary electric lighting circuit possesses more or less capacity. Such is the case, but the capacity is *in parallel with the circuit*, not in series with it as in Figs. 6, 7, 8 and 9.

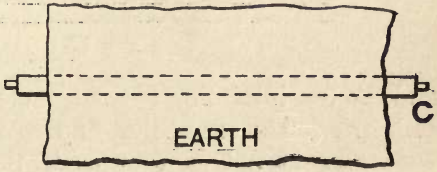

Fig. 10.

In Fig. 10, *C* is an electric-light cable laid direct in the ground, or in a conduit; the conductor forms one coating of the condenser, the insulation of the cable the dielectric, and the outer sheathing, material of the conduit (if metal), or the Earth, the other coating. This state of things may be diagrammatically represented as in Fig. 11, where we may imagine the conductor of the cable as joined at intervals to the coatings of condensers, the other coatings being connected with Earth: from this it is clear that the capacity is in parallel with the cable.

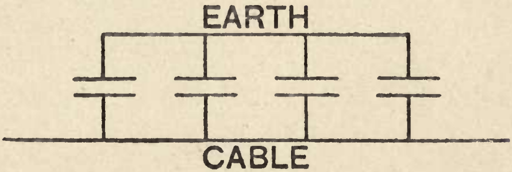

Fig. 11.

Or suppose there are two cables running side by side in a pipe or conduit, or in the ground, as represented in Fig. 12, which cables may or may not form part of the same circuit: we may then look upon the two cable conductors as the respective coatings of the condenser, and the two insulating coverings, etc., in between as the dielectric. The conception of this state of things as a condenser is not so easy as in the case of a single cable laid in the ground; but it is made clearer in Fig. 13, which represents a section of what lies between one conductor and the other. The break in the condenser dielectric (cable insulation) caused by the presence of the cable sheathing or containing pipe, the earth or air practically makes little difference in the 'condenser action' between the two cable conductors, as the cables usually lie close together.

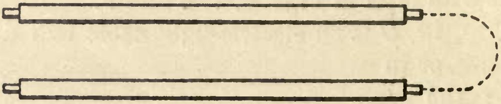

Fig. 12.

Fig. 13.

The greater the length of the cables, and the closer together or to Earth they are, the greater their capacity.

The capacity of underground mains varies from about ·3 to ·6 microfarads per mile. It depends somewhat on size and construction, and is reduced by employing paper instead of india-rubber as dielectric. The paper being sometimes wrapped comparatively loosely round the conductor, especially in the case of telephone cables, a certain amount of air is imprisoned between the folds, and air and paper allow influence (§ 6) to take place across them to a less extent than india-rubber.

8. Effect of Capacity in the Circuit.—The effect of capacity upon the current in an alternating-current circuit is exactly opposite to that of inductance, for it assists or tends to assist the current to rise to its maximum value sooner than it would otherwise do, whereas inductance retards or tends to retard the current (§ 4). This effect is the same whether the capacity is in series or in parallel with the circuit.

In Fig. 14, *A* is an alternator, the mains from which run for a long distance side by side, and feed a number of transformers, etc. For convenience we place the transformers, *T T*, at the latter end of the circuit, and think of the condenser effect of the first portion.

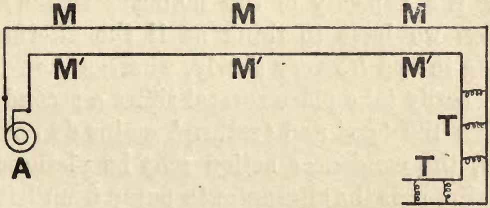

Fig. 14.

The alternator is constantly pumping electricity backwards and forwards between the mains $M M M$ and $M' M' M'$, and these may be looked upon as the opposite coatings of a condenser. Let us suppose the alternator first pumps from M to M', electricity will be, so to speak, heaped up on M', and a deficit left on M, M' being + and M −. Now, neglecting for the moment the latter end of the circuit, suppose the alternator were suddenly stopped: there would then be a momentary return flow of electricity from M' to M through the alternator; in other words, the condenser would discharge itself. If the alternator goes on working, however, it is obvious that the electricity heaped up on M' helps or increases the flow when the alternator begins to pump from M' to M. M then becomes + and M' −, and when the alternator again reverses its E.M.F., the + charge on M flows round to M', and helps the ordinary current. This auxiliary current, if we may so call it, is generally termed the *condenser current*, and is clearly greater the greater the capacity of the mains. In the above explanation we have to think as if the alternator were pumping to and fro very slowly, whereas the reversals of E.M.F. really take place several times a second (§ 16).

When the 'go' and 'return' mains do not run side by side, the condenser action may be pictured as follows:—Suppose the alternator to pump from left to right (Fig. 15), a surplus is heaped up on the right-hand cable, and a deficit created in the left-hand one; influence takes place, and + and − charges are respectively influenced (or induced) on the outsides of the cables, as shown by the signs. If the alternator E.M.F. suddenly stopped, there would be a momentary current from right to left through the alternator: it is clear, therefore, that when the alternator reverses its E.M.F., there will be a greater transference of electricity from right to left than there was when the alternator first started and pumped from left to right. The left-hand cable now becomes +ly. charged, and the right-hand one −ly. charged, and the discharge helps the alternator when it again reverses its E.M.F.

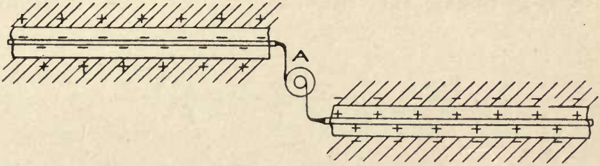

FIG. 15.

There is one difficulty which will probably have occurred to the reader, and that is, that the two cables in Fig. 14 being connected across at various points by transformers, &c., are not, consequently, strictly analogous to the insulated plates of a condenser. In Fig. 16, for instance, *C C C*, &c. are condensers representing the capacity of the two cables, *T T T*, &c. the primary coils of transformers connected between, and *A* the alternator. Now of course, any metallic cross-connection would prevent the charging of the condensers with a steady pressure; but it is conceivable—and, indeed, is proved by practice—that with a rapidly alternating pressure the condenser action is not perceptibly affected if the cables be connected across by some *non-inductive resistance*—glow lamps, for example. When *inductive resistances*, such as transformers, are joined to the cables (Fig. 16), the capacity effect will be reduced in consequence of the inductance thus put in circuit, though when a transformer is fully loaded with glow-lamps or other non-inductive work, its inductance becomes negligible.

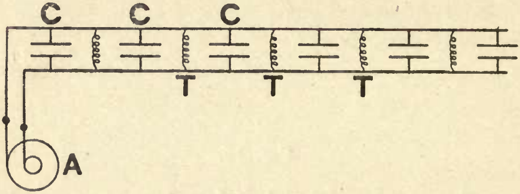

Fig. 16.

Capacity and inductance only tend to neutralise each other when both are distributed along the whole length of the circuit, as in Fig. 16. In Fig. 14, the capacity of the first part of the circuit would be little affected by or have little effect on the inductance at the far end (§§ 10, 20).*

9. Inductance, Capacity, etc., in a Direct-Current Circuit.—In direct-current work it is generally sufficient to liken a current to a steady flow of water through a pipe, the rate of flow representing current, the pressure on the water—E.M.F., and the resistance of the pipe—resistance in the electrical circuit. But here there is

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[*] The oscillatory nature of the discharge of a condenser has been alluded to in § 3; but it is not taken into account in the rudimentary explanations of the capacity effect given in this paragraph and hereafter.

no good analogy for inductance, or for capacity; which two quantities are nearly always present in an alternating-current circuit. Consequently, some other help is necessary to enable us to picture in our minds the phenomena of an alternating current, and in comparing it with a direct current. In a course of lectures delivered at the Royal Institution, in 1895, Professor Forbes employed various mechanical analogies to illustrate electrical phenomena, and these we shall here make use of, with certain extensions and modifications.*

In Fig. 17 (*a*), *T W* is a short length of thick wire, which is supposed to be held vertically by its upper end, *T*, between the fingers and thumb of the left hand. Twist the top of the wire with the fingers and thumb of the right hand continuously round in the direction indicated by the curved arrow, and assume the twisting force applied to correspond with the E.M.F. in the electric circuit, and the rate of rotation of *T W* to represent the current. Then, assuming that the wire is merely steadied by the left hand while it is being twisted by the right, *T W* corresponds with an electric circuit in which there is practically no resistance, inductance, or capacity; for it may be set rotating, kept rotating, and stopped without appreciable effort—*i.e.* the current may be started or stopped at once, or kept up with a very small expenditure of energy.

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* The teacher or student should not be content with merely explaining or reading through the account of the following experiments, but should himself experiment with the simple contrivances depicted in Figs. 17 and 18.

In Fig. 17 (*b*), a large paper vane, *V*, is fastened to the wire. The effect of this is to oppose continuous air resistance to the rotation of *T W*, although it does not appreciably retard the setting up or stopping of that rotation. This air resistance must be compared with electrical resistance, and the arrangement then corresponds with a circuit in which there is appreciable resistance, but practically no inductance or capacity. If the same twisting force be applied as in case (*a*), the rotation of the wire will not be so rapid ; in other words, with a given E.M.F. the increase of resistance diminishes the current.

In Fig. 17 (*c*), a flat circular lump or disk of lead, *L*, or other heavy body, is tightly fixed to the end of *T W*. Now, while the air offers little or no resistance to the turning of *L*, on account of its shape; the latter, because of its inertia,* opposes considerable momentary resistance to the setting up of motion in *T W*, and it also tends to prevent the sudden stopping of *T W*. The addition of *L* therefore has the effect of adding inertia to the contrivance as a whole, and it will be found to require appreciable effort to set *T W* rotating; and when in motion it will resist any sudden stoppage. This mechanical inertia is comparable with the inductance (sometimes

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* *Inertia* is that property of a body in virtue of which it resists being set in motion, having its motion changed, or being stopped when in motion. The inertia of a body depends upon its weight (or, more strictly, its mass), and also, to some extent, upon its shape. Force is necessary to overcome inertia, for it requires considerable force to set a heavy body (a flywheel, for instance) in motion, and also considerable force to stop it. When a body is in motion, it is said to have *momentum.*

called *electric* or *electromagnetic inertia*) in the electric circuit, the effect of which is to momentarily oppose the starting, change, or stopping of a current (§ 4); and Fig. 17 (*c*) thus presents the mechanical analogy of a circuit with resistance and inductance, but without capacity.

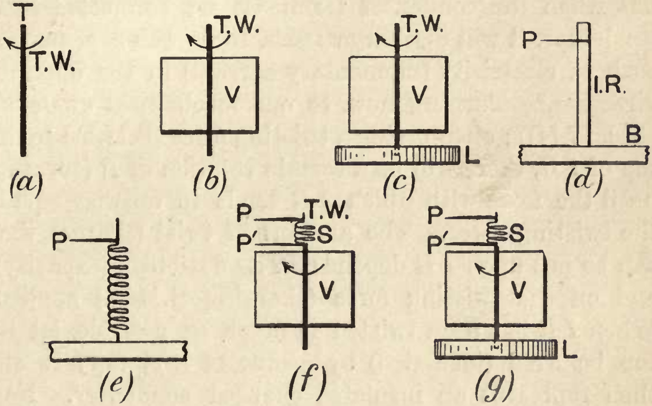

Fig. 17.

In the above examples we have likened E.M.F. to a twisting or rotating force, current to rotation, electrical resistance to air friction or resistance, and inductance to inertia. We must now get something to represent capacity. In Fig. 17 (*d*), *I R* is an india-rubber or other flexible rod or tube rigidly fixed at the bottom, say, to a block of wood, *B*, which cannot move. *P* is a pointer (such as a pin) stuck into the upper end of *I R*, to indicate its movement. It will now be shown that this arrangement is typical of a condenser. If E.M.F. is applied to a condenser, there will be a momentary current due to the rush of electricity into one of its coatings (or set of coatings) and out of the other, which in amount will depend upon its capacity, and the displaced electricity will represent the charge in the condenser. If the E.M.F. be removed, and the condenser left insulated, it will retain its charge: but when the condenser terminals are connected by a conductor, it will discharge itself, there being a sudden rush of electricity (momentary current) in the opposite direction.* Turning now to our mechanical analogue (Fig. 17 (*d*)); on applying a twisting force (E.M.F.) to the top of *I R*, there will be a certain rotation of *P* (current) until the force with which *I R* tends to untwist equals the twisting force. The amount of twist (charge) that can be put upon *I R* depends on its flexibility (capacity), and on the twisting force (charging E.M.F.) applied. When *I R* has been twisted as much as possible, let its top be fixed (insulated) by means of a clamp; it will then represent an insulated charged condenser. Now release the clamp, and *I R* will fly round, as indicated by *P*, this being equivalent to discharging the condenser, the momentary movement of *P* representing the momentary current of discharge. It is evident that *I R* might be replaced by a coiled spring, as shown in Fig. 17 (*e*). These experiments (*d* and *e*) only serve to show the effect of capacity in a condenser circuit, as distinguished from one which is completely closed to allow of the continuous passage of electricity.

Fig. 17(*f*) illustrates a circuit with capacity (due to the light coiled spring *S*), and resistance (due to *V*),

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* See footnotes, pp. 14, 24.

but practically no inductance. *S* has two pointers, *P* and *P′*, fixed one at each end, and when *S* is untwisted *P* and *P′* should be exactly in line as viewed from the top. Now begin to twist the top of the wire, *T W*, keeping the eyes fixed on the pointers. It will be found that *P* moves round a little in advance of *P′* (if the spring is not too thick,) before *V* begins to rotate, this representing the preliminary charging of the conductor: *P* keeping in advance of *P′* all the time the rotation is continued (the permanent charge in the conductor). If, now, the twisting force (E.M.F.) is suddenly stopped at *T W*, *V* will continue its motion through a short distance, until *P′* catches up to *P*, this being representative of the discharge from the conductor, which tends to prolong the current.

In Fig. 17 (*g*), the disk of lead, *L*, is added to represent inductance in the circuit. On applying a twisting force (E.M.F.) to the top of the wire, *P* first moves round slightly in advance of *P′*, then the inertia (inductance) of *L* has to be overcome, and at last *V* gets up full speed (current). On trying to stop the rotation (current), the momentum of *L* (E.M.F. due to inductance) and untwisting of *S* (discharge due to capacity), but principally the former, tend to prolong the rotation (extra current); this, be it remembered, being the case of a direct-current circuit.

10. INDUCTANCE, CAPACITY, ETC., IN AN ALTERNATING-CURRENT CIRCUIT.—In the preceding paragraph, mechanical illustrations of the direct-current circuit were given. In his lectures (p. 25) Professor Forbes followed up

these analogies still further; but, like most others, they must not be carried too far. The last portion of the preceding paragraph paves the way for their application to the alternating-current circuit.

In Fig. 18 (*a*), *T W* is a piece of thick wire. Hold it vertically at the top in the right hand, and steady it lightly with the left. Twist it rapidly to and fro, giving a turn first in one direction and then in the other, as indicated by the double-headed arrow. This represents the application or 'impression' of an alternating E.M.F. to or on the circuit. If we suppose that *T W* has no inertia or flexibility, and that no resistance is opposed to its rotation, it may be taken to represent a circuit with no inductance, capacity, or resistance: and the direction of twist (E.M.F.) and rotation (current) may be changed immediately; and one might almost say that the rate of rotation (strength of current) is uniform, though rapidly alternating in direction. This case may, therefore, be taken as an analogy for the imaginary alternating current represented by the 'curve' in Fig. 2.

In case (*b*) (Fig. 18), a paper vane *V* is put on to represent resistance in the electrical circuit; but it must be supposed that it does not materially add inertia to the arrangement. Then, if the same alternating twisting force (E.M.F.) be applied to the wire as before (case *a*), the rate of rotation (strength of current) will be less than in the first instance, in consequence of *V*; but there being no inertia, as we suppose, the rotation (current) will change directly the twisting force changes, and will be always at the same rate. Here we have the representation of an alternating-current circuit in which there is practically only resistance, and no appreciable inductance or capacity. In Fig. 18 (*c*) is shown the mechanical analogue of a circuit with resistance (due to *V*), and inductance (due to *L*). Apply an alternating twisting force (E.M.F.) to the top of *T W*; the result will be that the rotation (current) will be far from uniform, it taking appreciable time to set up, stop, or reverse. Furthermore, the rotation (current) will 'lag behind' the twisting force (E.M.F.); that is to say, the rotation (current) will start, stop, and reverse, after the twisting force (E.M.F.) has been started, stopped, or reversed.

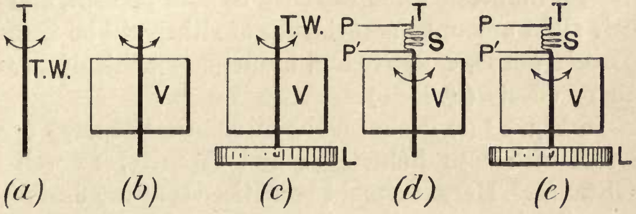

FIG. 18.

In Fig. 18 (*d*), the spring *S* is introduced to represent capacity in the circuit. On applying an alternating twisting force to the top *T*, the effect of this flexibility (capacity) in the wire (circuit) will be opposite to that of inertia (inductance): for it will be found to assist the setting up and stopping of the rotation (current),* the

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* This seems to contradict what was said at the end of the preceding

movement of the pin-head P' being in advance of the twisting force (E.M.F.). There is this important difference between the effects of capacity and inductance, that capacity in an alternating-current circuit apparently increases the current, and inductance decreases it. That such is the case has already been pointed out (§§ 4, 8). Thus, if inductance and capacity be both present, and in their right amounts, no evidence of either will be found: in other words, capacity and inductance neutralise each other's effects (§§ 8, 20).

In Fig. 18 (*e*) is shown the mechanical analogy for a circuit with both inductance and capacity, as well as resistance. Here it should be noticed that the flexibility (capacity) increases the amount of turning that can be done by a given force through a fixed distance; that is to say, it points to the fact that the addition of capacity to a circuit will decrease the effective inductance. Anyhow, it will be clearly seen that on applying an alternating twisting force to T, the effect of both flexibility (capacity) and inertia (inductance) will be to alter the rotation (current) with a given twisting force (E.M.F.) from what it would be were these properties absent.

In the mechanical analogies given (Figs. 17 and 18), the effect of inductance, as represented by inertia, is considerably greater than the effect of flexibility or capacity: but, of course, in some circuits there may be greater capacity than inductance, as might be repre-

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paragraph; but it should be remembered that here we are dealing with an alternating-current circuit, whereas § 9 refers to the direct-current circuit.

sented by using a stronger spring, *S*, and a lesser weight, *L* (Fig. 18 (*e*)). As a general rule, however, the effects of inductance preponderate.

With a given wire (circuit), in which there is principally inertia (inductance), the average rate of rotation (current) will be much greater in the case of a unidirectional twisting force (E.M.F.) than in the case of an alternating twisting force. In other words, a direct constant E.M.F. will set up a greater current in a given circuit than will an alternating E.M.F. of the same equivalent value; for in the first case inductance exerts its effect only on making and breaking circuit, or when the current strength is suddenly changed: whereas in the latter its effects are observable the whole time.

With a constant direct E.M.F. the current is uniform, but with an alternating E.M.F. it is wavy or undulatory, *i.e.* constantly varying in strength. Even if the impressed alternating E.M.F. were constant in value, as in the experiment described in § 2, this would be the case, because of inductance, &c.; but as the E.M.F. of an alternator constantly varies in strength as well as in direction (§ 15), the waves of current are much more accentuated.

Perhaps it is hardly necessary to point out that one particular in which the above mechanical analogies do not fit the true condition of things, is that the resistance (air friction), inductance (inertia), and capacity (flexibility), are contained in separate parts of the circuit (wire); whereas in the real electric circuit these properties are, as a rule, more or less intermingled along the whole of its length.

11. INDUCTANCE IN A CIRCUIT.—It has been several times stated that the effect of inductance in an alternating-current circuit is to cut down the current. The following experiment conclusively proves this. The circuit *LKB* (Fig. 19) is fed at a virtual* alternating pressure of, say, 100 volts, from the mains *M*. *B* is a laminated iron bar, built up of thin wires, on which are coiled several turns of thick wire of negligible resistance, which may be short-circuited by the key *K*. *B* obviously possesses considerable inductance (§ 4), whereas the rest of the circuit has very little. The light given by *L* depends upon the strength of the current passing through it, and is a convenient indicator of it. Suppose when *K* is depressed so as to cut out *B*, the lamp is fully lighted; when *B* is put in circuit by opening the key *K*, the lamp will burn dimly, proving that the effect of inductance is to permanently reduce the current. This effect is the same as if a back E.M.F. had been introduced into the circuit, which, in fact, is the case, the back or counteracting E.M.F. being that due to the inductance of *B*.

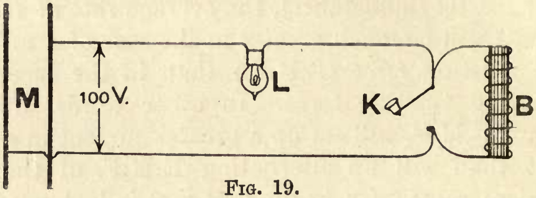

FIG. 19.

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* See § 18.

If a direct current is used, the insertion or cutting out of *B* will make no appreciable difference, as its resistance is small, except, perhaps, a faint flicker of the lamp at the moment of depressing or releasing *K*; but this would be hardly noticeable.

12. EFFECTS OF AN ALTERNATING CURRENT AND OF INDUCTANCE AND CAPACITY ON THE INSULATION OF A CIRCUIT.—In a conductor carrying a given virtual alternating current, there is a greater tendency to leak through or break down the insulation than in the case of a direct current of the same value; for the reason that in the first case the electricity is moving rapidly backwards and forwards, and the impressed virtual E.M.F. is only about seven-tenths of its maximum values (§ 18); while in the latter case it is flowing steadily in one direction, and the E.M.F. is also steady.

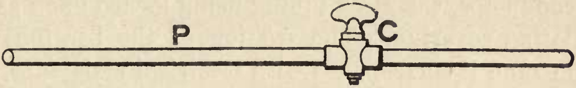

FIG. 20.

Let us illustrate this by an analogy. Consider a pipe, *P* (Fig. 20), with water flowing in it, as resembling a conductor carrying current; and suppose the material of the pipe to represent the insulation round the conductor: then, if the pressure of water causes a fracture of the pipe, it is clearly analogous to the breaking down of the insulation of the conductor. Now it must be evident that there is a greater strain on the sides of the pipe when the water is rapidly moving to and fro (alternating current), than when it is flowing steadily in one direction (direct current).

The effects of inductance and capacity in a direct-current circuit are only observable on making or breaking the circuit, or on suddenly changing the strength of current therein (§ 4); but in an alternating-current circuit they exert a continual influence on the current, and, indirectly, on the insulation of the circuit.

Fig. 21 presents an analogy. Here S is a stand carrying two bearings $B\,B'$, in which is mounted an upright glass tube G, which may be rotated by the handle H. A portion of the glass is cut away, and a short length of rubber tubing, R, inserted, to represent capacity in the circuit. Down the centre of both glass and rubber tubes passes a metal wire which stands for the conductor, the glass tubing being looked upon as the insulating covering. The friction of the bearings and of the vane V corresponds with electrical resistance, and the inertia of the lead disk L represents inductance. The strain on the glass tubing, to the outside of which V and L are fixed, may be taken as analogous to the strain on the insulation in an electrical circuit. We will first take a case in which L is removed—*i.e.* where there is no inductance in the circuit. Now, if H be rotated steadily in one direction (steady direct current), the strain on the glass tubing (insulation of the circuit) will be comparatively small; but if H is sharply and continuously turned, first in one direction and then in the other, clearly a good deal of strain is thrown on G, but this is lessened in proportion to the flexibility of R (capacity of the circuit). This seems to point out that if a circuit has capacity but no inductance, the presence of the former will not increase the strain on the insulation, but rather the reverse. If *L* be now put on (inductance put in circuit), with continuous rotation (direct current), an extra strain will be thrown on *G* at the moment of starting, stopping, or altering the speed of rotation (current); and will be the greater the more suddenly the starting, stopping, or alteration of the speed is brought about. The reason of this is that the flexibility (capacity) exists at the near end of the circuit, while the inertia (inductance) is all at the far end; a condition of things which obtains in electricity distribution work when the 'feeders' supplying the distribution network have great length. If the inductance, as represented by the inertia of *L*, were more distributed along the circuit, the extra strain on the insulation would be correspondingly lessened; while if it were all at the near end—*i.e.* if *L* were placed in the position of *R*—there would be practically no strain on the insulation directly due to inductance or capacity, except when the current (rotation) was suddenly stopped.

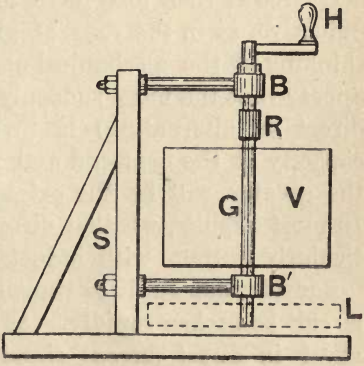

Fig. 21.

In the case of alternating rotation (alternating current) the strain on *G* will be continuous and very considerable if the condition of things be as represented in the figure; so much so, in fact, that if *G* is not thick enough or has any flaws in it, it will be fractured (insulation broken down). But if the inductance and capacity be more intermingled, the strain will be lessened; and if the inductance be all brought to the near end of the circuit, it will be still further reduced. This mechanical analogy affords a capital illustration of the opposite effects of capacity and inductance in the circuit, and the fact that one neutralises the other.

The presence of dynamos and other electro-magnetic apparatus in direct-current circuits is the main cause of inductance (§ 4); but alternating-current circuits generally have much more inductance than direct-current ones, because of the numerous transformers therein; though, by the way, the inductance of these latter decreases as their load increases, when the load is non-inductive, as in the case of glow-lamp lighting. Now, thinking of the mechanical analogy (Fig. 21), it would appear that the more suddenly the full E.M.F. (whether direct or alternating) is thrust upon a circuit, with capacity at the near end and inductance at the far end, the greater will be the extra strain on the insulation. In most circuits, whether direct or alternating, but particularly in those with inductance—however distributed—considerable strain is thrown on the insulation if the circuit be broken rapidly. As an example of this latter effect in direct-current circuits, if, while the water is flowing (Fig. 20), the cock, *C*, is suddenly turned off, a great strain will be thrown on the pipe. An illustration of this may be found in some houses where water is supplied direct from the main, and therefore at considerable pressure, and old-fashioned taps are used. On suddenly turning the tap off, the momentum of the water expends its energy on the pipe. Screw taps are designed to prevent this sudden strain being thrown on the pipes.

The strain due to inductance is not very noticeable on 'making' the circuit, though its analogue is observable in the mechanical illustrations.* On breaking the circuit, inductance is very manifest, as it shows itself in the form of an 'extra-current' arc or spark. Now it is a common but very erroneous idea that the more suddenly any circuit is broken the better, as the extra-current spark tends to destroy the ordinary switch contacts. This spark, or arc, represents energy, and if this energy is prevented from expending itself in the form of a spark, it will wreak its force somewhere else—viz. on the insulation of the circuit. Main switches for circuits having large inductance should therefore be so designed that the circuit is both made and broken gradually. A small switch fulfilling these conditions is depicted in Fig. 22.† On one of the fixed contact pieces, and on one end of the movable contact arm, there is a short cylinder of carbon. When putting the switch on, the carbons come into contact first of all, then the one on the movable arm, being mounted on a spring-hinged pivot, gives way to allow the arm to go into place. When the switch is put off, the carbon con-

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* Experiments which illustrate the effect of inductance, both on making and breaking circuit, are described in § 14.

† Made by Messrs. Siemens Bros. & Co.

tacts and the slight arc formed between them momentarily prolong the connection of the circuit. Though the switch was probably designed for the single purpose of preventing or minimising the 'spark-wear' of the contacts, it will be seen that it also eases the strain on the insulation of the circuit.

Some electricians will probably disagree with the statement that it is necessary in practice to gradually 'make' as well as 'break' alternating-current circuits, and will maintain that there is really no excessive stress on the insulation of a circuit when the full pressure is suddenly thrust upon it; but theoretical considerations, and the mechanical illustrations (Figs. 17, 18, and 21) seem to indicate otherwise; the amount of extra strain (if any) thrown on the circuit at the moment of making it appearing to depend upon the relative distribution of the inductance and capacity, as already pointed out.

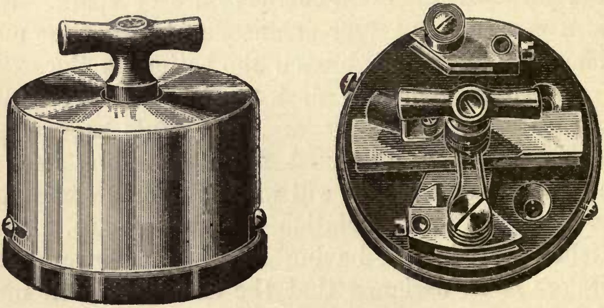

Fig. 22.

The matter of slow 'making' probably only becomes of really practical importance when pressures above, say, 2,000 volts are used; or when the circuits consist of a number of miles of cables of large capacity. Professor Forbes has arranged for slow 'making' and 'breaking' on the Niagara power circuits, and it is now being done at Deptford, and elsewhere.

It is interesting to note that on breaking a high-pressure alternating-current circuit the switch may show a large, small, or no spark at all, according to the point in the current wave where separation occurs. Thus, if the circuit happens to be broken at the moment the wave is at its peak or maximum (Fig. 31), the largest spark will be obtained, while if the current is just reversing there will be no appreciable spark.

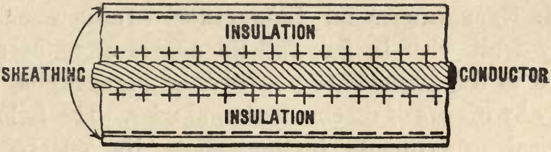

FIG. 23.

13. ELECTRIFICATION OF CONDUCTOR DIELECTRIC.—There is one particular point in which the mechanical analogies fail, and that is, they furnish no good example for the action taking place across the dielectric or insulation—viz. the *electrification* due to condenser action. In Fig. 23 is given a section of a cable conductor, its insulation, and the surrounding sheathing, pipe, or Earth. Let the conductor be carrying a steady direct current, and suppose that particular portion of it under consideration is at a higher potential than the

Earth ;* it will then have a steady + charge. Influence will take place, and a − charge will be created on the inner surface of the metallic sheathing of the cable, or other surroundings, the system acting like a condenser (§ 7). Now these charges will mutually attract each other, and will soak into the dielectric and tend to approach nearer to one another, and so in a sense lessen the thickness of the insulation surrounding the conductor. With an alternating current, on the other hand, there is little or no electrification of the dielectric ('soaking-in' action), as the charge of the cable is constantly and rapidly alternating in sign.

14. EXPERIMENTS ON INDUCTANCE.—Inductance was briefly dealt with in § 4, and its effects have been described in the immediately preceding paragraphs, principally by means of mechanical analogies. The following electrical experiments further show its effects, and should be considered in conjunction with that depicted in Fig. 19.

In Fig. 24, *L* is a glow lamp, connected through the switch or key, and wires, + and −, with a source of direct E.M.F. *C* is a coil of fairly fine wire, with a removable iron core, and is connected as a shunt to the lamp. The resistance of *C* should be such that when the current is flowing steadily the lamp filament is just perceptibly red, or thereabouts. At the instant of

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* There is a gradual fall of pressure or potential along a conductor carrying a direct current; but there is almost bound to be a P.D. between the conductor and the Earth, and the conductor will be either +ly or −ly charged.

making the circuit, the lamp will momentarily glow more brightly than when the current is steady; on breaking the circuit, the lamp will momentarily flash with great brightness. In the first case the counter E.M.F. due to inductance, as indicated by the small dotted arrow, will momentarily oppose the main E.M.F. in the shunt circuit, *C*, so that the latter is enabled to send a momentarily stronger current through the lamp. On breaking the main circuit, the field of *C* will collapse, generating a momentary and much greater E.M.F. than in the first instance, in the direction shown by the larger dotted arrow: a momentary current will flow through *C* and *L* in a counter-clockwise direction, and the lamp will flash up brightly in consequence.

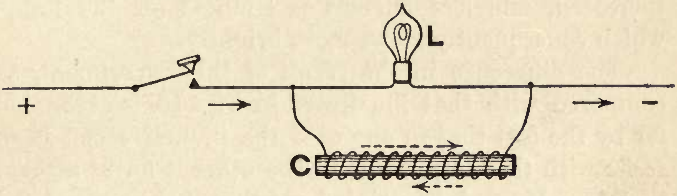

Fig. 24.

Now remove *C*, with its iron core, and insert instead a coreless coil having the same resistance as *C*, but wound as in Fig. 5, so that it shall have no inductance: pass an alternating current through the lamp and coil, of such a strength that the filament of *L* is perceptibly, but dimly, heated. Now insert the former coil, *C*, with its core, and it will be found, in consequence of the inductance of C, that L is increased in brilliancy. The explanation of these different effects on the lamp is as follows. In the first case, the non-inductive coil shunts a certain amount of current from the lamp circuit, but otherwise exerts no effect. In the second, where the coil has the same resistance, and also considerable inductance, the back E.M.F. due to the latter constantly opposes the working E.M.F., offering a kind of extra resistance in addition to the ordinary resistance of the coil (§§ 21, 22, 23); so that the total apparent resistance of the coil is increased, and less current is shunted off the lamp, which consequently glows more brightly.

The difference in the result of this experiment, as compared with that illustrated in Fig. 19, is accounted for by the fact that in one case the inductive coil is *in series* with the lamp, while in the other it forms a *shunt* thereto. It must be pointed out that if the ends of the circuit in Fig. 24 be kept at a constant potential difference, the insertion of C will not affect the current passing through L.

The following experiment, due to Edlund, which, however, is only performable with direct currents, serves to show in a marked manner the effect of inductance both on completing and breaking the circuit. G (Fig. 25) represents diagrammatically a differential galvanometer, of which C' and C'' are the two coils; B is a battery, and K a key. R and C are two coils, equal in resistance, but R is wound so that it shall be non-inductive, while C is wound in the ordinary way, and provided with an iron core. C and G must be so far removed that the magnetism of the former cannot act directly on the galvanometer needle. The galvanometer coils C' and C'' being, of course, equal in resistance, it follows that after K has been depressed equal steady currents will flow round the circuits C' R K and C'' C K, and the galvanometer will be unaffected, as the coils C' and C'' will exercise equal and opposite effects upon the needle. But at the moment of depressing K, the opposing counter or back E.M.F. of C, as indicated by the small dotted arrow, opposes the battery E.M.F., and the current in C'' is consequently momentarily weaker than that in C', so that the needle, N, moves, but afterwards returns to its zero position. On breaking the circuit, the momentary induced E.M.F. in C, which is now in the direction of the large dotted arrow, *i.e.* in the same direction as the battery E.M.F., for the instant increases the current in C'', and the galvanometer needle makes a momentary deflection in the opposite direction to that of its deflection on the closing of the circuit.

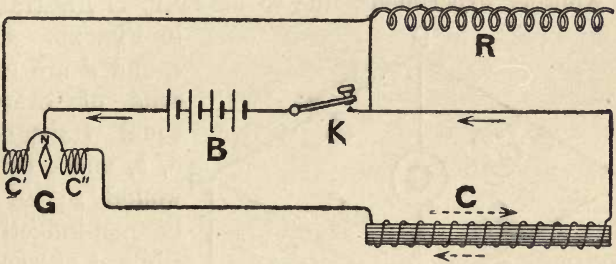

FIG. 25.

There will be little or no spark at the contact points of K on breaking circuit, for the reason that it is shunted by R and C'. This latter fact introduces an error in the experiment, for the momentary induced currents due to C, on both making and breaking circuit, travel *viâ* R through both coils C' and C'' of the galvanometer, so that both exercise the same directive effect on the needle, and the inductance in the circuit thus appears to be greater than it really is.

Another experiment, due to Maxwell, is illustrated in Fig. 26. a, b, c, and d are four coils of exactly equal resistance, a, b, and c being wound so as to be non-inductive, while d is wound in the ordinary way, and provided with an iron core. The four coils are joined up with a galvanometer (G), battery, and key, exactly as in the Wheatstone Bridge method of measuring resistance.* When a steady current is flowing through the system, the fall of potential along the path 1 a 2 d 4 will be equal to that along the path 1 b 3 c 4; and because

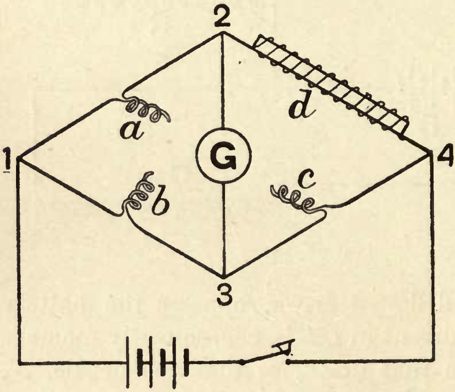

Fig. 26.

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* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 112.

the coils are all equal in resistance, the potentials at 2 and 3 will be equal, and there will be no current through the galvanometer. When the key is first depressed, the back E.M.F. of inductance due to *d* will cause the potential at 2 to rise more slowly than the potential at 3, and there will consequently be a momentary current through the galvanometer from 3 to 2. When the battery circuit is broken, the momentary direct E.M.F. in *d*, due to the collapsing of its lines, will prolong the potential at 2, and there will consequently be a momentary current from 2 to 3.

15. GRAPHICAL REPRESENTATION OF AN ALTERNATING CURRENT.—It has been demonstrated that because of the inductance and capacity in an alternating-current circuit, the current is in the form of waves, even if the impressed alternating E.M.F. is constant in value, as in the experiment shown in Fig. 1. In an alternator, however, the E.M.F. itself is constantly altering in value, as well as in direction—*i.e.* it is in the form of waves, and this further accentuates the waves of current.

To show approximately what an alternating current is like, one may draw a picture, in the form of a curve, of the changes which take place in the strength and direction of the impressed E.M.F. which sets it up, and this will enable us to explain what is meant by the *sine curve* or *sine wave*, terms frequently used in speaking of alternating currents.

The reader is, of course, aware that when a simple coil of wire is rotated in a magnetic field, it has alternating E.M.Fs. induced in it.* A simple two-pole field and coil is shown in Fig. 27, and we will consider what happens to the top half, *p*, of the coil, *a b c d*, when the latter is evenly rotated in the direction shown by the curved arrow.

Now *p* will, if viewed sideways from one of the pole faces, *N* or *S*, have an up-and-down motion; and its apparent velocity will be variable during any one complete revolution of the coil; but the changes that take place will be repeated over and over again at regular intervals. This will be more clearly understood from Figs. 28 and 29. Fig. 28 represents the circular path traversed by *p* when the coil is looked at from the front end, only one pole, *N*, being shown for simplicity's sake; and, as we suppose that the coil is being turned with uniform velocity, the actual rate of progress of *p* round

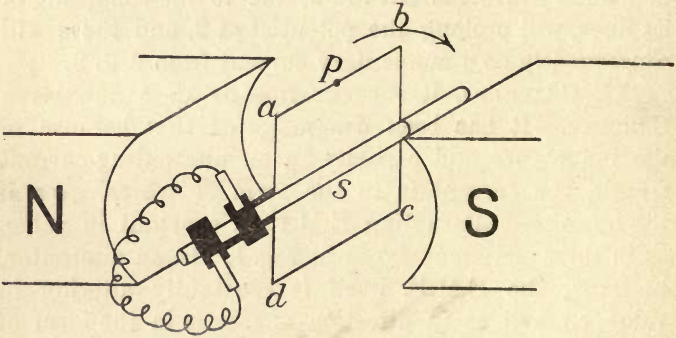

FIG. 27.

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* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 153.

its circular path will also be uniform. But if we look at p from one of the sides of the coil, it will appear to travel up and down in a straight line, $a\,b$ (Fig. 29), and its rate of motion in an actual up or down direction will not be uniform. When p has travelled round 10° from its topmost position, *i.e.* from p to p_1 (Fig. 28), its actual progress in a downward direction will be represented by the distance $p\,p_1$ in Fig. 29, which is relatively much less than the circumferential distance $p\,p_1$ in the first figure. Another 10° travel is from p_1 to p_2 (Fig. 28), from p_2 to p_3, from p_3 to p_4, and so on; and, as these distances are traversed in equal times, the apparent velocity of p, as viewed in Fig. 29, will at first be very slow, and will gradually increase until it reaches the 90° position, p_5. From p_5 to p_6 its apparent velocity will gradually decrease. The same thing will be

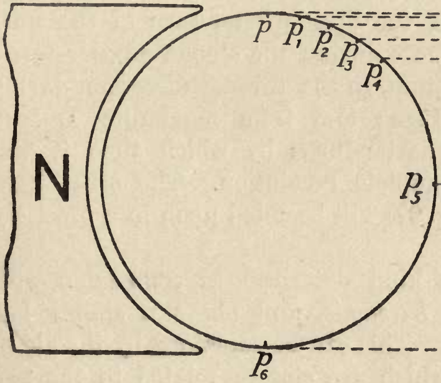

Fig. 28. (View from end of coil.)

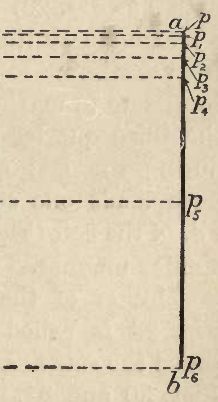

Fig. 29. (View from side of coil.)

observed when the coil is making its second half-turn—*i.e.* when p is travelling from p_6 back again to its topmost position. Now, the E.M.F. induced at p depends upon the rate at which it cuts the lines of the field, and, supposing the field to be uniform, this depends upon its rate of motion in an actual up or down direction, as viewed in Fig. 29. It therefore follows that the E.M.F. in p will vary just as the rate of its travel along the path $a\ b$ (Fig. 29) varies, and it will change from zero to a maximum during the first quarter-turn of the coil; from maximum to zero during the second quarter-turn; from zero to maximum, in the reverse direction, during the third quarter-turn; and from maximum to zero during the last quarter-turn: by which time it will have made one complete revolution. The other half, $c\ d$, of the coil (Fig. 27) will be acted upon in a precisely similar manner.

Motion of the kind described in connection with Fig. 29 is called *harmonic*, and obeys a simple law called the *sine law*. This can be explained by the aid of Figs. 30 and 31, which are closely related to the two preceding figures.

Looking at the coil from the collector or front end (Fig. 27), the path described by the point p (Fig. 30) will be a circle, having its centre at O, p 0 being its zero or starting position, and 1, 2, 3, 4, 5, &c., successive points on its journey during one revolution of the coil.

The sine curve or curve of E.M.F. is plotted as follows. Take a horizontal line, such as that marked TIME BASE (Fig. 31): since the point p moves with uniform velocity round its circular path, distances measured along the time base may be taken to represent either 'time from the beginning of measurement,' or 'distance moved by *p* round its circular path.' *p* is connected to its 'centre of travel' or axis, *O*, by the radius *R* of the circle in which it moves, and this is clearly the greatest height to which it can rise, as in position *O* 4 (Fig. 30): we therefore take this height as the maximum height for our sine curve (Fig. 31), which represents the rise, fall, and reversal of E.M.F. The radius *R* will make an angle with

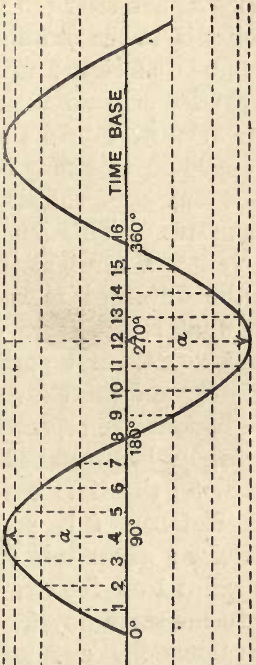

Fig. 31.

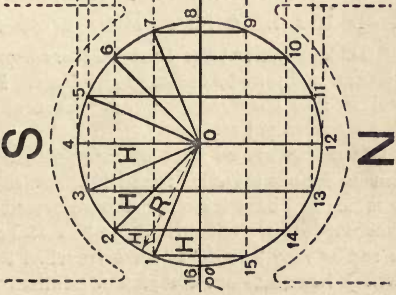

Fig. 30.

the horizontal diameter of the circle, which will begin at zero when *p* is in the position *p* 0, and will increase as *p* travels round the circle, until, at position 4, the radius is 90° from its original position. To draw the E.M.F. curve, we must first take a length along the time base, and call it 360°: this may conveniently be made equal to half the length of the circumference of the circle in which *p* moves.* This length is then equally divided up, and we get a straight line with subdivisions representing the distances moved by *p* along its circular path, or, what is the same thing, the angles made by the radius with its first position in its revolution round the centre *O*; and these divisions, as before pointed out, may also be taken to represent time.†

Suppose *p* has reached the point 1, we take a distance along the time base equal to half the circumferential distance, 0 1, and at that point erect a perpendicular: where this cuts a horizontal line drawn through point 1 on the circle, we get one point on the curve. In the same way for position 2, we take half the distance along the circumference 0 2, and mark this off on the time base, then erect a perpendicular, and

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* Distances along the time base are proportional to circumferential distances, and may be drawn to any scale. In the present case they are equal to *half* the circumferential distances which they represent, this being a convenient scale.

† If *p* has moved from its zero position to position 2 (Fig. 30), the radius will have travelled round 45°. When *p* reaches the position 4 the radius will have travelled or have described an angle of 90°. When *p* has made one half-turn, *i.e.* when it has reached the position 8, the radius may be said to have travelled 180° from its zero position. When *p* has made one complete revolution, we say that its radius has travelled round or described an angle of 360°.

where the latter cuts a horizontal line drawn through 2 on the circle, we get the second point on our curve. This operation being repeated for different positions of p round its circular path (3, 4, 5, 6, etc.), a series of points is obtained, which, when connected, are found to lie on a wavy line called the sine curve (Fig. 31).

This curve depends upon the relationship that the distance, H, of each position of p (above or below the horizontal line) bears to the radius, R. For, the greater H is, that is, the greater the distance p is above or below the base line, the more effectively is it cutting the magnetic lines of the field, and the greater is the E.M.F. H is a maximum at the positions 4 and 12, and these are consequently the maximum points on the curve. The connection between H and R is as follows:—

$$H = R \sin A,$$

where A is the angle which the radius, R, makes with the horizontal line, in the particular position taken.

The sine of the angle A (Fig. 32) (written *sin A* or *sine A*) is the number obtained by dividing the length of the perpendicular or height H by the length of the hypotenuse (side opposite the right angle) or third side R; in this case the radius of the circle—*i.e.*

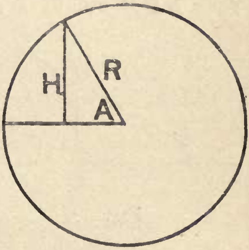

FIG. 32.

$$\sin A = \frac{H}{R},$$

this ratio being dependent on the angle itself, not on the individual length of either of its sides.*

The curve obtained shows the variation in the E.M.F. of a simple alternator, such as that illustrated in Fig. 27, for one revolution of its coil or armature. The E.M.F. is at zero when the plane of the coil or armature is at right angles to the lines of force of the field, and gradually rises, reaching a maximum when the plane of the coil is parallel with the direction of the field. The field in this case is assumed to be uniform ; if it is not so, the simple sine law no longer holds good, and the E.M.F. curve will be more or less altered in form. In practical alternators, owing to the non-uniformity of the fields, and the various shapes of coils used, the form of the E.M.F. curve may vary considerably from that of the true sine curve. The design of alternators has been

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* Let ABC (Fig. 33) be any angle, a, of which the sine value is required. Take any point, D, in either side, say in AB, and drop therefrom a perpendicular, DE, to the other side, BC, cutting it at E. Then BDE will be a right-angled triangle, of which BD is the hypotenuse, and DE the perpendicular. Now, in such, the ratio $\frac{\textit{perpendicular}}{\textit{hypotenuse}}$, i.e. $\frac{DE}{BD}$, represents the sine value of the angle a. If the angle remains the same (in the present case it is 30°), no matter how long the sides BD or BE may be, or from which point or side the perpendicular is dropped, the ratio $\frac{\textit{perpendicular}}{\textit{hypotenuse}}$ will always be the same. In the present case, for instance, it is $\frac{1}{2}$, *i.e.* sin 30° = ·5. Sine values may be directly obtained from tables. (*Vide* the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 104.)

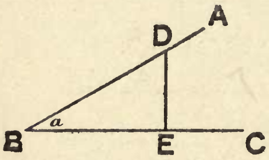

Fig. 33.

brought to such a pitch of perfection that they may be made to give a true sine wave of E.M.F., or one which differs in respect of height, breadth, &c., according to the ideas of the designer. The fact of thus being able to obtain variously shaped waves of E.M.F. within certain limits is of importance; and one question which naturally arises is, what is the most efficient form of wave for a given circuit? This is a matter, however, beyond the scope of this book.

16. Frequency.—The E.M.F. of the coil shown in Fig. 27 is nothing in the upright position there depicted, but gradually increases until the plane of the coil lies horizontal—*i.e.* until the coil has moved through 90° and has no lines through it; it then gradually decreases, reaching zero when the coil has made one half-turn. In the second half-turn the E.M.F. will again gradually rise and fall, but this time in the reverse direction. This rise, fall, and reversal, and the corresponding distance travelled by the coil, are shown in Figs. 30 and 31.

If the coil is connected up with an outer circuit, in one revolution the induced E.M.F. and resulting current will make two *alternations*, or one complete *period* or *cycle*; and the *rate of double alternations per second*, or *number of complete periods* or *cycles per second*, which is termed the *frequency* or *periodicity*, will depend upon the number of revolutions which the coil makes in that time. Thus, supposing it revolves 600 times in one minute, the frequency of the E.M.F. and of the current set up will be 10.

Frequency is denoted by the symbol ∼, thus 70 ∼ signifies a pressure or current making 70 complete periods per second—*i.e.* having a frequency of 70.

The frequency of alternating currents, as used for ordinary work in this country, varies from 40 ∼ to 130 ∼, the present tendency in central station work being to reduce it to something like 50 ∼ or 60 ∼. For special purposes, E.M.Fs. of very much higher frequency are sometimes employed.

The rise and fall of the current in *one* direction should be called an *alternation*; but this term is sometimes employed to indicate a complete reversal—*i.e.* a *period* or *cycle*, a disagreement which is somewhat confusing. Referring to Fig. 31, the portion of the curve from 0 to 180 is really an alternation, and the portion from 0 to 360 a cycle or period, and the symbol for frequency (∼), being derived from the shape of the curve, should assist the student in remembering this. An *alternation* is, as its name indicates, an alternative wave or alteration in direction. Thus a frequency of 80 ∼ means 80 periods, or 160 alternations per second.

17. Frequency of Alternators.—In the case of a simple coil rotating in a 2-pole field, it was shown that the frequency is proportional to the number of revolutions per second (§ 15). Practical alternators are, with few exceptions, constructed with multipolar field-magnets, as well as a number of coils: but the frequency is got by simply multiplying together the revolutions per second and the number of pairs of poles, a consequent pole counting as a single pole.

Example.—An alternator has 12 pairs of poles (N and S), and runs at 300 revolutions per minute. Each coil will pass through 12 fields in one revolution —*i.e.* there will be 12 complete reversals or waves of E.M.F. (~) in each revolution. Consequently, the resulting frequency will be :—

$$12 \times \frac{300}{60} = 12 \times 5 = 60 \sim.$$

18. Virtual Volts and Amperes.—The E.M.F. of a practical alternator is constantly rising, falling, and reversing, in much the same manner as described in § 15; and the current in the circuit must rise, fall, and reverse in sympathy though not necessarily in step with the E.M.F. (§ 19).

It is clear that we cannot take the maximum points of the pressure or current wave as the nominal value, for the pressure or current are only at these maxima for comparatively short periods. What is rightly called an alternating E.M.F. of, say, 100 volts, must at some times be considerably above 100 volts, and at other times at zero. Similarly, an alternating current of, say, 10 amperes, is at times greater than 10 amperes, and at others less. We must take a value, called the *virtual value*, which is equivalent to that of a direct E.M.F. or current which would produce the same effect: and those effects of the E.M.F. and current are taken which are not affected by rapid changes in direction and strength; in the case of E.M.F. or pressure—the reading on an electrostatic voltmeter; and in the case of current—the heating effect.

Thus, a *virtual* E.M.F. of 100 volts is one that would produce the same deflection on an electrostatic voltmeter as a direct E.M.F. of 100 volts ; and a *virtual* current of 5 amperes is that current which would produce the same heating effect as a direct current of 5 amperes—say, on a 'bank' or group of incandescent lamps : but both pressure and current will be continually varying above and below these values.

Neglecting the effects produced, the virtual value of an alternating E.M.F. or current having a sine curve form (Fig. 31) is about ·707 of its maximum value. For example, an E.M.F. which alternates between maximum values of 100 volts in one direction, and 100 volts in the other, will have a virtual value of about 70·7 volts. Similarly, a current which alternates between 10 amperes in one direction, and 10 amperes in the other, will have a virtual value of about 7·07 amperes. The reciprocal* of ·707 is 1·41, so that if any virtual value of pressure or current be multiplied by this number, the product will give the approximate maximum value. Thus, a virtual alternating pressure of 220 volts alternates between (220 × 1·41 =) 310 volts in one direction, and 310 volts in the other ; and a virtual current of 50 amperes alternates between maxima of (50 × 1·41 =), say, 70 amperes in one direction, and 70 amperes in the other direction.

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* The reciprocal of any number, n, is obtained by dividing it into unity—*i.e.* reciprocal of $n = \frac{1}{n}$. Thus, reciprocal of $\cdot 707 = \frac{1}{\cdot 707} = 1\cdot 41442\ldots$, or, say, 1·41. The product of any number multiplied into its reciprocal is unity : thus, $\cdot 707 \times 1\cdot 41442\ldots = 1$.

A given virtual alternating pressure throws more strain on the insulation of a circuit than a direct pressure of the same value (§ 12); and in this connection it should be remembered that, as we have just pointed out, any given virtual pressure fluctuates between values nearly half as high again as its virtual value. If the wave of pressure differs from the sine curve form—a matter which depends on the design of the alternator, as mentioned at the end of § 15—the maxima may be as much as twice the virtual values.

The difference between *virtual* and *effective* values of pressure and current is explained in § 29.

19. Amplitude and Phase.—The *amplitude* of an impressed (virtual) alternating E.M.F. or current is the maximum value or height of each wave. Thus, in Fig. 31, the distances *a a* represent the amplitude of the waves of E.M.F.

Both E.M.F. and current suffer periodic changes of strength, that is, they pass through different *phases* or states. If we take a case where the current rises, falls, and reverses exactly at the same time as the E.M.F., the current would then be said to be *in phase* or *in step* with the E.M.F.; but, as already explained, this is not always so, the current wave being more often *out of phase* with the E.M.F. wave, owing to the effects of inductance and capacity. The frequency of the current is, however, always the same as that of the impressed E.M.F.

20. Lag and Lead.—It was explained in § 4 that the effect of inductance in a circuit is to cause the

current to take time to 'grow,' and time to die away. In fact, the current does not generally start till after the E.M.F. has been impressed on the circuit, and does not stop until after the E.M.F. has been stopped or reversed. Inductance in an alternating-current circuit consequently causes the wave of current to *lag* behind the wave of E.M.F. This is depicted in Fig. 34, where the dotted curve, *P*, represents the E.M.F. or pressure wave; and the other curve, *C*, the current wave. Starting from the left-hand end of the horizontal line or *time base*, it will be seen that the current starts after the E.M.F. starts, and reverses after the E.M.F. reverses, and so on. In other words, the current *lags in phase* behind the E.M.F., although its frequency is exactly the same.

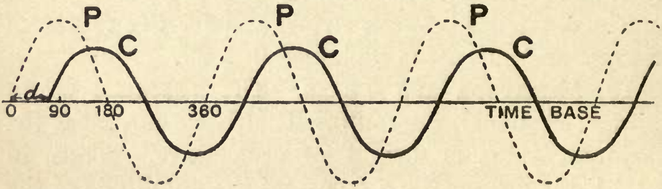

Fig. 34.

The amount of the *lag* is measured in degrees as set out along the time base (Fig. 31). Thus, in Fig. 34, the lag is indicated by the distance, *d*, between the beginning of the pressure curve and the beginning of the current curve, and is in this case about 70°. The lag due to inductance may be anything up to 90° (a quarter period), but cannot exceed this.

The effect of capacity in a circuit is generally said to cause the current to *lead* in phase, but this effect is rather difficult to conceive, though we will endeavour to explain it by means of a mechanical analogy, such as has already been employed. Apply an alternating twisting force to the top of the wire, *T* (Fig. 35); the action of the spring, *S*, being taken to represent the effect of capacity, and the movement of the vane, *V*, movement of electricity or current. On commencing the experiment, of course the twisting force (E.M.F.) must first be applied *before* the rotation (current) starts; but after a time, though it will be difficult to discern, the resiliency or rebounding effect of the spring acts so as to cause the vane, *V*, to move in *advance* of the twisting force (E.M.F.), thus representing the current *leading in phase.* The explanation of the effect of capacity, as given in §§ 8 and 10, will also assist the reader to understand what is meant by the term. As a general rule, alternating currents lag more or less in phase, as the inductance usually greatly preponderates over the capacity; but, on very long lines, or by purposely introducing capacity into a circuit, the lag may be neutralised or even exceeded by the lead, and the current will then be either in phase with the pressure, or it may lead in phase.

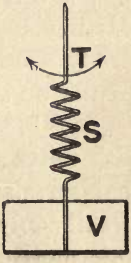

Fig. 35.

There has been some objection to the terms 'lead of current' or 'lead in phase,' principally on the ground that they tend to convey the idea that the effect precedes the cause—*i.e.* that the current is in advance of the E.M.F. causing it. The latter is true in one sense, but untrue in another. Of course, there can be no flow of electricity in a circuit until E.M.F. has been applied; but if the circuit has capacity, and supposing firstly that a direct E.M.F. is applied, the current will on starting be momentarily greater than the ultimate steady current; and it will again be momentarily greater on stopping the E.M.F.

In § 3, we likened an electrical circuit to a pipe filled with water: this analogy may be extended by supposing that an electrical circuit with capacity is like a pipe circuit only partially filled with water: then when watermotive force is applied—for instance, when the connection of the circuit with a cistern or reservoir is established by opening a tap—there will be a rush of water (till the pipe is filled up) that will be greater than the ultimate steady flow. The hydraulic circuit, however, does not offer a good analogy for the electric circuit when capacity is taken into account. The capacity of a rigid pipe for water is fixed, whereas the capacity of a conductor for electricity depends upon its surroundings, and on the E.M.F. or P.D. applied.* The illustration just put forward will serve to give the reader an idea as to how capacity may be said to 'suck' the current out in advance of a direct E.M.F., but does not afford a parallel for the discharge flow, or for the action with an alternating E.M.F.

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* See the Author's *First Book of Electricity and Magnetism*, Second Edition, § 159.

When the direct E.M.F. is cut off, the direction of the capacity or condenser current of discharge may be roughly said to be opposite to the charging current when the capacity is in series with the circuit as in Figs. 6, 7, 8, etc., but in either or both directions when the capacity is in parallel with the circuit, as in Figs. 11, 16, &c.

The lead of current due to capacity in an alternating-current circuit is best illustrated by the mechanical analogies given at the beginning of this paragraph and in § 10, while a partial explanation is given in §§ 6, 8, and 28. Fig. 36 represents the current curve, *C C C*, leading in advance of the pressure curve, *P P P*.

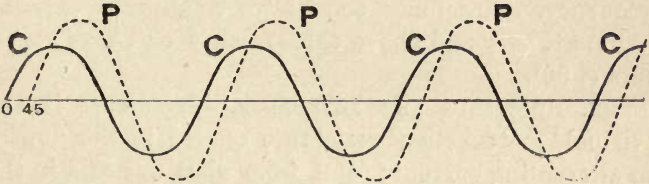

Fig. 36.

Lag and lead are further dealt with in §§ 31 and 32.

21. Reactance.—The resistance offered by a conductor to a steady flow of electricity is expressed in ohms; and this value is the same whether the conductor is coiled up or stretched out, and is unaffected by the presence of neighbouring conductors. With a constantly changing current, such as an alternating one, the *apparent resistance* offered to its flow is greater if the circuit conductor be coiled up than if it is straight, is affected by the presence of neighbouring conductors,

and also depends upon the frequency. In short, Ohm's simple law cannot be applied to alternating-current work.

The cause of this apparent additional resistance in the circuit is the combined effect of inductance and mutual induction, and is called *reactance.** The inductance is increased by the presence of electro-magnets or coils of wire in the circuit, but is decreased by capacity; while the mutual induction depends upon the presence of neighbouring conductors; and their combined effect—*i.e.* the reactance—increases with the frequency. Reactance constitutes a kind of *spurious resistance,* over and above the ordinary or *ohmic resistance* (§ 30).

22. REACTANCE AND IMPEDANCE.—*Impedance* is the 'virtual' or 'effective' resistance offered to the flow of an alternating current; and, from what was said in the preceding paragraph, is clearly the combined effect of the ohmic and spurious resistance in a circuit; or in other words:—

$$\text{Reactance} \propto \frac{\text{inductance, mutual induction, and frequency.}}{\text{capacity.}}$$

And:—

$$\text{Impedance} \propto \text{resistance and reactance.}\dagger$$

The two terms reactance and impedance must not be confused.

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* The term *inductance* was originally introduced to take the place of *self-induction.* Some few writers extend its meaning, and make it include *mutual induction* also; the terms *self-inductance* and *mutual-inductance* are consequently sometimes employed.

† The sign $\propto$ signifies 'is proportional to.'

It should be easy to remember that *reactance* refers only to the *reactive effects* in the circuit, or what is otherwise called the 'spurious resistance'—*i.e.* an extra resistance brought about when the flow of electricity is not steady; whereas *impedance* implies the virtual or effective or total resistance which *impedes* the flow of an alternating current of electricity.

The connection between resistance, reactance, and impedance is further explained in § 30.

23. DIFFERENT ACTION OF RESISTANCE AND REACTANCE ON CURRENT. CHOKING COILS.—There is a very important difference in the obstruction offered to an alternating current by ordinary resistance and by reactance, as the reader will have observed in performing the experiments mentioned in §§ 11 and 14. Resistance obstructs the current by dissipating its energy, which is converted into heat. Reactance, on the other hand, obstructs the current by setting up an alternating E.M.F. in opposition to the impressed E.M.F., and so reduces the effective current in the circuit *without wasting much energy*, except by hysteresis in any iron magnetised.*

This may be regarded as one of the advantages of alternating over direct currents, for, by introducing reactance into a circuit, we can cut the current down with comparatively little loss of energy. This is generally done by increasing the inductance in a circuit, and consequently also its reactance and impedance, by means of

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* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 100.

a device called variously a *reactance coil*, *impedance coil*, *choking coil*, or '*choker*.'

Figures 37, 38, and 39 illustrate the principle of choking coils. In Fig. 37, *C* is a coil of thick wire provided with a laminated iron core, *I C*, which may be either fixed or movable. In the first case, the inductance, and therefore, also the reactance of the coil, is invariable, with a given frequency: in the second case, the inductance and consequent reactance may be respectively increased or diminished by inserting the core farther within the coil or by withdrawing it.

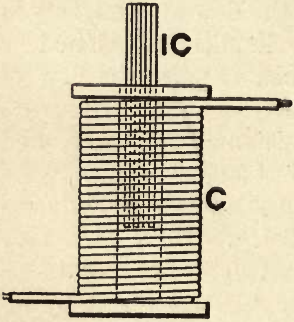

Fig. 37.

In Fig. 38, *C* is a coil of thick wire with a fixed laminated iron core, *I C*, and a movable thick copper sheath or sleeve, *C S*. When *C S* is apart from *C*, the latter will have its maximum inductance—*i.e.* its

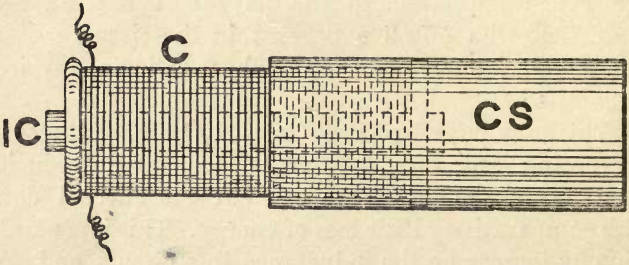

Fig. 38.

greatest choking effect: but this will decrease as *C S* is slipped more or less on to *C*. When *C S* is placed over *C*, mutual induction takes place between *C* and *C S*, the latter forming a closed secondary circuit. The E.M.F. due to the inductance of the coil *C* will then expend more or less of its energy in setting up currents in *C S*, instead of in weakening the current in the main circuit. The sheath, *C S*, however, also tends to absorb some of the energy of the current flowing through *C*; hence a choking coil on the first-described principle (Fig. 37) is more generally used.

The choking coil depicted in Fig. 38 is virtually a small transformer, of which *C* is the primary coil, and *C S* the secondary coil. Now the copper sheath, *C S*, has very little resistance, and the currents set circulating in it—which represent energy transferred from the primary circuit, *C*—are comparatively large. If we could increase or diminish the resistance of *C S* at will, instead of slipping it on or off *C*, we should be equally well able to regulate the choking effect of the apparatus as a whole. This is sometimes done in practice, as diagrammatically represented in Fig. 39, where *I C* is a laminated iron core,

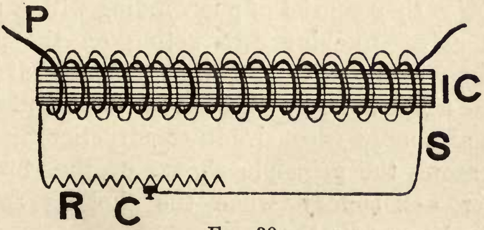

Fig. 39.

on which are wound the fixed primary and secondary coils *P* and *S*. *P* is in the main circuit, and joined up to *S* is an adjustable resistance, *R*, and some kind of sliding contact, *C*, by which the amount of *R* may be increased or diminished. The iron core, *I C*, may or may not be movable. Supposing, first of all, that it is fixed. The greater the resistance of the secondary circuit, *S R C*, the smaller will be the currents induced therein, and the less the energy of inductance absorbed from the primary circuit, *P*: consequently, when *R* is small, the least choking effect will be exercised, but as *R* is increased the choking effect will increase. If *I C* is movable, the choking effect may be further diminished or increased by respectively withdrawing or inserting it.

24. PRACTICAL FORMS OF CHOKING COILS.—All the 'chokers' described here belong to the class depicted in Fig. 37—*i.e.* they consist of one winding with a movable or fixed core. Choking coils acting on the principle shown in Fig. 38 are used in America, but besides being less efficient, as pointed out in the last paragraph, they are also more expensive in construction.* For the same reasons, the principle shown in Fig. 39 is not altogether satisfactory when the choking coil is in circuit for hours at a time.

Fig. 40 shows a choking coil for heavy work, as made by Messrs. Johnson & Phillips. The coil consists of one winding in two sections, the bobbin being divided

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* The sliding brass tube regulator used in some medical coils is of this type, and works on the principle enunciated.

midway by an insulating 'cheek.' A guide-tube of 'presspahn'* is fixed to the top of the bobbin, and in this slides the core. The latter is made of a bundle of fine iron wires securely bound together; it is hung at one end of a steel cord, which makes a couple of turns round a pulley, and terminates in a counterweight; the cord being fixed at one point to the pulley, so that it cannot slip thereon. A sensitive adjustment is secured, the hand-wheel operating a worm which gears into a spur-wheel fixed alongside the pulley. The latter may be locked in any required position by means of the small bolt at the right-hand end of its spindle. The terminals of the coil are at the back of the wooden stand, the switch at the top being so connected as to short-circuit it if required.

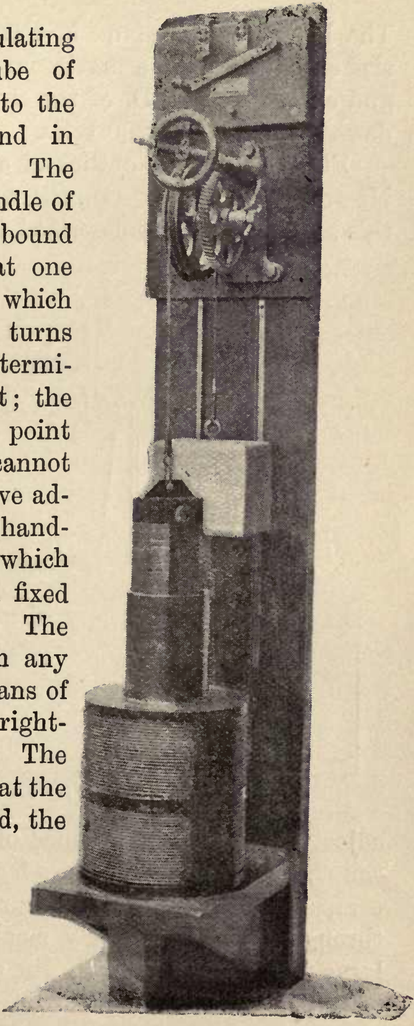

Fig. 40.

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* *Presspahn* is a material made of wood fibre. It is cheaper than vulcanite, and more durable than pasteboard.

The height of the stand is 4 ft. 10 in., the particular size shown carrying a maximum current of 15 amperes, and choking the P.D. of the circuit in which it is fixed down from 1,400 to 200 volts.

Fig. 41 gives an outline of a choking coil made by Messrs. Crompton & Co., the main difference between this and the one just described being in the method of adjustment, and the absence of a counterweight. The coil *C*, and iron core *I C*, are both great in diameter, as compared with length, the core thus having to pass through only a relatively small distance to secure a large difference of effect. The core, *I C*, is made up of

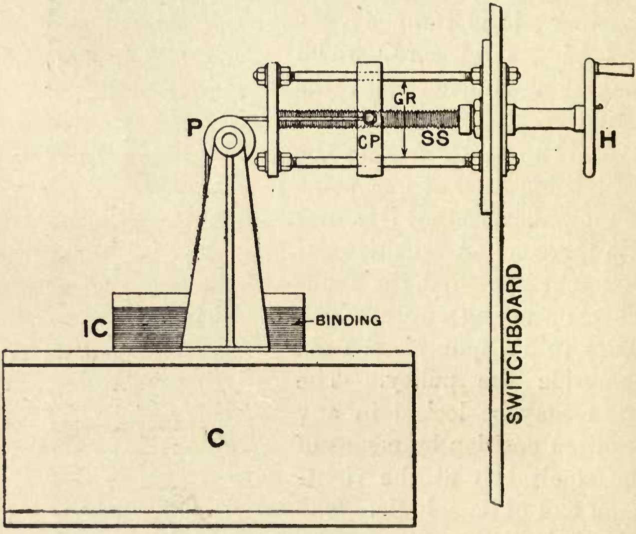

Fig. 41.

fine soft iron wires bound together, and is fastened to one end of a steel band which passes over the pulley *P*: the other end of this steel band is secured to the cross-piece *C P*, which travels along the two guide rods, *G R*. The horizontal lines on *I C* represent the binding round the iron wires, the latter running of course in a perpendicular direction. The handwheel *H*, on the front of the switchboard, turns the screwed spindle *S S*, which is tapped into *C P*; and according to the direction in which *H* is turned, so *C P* moves either to the right or to the left, and *I C* is withdrawn from or dropped further into the coil. Of course the design of the coil and the method of adjustment may be altered to suit different circumstances.

A 'choker' for use on arc-lamp circuits, also made by this firm, consists of a bobbin about 9½ in. long, wound with a single coil of wire, and provided with a movable rectangular core made up of thin flat strips of soft iron. It thus resembles Fig. 37.

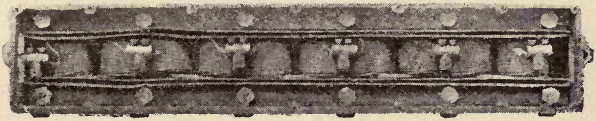

Fig. 42.

Fig. 42 shows a choking coil, or rather a collection of choking coils, mounted in a cast-iron case. Each separate 'choker' has two coils mounted on a laminated core, as illustrated in Fig. 43. These cores cannot be seen in Fig. 42, as strips of vulcanised fibre are placed between their ends and the holding-down bolts. The coils are relatively small, as the case which holds them is only 2 feet long. This apparatus was made by the Electric Construction Corporation for the system of street lighting adopted at Lagos, W. Africa, where 50-c.p. incandescent lamps are run in series circuits off constant potential mains. A sketch of the connections is given in Fig. 44, where it will be seen that the choker (or rather chokers) are joined up with a multiple-contact regulating switch. Each lamp is provided with an automatic short-circuiting cut-out, and

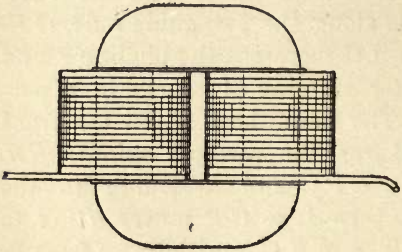

Fig. 43.

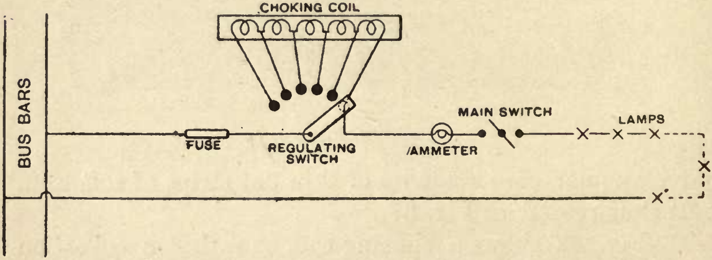

Fig. 44.

should one, two, or more of them fail, a corresponding number of sections of the choking apparatus is put in circuit to take the place of the broken lamp or lamps, and thus keep the current constant. It must not be supposed that this arrangement of lamps, &c., is a general one; it being adopted to suit certain special conditions. The matter is cited as illustrating an application of choking coils.

Another type of choking coil, made by Messrs. Miller & Woods for very light work, consists of a fixed core and coil, the turns of the latter in circuit being varied by means of a sliding contact. A diagram of this arrangement is given in Fig. 45, and an exterior view in Fig. 46. *I R* is a laminated iron ring built up of soft iron ribbon: on this, but well insulated therefrom, is a coil of thickly covered copper wire, one end of which *E* is free, *i.e.* unconnected with anything, while the other is joined to terminal *T*. *I R* is closely wound

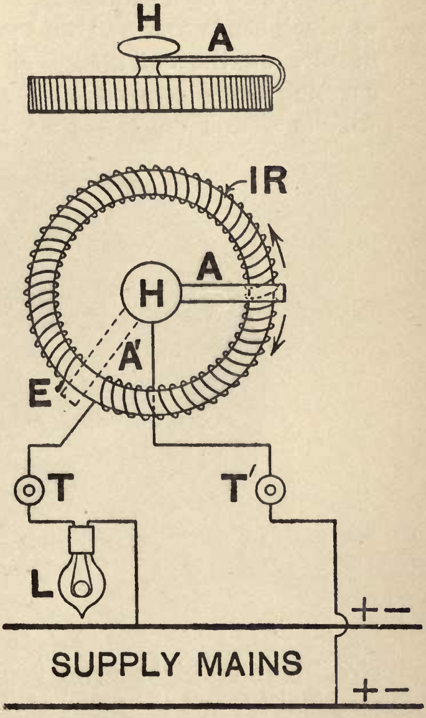

Fig. 45.

with the wire—*i.e.* the turns lie close side by side, not as shown in the figure. Pivoted in the centre of the ring and operated by a handle *H*, is a brass arm *A*, the end of which bends over and makes contact with the turns of wire on the outer edge of the ring, the insulating covering being scraped off for this purpose, after the wire is wound on the ring, without, however, short-circuiting the neighbouring turns. *A* is connected with terminal *T′*, and the figure shows the connection of the choking coil to the mains, with one lamp *L* in circuit. If the arm *A* is in the dotted position *A′* no current will flow. By turning *H* one way or the other, more or less of the turns of wire will be put in circuit with the lamp, and the latter will give less or more light. It may

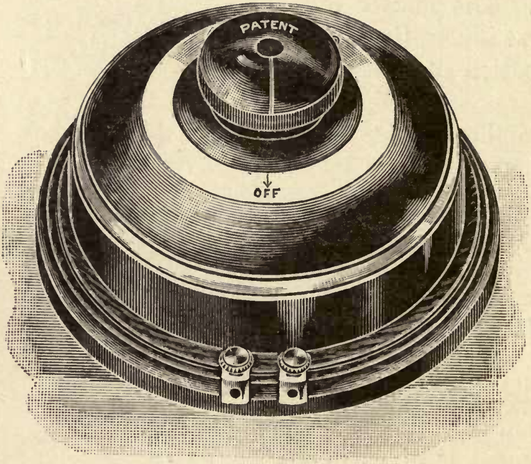

FIG. 46.

appear that the actual resistance of the turns put in circuit has something to do with the cutting down of the current; but if the apparatus is well designed, the resistance of the whole of the coil should be such that if it were all put in circuit with the lamp without its iron core, *i.e.* without appreciable reactance, there should be very little effect on the brightness of the lamp. For if the coil has much resistance as well as reactance, energy will be absorbed in heating the coil, and the current will not be cut down without material waste, the primary object of a choking coil. An exterior view (about half-size) is given in Fig. 46, where will be seen the handle and the terminals (H and $T\ T'$ in Fig. 45).

These choking coils are suitable for regulating a single or even two or three lamps, but cannot be used for large currents. Fig. 47 shows this apparatus or *regulating switch* as it is sometimes called (for it acts both as switch and regulator), fixed in conjunction with a glow lamp.

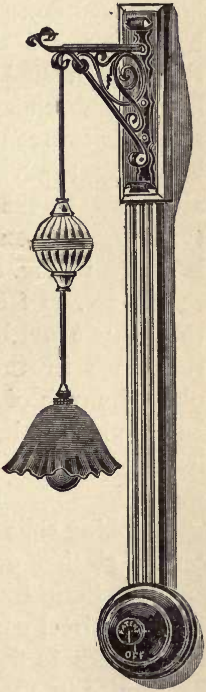

Fig. 47.

25. Use of Choking Coils.—It has been shown that choking or impedance coils are made in many different forms; and their use is to cut down, 'choke,' or 'throttle' the current in a circuit or portion of a

circuit: the principle of their action being illustrated by the experiment mentioned in § 11. In electric-light work for instance, a glow lamp or group of lamps may be 'turned down' or 'dimmed' to any desired extent by operating a choking coil in its or their circuit. In theatres, music-halls, churches, etc., where there are a large number of inaccessible lamps to be simultaneously raised or lowered in brilliancy, the use of choking coils is of great advantage. In ordinary house work, an alteration in the light is generally effected by simply turning lamps on or off, though a choking coil such as is shown in Fig. 47, is useful in some cases—*e.g.* in bedrooms, etc. Of course this turning down or lowering of the lights could be effected by simply inserting ordinary resistance in the circuit, but here, as previously explained, much of the energy taken from the lamps would be expended in heating the resistance, whereas by using impedance coils the current is cut down with very little waste.

Choking coils are also used for regulating purposes in central station work.

26. 'SKIN RESISTANCE' OR CONDUCTOR IMPEDANCE.—

When a direct current begins to traverse a conductor, it commences to flow first at the surface, and then at last penetrates to the interior: on stopping it, it leaves off first at the surface and lastly in the interior. This effect is due to the inductance of the conductor, and may be explained as follows. Imagine the conductor to consist of a number of separate small insulated wires packed closely together side by side (Fig. 48); now, when a current is started along these separate wires, mutual induction will take place between them, and momentary reverse E.M.Fs. will be set up therein; but clearly those wires which are nearer the centre and consequently completely surrounded by neighbouring wires will have stronger reverse E.M.Fs. set up in them than those on or near the outer surface, so that a direct current will find less momentary opposition to it near the surface than in the interior of the conductor, and thus a direct current may be said to flow first at the surface and lastly evenly through the whole section of the conductor; the time occupied in settling down being of course only a fraction or so of a second. When the steadily flowing direct current is suddenly stopped, again imagining our conductor as subdivided (Fig. 48), mutual induction will take place, and momentary 'direct' E.M.Fs. (*i.e.* in the same direction as the current is flowing) will be set up in the separate wires and tend to prolong the current, and these induced E.M.Fs. will be greater in those wires in the centre than in those on the surface, hence the current will leave off first at the surface and lastly at the interior. If we suppose for argument that the conductor is subdivided into separate

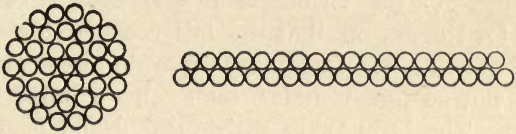

Fig. 48.

conductors or wires we may put down the effect to mutual induction: but if we think of the conductor as a whole, the effect may be attributed to self induction (inductance), which is perhaps after all the real cause. This phenomenon has been given the name of *skin resistance*, a bad and misleading term, as after all it is plainly an effect of induction and has nothing to do with ohmic resistance: for if we take two conductors of equal length, resistance, and material; one being of circular section and the other in the shape of a ribbon (Fig. 48), it will be found that the so-called 'skin resistance' of the former is greater than that of the latter, for the reason that the latter conductor is more spread out—*i.e.* the imaginary separate wires composing it are not so much under each other's inductive influence. The term 'skin resistance' would lead one to think that of two or more conductors of equal cross-section, the phenomenon in question would be more marked in the one with the greater surface, whereas the reverse is the case. The Author suggests that *conductor impedance* would be a better and more expressive name for this effect.

It was stated in § 4 that inductance is not very noticeable in straight conductors, but there is no doubt that it exists therein, and is the greater the greater the mass and the more compact the shape of the conductor: but with direct currents its effects (in uncoiled conductors) may be disregarded.

27. CONDUCTORS FOR ALTERNATING CURRENTS.—As is the case with circuits in general (§ 4), the inductance of

a straight or thick conductor (*i.e.* its so-called ‘skin resistance’) exercises a continual effect on the flow of an alternating current, which effect increases with the frequency and strength of the current. When an alternating current commences to flow in a conductor, it starts first at the outer surface and then penetrates more or less to the interior; but, unless the frequency be very low, and the conductor thin (presuming it to be of circular solid section), it may happen that very little or no current flows through the centre. Let us try to picture the probable cause of this. When the current starts in one direction, the reverse E.M.F. due to inductance is, as was shown in the preceding paragraph, greatest at the centre; supposing the current to stop, the induced E.M.F. is again greatest at the centre, and is at the moment ‘direct’—*i.e.* in the same direction as the current, but the latter at this moment reverses, and this direct E.M.F. acts in opposition to it, and so on. Thus the induced E.M.Fs., which exist principally in the centre, alternate as the current alternates, but are constantly opposite in direction. Though the effect of inductance in straight conductors is practically nothing as compared with that in coiled ones (as in electromagnetic apparatus), still it does exist, and Lord Kelvin has shown that in the case of a current at a frequency of 150 ∼, the current only penetrates the copper conductor to a depth of about three millimetres*—*i.e.* a little over one-tenth of an inch. At the ordinary frequency of 100 ∼, it has been calculated that the

* A millimetre = ·03937 in.—*i.e.* between $\frac{1}{32}$ in. and $\frac{1}{16}$ in.

current in a copper conductor at a depth of 12 millimetres (nearly ·5 in.) from the surface is only about one-seventh of its value at the surface. Thus the largest useful size of cable in alternating current work at ordinary frequencies is about 19/14s—*i.e.* a strand made up of 19 wires each of No. 14 size, the total diameter being about ·4 in.: larger sizes are less efficient than the cross-section of copper would seem to indicate.

Some writers aver that the effect just dealt with is due to capacity as well as inductance, and such is probably the case, though if capacity be taken into account the explanation becomes less simple. However the effect be explained, it seems certain that the conducting power of a conductor for alternating currents depends not so much upon its mass as upon its surface, so that a hollow tube may conduct nearly as well as a solid rod of the same diameter: and with the same area of cross-section, a ribbon-shaped or tubular conductor is preferable to a circular stranded or solid one. As was mentioned at the beginning of this paragraph, the 'skin resistance' or *conductor impedance* (§ 26) increases as the frequency increases; but unless either the frequency of the current or the thickness of the conductor be very great, it may be disregarded in practice for the sizes most commonly in use. Low-tension alternating cables for large currents have however to be designed with this point in view.

28. ELECTRICAL RESONANCE.—The mains of the London Electric Supply Corporation extend from their central station at Deptford to various distributing

centres in the western and southern districts of London. Each 'go' and 'return' main has up to the present consisted of concentric copper tubes insulated from each other with tightly compressed paper, and owing both to their shape and great length they possess considerable capacity.* Soon after the supply was started, the fall of pressure along the mains was found to be much less than anticipated, in other words the pressure at the distributing ends was greater than could be then accounted for. After a time it was seen that this effect was owing to the great length and consequent capacity of the mains, and the rise of pressure due to this cause has been given the name *electrical resonance*, though it is more popularly known as 'rise of pressure effect,' 'capacity effect,' or 'condenser effect.'

In his Royal Institution Lectures (§ 9), Professor Forbes presented a mechanical analogy for this so-called 'electrical resonance.' A long spiral spring was suspended from the ceiling, the free end being held in the hand: the end of the spring was pulled down and allowed to rise again at regular intervals and with small force. After a time, the spring accumulated energy by reason of its resilience, and its movements up and down showed greater amplitude than that which the operator gave it at each downward pull—that is to say, the spring 'jumped' up and down of its own accord beyond the range of the hand at the other end.

To construe this effect into electrical language, we

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* The London Electric Supply Corporation are now (1897) replacing these tubular conductors by ordinary cables.

must first of all assume that the direction of the axis passing down the centre of the spring is the direction of the circuit conductor (or rather part of it); that the elongation and shortening of the spring represent currents first in one direction and then in the other; and that the downward pulls represent the impressed E.M.Fs. in one direction, there being no analogue for E.M.Fs. in the opposite direction, as the spring is not pushed up, but contracts of its own accord.

If both the E.M.F. and frequency be very low indeed, *i.e.* if the end of the spring be pulled down slowly and at long intervals, the 'jumping effect' (capacity current) will be absent: but as the 'frequency' of the downward pulls increases, or the E.M.F., as represented by the sharpness with which the spring is pulled, so also will the jumping effect, until at last the movement of the spring (current) will refuse to be governed by and will be out of step with the successive pulls (E.M.F. impulses) given by the observer. The above explanation is doubtless somewhat crude and weak, but it will serve to give the reader an inkling of the cause of electrical resonance, the effect being, as already stated, to lessen the fall of potential along the conductor or circuit in which it exists.

It is hardly necessary to point out that what is here termed 'electrical resonance' is merely the ordinary effect of capacity on an alternating current in circuits (or portions thereof) which happen to have considerable capacity and very little inductance, the result being a lead in phase of the current.

29. Effective Volts and Amperes.—In § 18 an explanation was given of the meaning of the terms virtual pressure, virtual current, &c. A virtual E.M.F. is about ·707 of the maximum values reached by the tops of the curve if the latter is of the sine shape (Fig. 31), and varies slightly as the form of the curve varies. When we speak of the E.M.F. *impresssed* on the circuit, we mean the virtual E.M.F. In most circuits the impressed or virtual E.M.F. meets with an opposing E.M.F. of reactance, and the *effective E.M.F.* is something less than the virtual E.M.F., it being that pressure which is ultimately available for driving electricity round the circuit, or for doing work.

For illustration, let us imagine a given non-inductive circuit, without appreciable capacity, containing a short-circuited choking coil; and suppose that a constant virtual or impressed E.M.F. is maintained at its ends: while the choking coil is short-circuited, there being no opposing E.M.F. in the circuit, the whole of the impressed E.M.F. will be effective in driving electricity round—*i.e.* the virtual and effective E.M.Fs. will be equal. If the choking coil is thrown in circuit, the reactive E.M.F. due to its inductance will oppose the virtual E.M.F., and the effective E.M.F. and consequent current will be proportionately reduced, and will be still further reduced as the reactance of the coil is increased, the virtual or impressed E.M.F. remaining constant the whole time.

Referring to what was said in § 18, if an electrostatic voltmeter be applied to the ends of a circuit, the reading will give the virtual volts under all circumstances, and if there be no reactance present, this reading will also represent the *effective volts.*

Current necessarily implies the flow of electricity, and a virtual current is that indicated when a reliable ammeter is put in circuit. If the current happens to be in phase with the pressure, this reading will also give what may be called the *effective current.* It has been shown (§§ 19 and 20) that the current is not always in phase or step with the pressure; it frequently lagging or leading in phase—generally the former. The amount of this lag or lead is called the *phase difference* or *angle of lag or lead*, as the case may be, and the greater this is the less is the power of a given virtual current to do useful work. That proportion of the current which can do useful work may be called the *effective current.* When there is no phase difference, the effective current is the same as the virtual current; but as the angle of lag or lead increases, so does the value of the effective as compared with the virtual current diminish.

The difference between virtual and effective current is further referred to in § 31.

It is necessary to point out that the terms *virtual* and *effective* are employed indiscriminately by some writers, while others use only the one term or the other. The necessity for both, and the distinction between them, should be clear from what has been said above and in § 18.

30. CONNECTION BETWEEN INDUCTANCE, REACTANCE, IMPEDANCE, IMPRESSED VOLTS, AND VIRTUAL CURRENT.

—We have seen (§§ 21 and 22) that the reactance in an alternating-current circuit depends directly upon the inductance and the frequency, and inversely upon the capacity. In a circuit with negligible capacity, if L be the inductance, and n the frequency, the reactance will be $2 \pi n L$.*

Reactance or spurious resistance is, like ohmic resistance, independent of the current; but the current must be taken into account when we wish to find the volts necessary to overcome these resistances. Thus if C be any virtual current, $R C$ denotes the volts necessary to force it through an ohmic resistance R: similarly $2 \pi n L C$ will be the volts necessary to force the same current through an inductive or spurious resistance $2 \pi n L$. This quantity $2 \pi n L C$ represents, in fact, the counter E.M.F. of reactance, or the *reactive drop* or *loss of volts*; just as $R C$ represents the *ohmic drop*.

Thus for example, if $C = 60$ amperes, $n = 80 \sim$ per sec., and $L = \cdot 005$ henry,† the E.M.F. of reactance will be $2 \times 3{\cdot}1416 \times 80 \times \cdot 005 \times 60 = 150$ volts.

If, as already stated, the reactive drop in an alternating-current circuit carrying a virtual current C be $2 \pi n L C$ volts, it seems to follow that the total volts necessary to be impressed on the circuit would be equal to

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* This formula requires an application of the differential calculus for its proof: so we will therefore take it for granted. π (Greek *pi*) stands for the ratio of the circumference of any circle to its diameter, *i.e.* 3·1416 (approximately).

† The *henry* is the unit of inductance. See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 67.

the sum of the volts required to send the given current through the ohmic resistance and the volts equal to opposed volts of reactance (*i.e.* $R\,C + 2\,\pi\,n\,L\,C$). This, however, is not the case, owing to the fact that the E.M.F. of reactance is not in phase with the impressed E.M.F.; that is to say, the wave of alternating E.M.F. of reactance does not reach its maximum values at the same time as the wave of impressed E.M.F., but afterwards: in other words, the E.M.F. of reactance lags behind the impressed E.M.F.

The impressed or virtual volts necessary to set up a current of C (virtual) amperes in a circuit of known ohmic resistance R, and reactance $2\,\pi\,n\,L$, is found as follows:—

Draw a horizontal line $A\,B$ (Fig. 49) proportional in length to the volts ($R\,C$) required to send the current through the ohmic resistance R of the circuit: and from A draw $A\,C$ perpendicular to $A\,B$, and proportional in length to the reactive drop, *i.e.* to $2\,\pi\,n\,L\,C$. Then join $B\,C$. The length of $B\,C$ will represent the required value of impressed E.M.F.

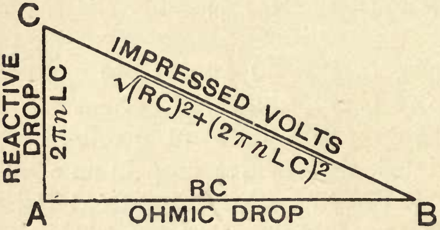

Fig. 49.

Now $C\,A\,B$ is a right-angled triangle, of which $C\,B$ is the hypotenuse—*i.e.* the side opposite the right angle. In such, the square of the hypotenuse is equal to the sum of the squares of the other two sides (by Euclid, I. 47.).

Thus :—

$$C\,B^2 = A\,C^2 + A\,B^2$$

and

$$C\,B = \sqrt{A\,C^2 + A\,B^2}$$

That is :—

$$\text{Impressed or virtual volts } (E) = \sqrt{(R\,C)^2 + (2\,\pi\,n\,L\,C)^2}$$

$$= \sqrt{C^2 \times (R + 2\,\pi\,n\,L)^2}$$

$$= C\,\sqrt{R^2 + (2\,\pi\,n\,L)^2}$$

Now as in Ohm's simple law :—

$$E = C\,R$$

and :—

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

We may write :—

$$(\text{Virtual})\ C = \frac{(\text{Impressed or virtual})\ E}{\sqrt{R^2 + (2\,\pi\,n\,L)^2}}$$

and this may be termed the Ohm's law for alternating currents: $\sqrt{R^2 + (2\,\pi\,n\,L)^2}$ being in fact the impedance or 'virtual resistance' in the circuit.

In words the above may be written thus :—

$$\text{Virtual current} = \frac{\text{Impressed E.M.F.}}{\text{Impedance.}}$$

If, in a steady-current circuit we multiply together the current and the resistance, the product will give the E.M.F. in the circuit: or

$$C \times R = E$$

The same result follows in an alternating-current circuit, for multiplying the current (virtual) by the virtual resistance (impedance) will give us the impressed E.M.F. *i.e.*:—

$$C \times \sqrt{R^2 + (2\pi n L)^2} = E \text{ (impressed)}$$

This being merely the foregoing equation transposed.

It will be seen (Fig. 49) that in each of the three quantities—impressed volts, reactive drop, and ohmic drop, the quantity C (virtual current) occurs. Obviously C, being a common factor, may be eliminated in each case, and the quantities will then respectively represent impedance, reactance, and resistance, as shown in Fig. 50.

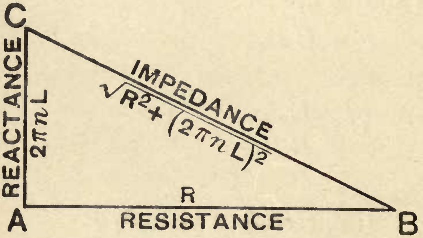

Fig. 50.

Thus:—

$$\text{Impedance}^2 = \text{resistance}^2 + \text{reactance}^2$$

i.e.:—

$$\text{Impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2}.$$

In Figs 49 and 50 it will be noticed that the length of $A\,C$, and therefore also the angle $A\,B\,C$, depends upon the reactive drop, or, with a given current, upon the reactance. $A\,B\,C$ is, in fact, the angle of phase.

31. Power in Alternating-Current Circuits.—The power in a direct-current circuit is obtained by simply multiplying together the pressure and the current; or—presuming the circuit has no back E.M.F. in it—the square of the current and the resistance, the product in either case representing *watts.*[*]

It might be thought that by taking the product of the virtual volts and virtual amperes in a circuit we should obtain the actual power developed. Such would be true in a sense, but the product would only represent *useful power* when the current was in phase with the E.M.F., the product in question being in all cases the *apparent power* or *apparent watts.* The phase difference or angle of lag or lead (§ 29) has to be taken into account, and the greater this is the less is the power actually being developed in a circuit with a given virtual pressure and current. In fact, if the phase difference is very great—*i.e.* if there is a large amount of either inductance or capacity in a circuit of comparatively low resistance—we may have what is known as a nearly *wattless current*, the *true power* or *effective watts* being far less than the *apparent power* or *watts.*

The idea of a ‘wattless current’ is difficult to grasp. If there be any current at all, it is not easy to understand why it cannot do work. But when it is re-

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[*] The *watt* is a unit of power or rate of doing work. See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 33.

membered that a flow of electricity—as of water—must have pressure behind it to enable it to do work, and when we are dealing with alternating pressure and flow, and can conceive that they may be more or less out of step with each other, comprehension becomes fairly simple.

The following analogy affords a rough but useful explanation. Let *P P* (Fig. 51) represent a pipe filled with water (or a conductor forming a closed circuit), and W, W_1, W_2, and W_3 waterwheels to which an alternating movement may be given by means of the handles *h*, *h*, *h*, *h*; these may consequently be looked upon as alternators. Let *W W* be a fifth waterwheel, to which a reciprocating motion is imparted by the to-and-fro movement of the water in the pipe. The motion of water in the lower part of the pipe-circuit may be considered as analogous to the effective current, and the consequent movement given to *W W* the effective power.

We will first consider a case where there is no phase difference—that is, when the watermotive-force of *W* acts directly in line with the circuit, as indicated by the dotted line: here the virtual E.M.F. of *W* may be said to also represent the effective E.M.F., and the virtual current or motion given to the water by *W* to equal the effective current operating *W W*. Then the apparent or virtual watts (*i.e.* virtual E.M.F. × virtual current) will also represent the true or effective watts (power given to *W W*).

To illustrate the effect of a small phase difference, we will next consider the waterwheel as placed slightly skew with the circuit, as at W_1; the angle of lag (or lead) being denoted by the angle *a* between the two lines. Supposing the frequency and virtual E.M.F. of W_1 to be the same as in the first case (W), the virtual current or actual movement of electricity (water) immediately about W_1 will also be the same; but, as part of the pressure will be uselessly employed in driving the water against the sides of the pipe, the repelling effect of which may be looked upon as analogous to the counter E.M.F. of reactance, the effective pressure and also the effective current about $W\,W$ (the product of which is the effective or true power) will be less. The backwash from the sides of the pipe is thus analogous to wattless current.

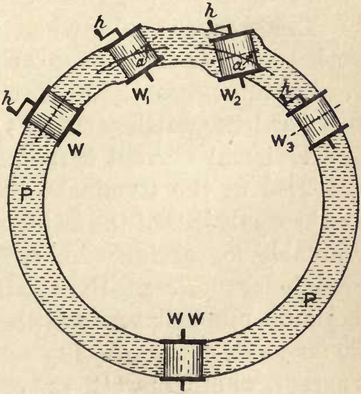

FIG. 51.

If there be a still greater phase-difference, as at W_2, though the virtual E.M.F., virtual current, and therefore also the virtual power, be the same is in the first case (W), the effective power will be still further lessened.

If the phase difference be 90°, as at W_3, where the waterwheel is placed at right angles with its most effective position; we may suppose that the current will be perfectly wattless—*i.e.* that there will be no useful power developed, and consequently no movement of *W W*.

The above explanation is rather weak, but is perhaps better than none at all; for at all costs the reader must get some idea—however vague—that a more or less 'wattless current' can exist.

A virtual current is the actual flow of electricity as observed at the terminals of a circuit, and depending on the conditions of the latter a certain proportion will be available for useful work (effective current), while the remainder represents the 'wattless current.' It must be borne in mind that a 'wattless current' is only wattless so far as its power of doing *useful* work is concerned. A current, whether 'wattless' or not, will develop a proportionate amount of heat in—or a proportionate magnetic field around—a given conductor.

The 'wattless current' is objectionable in central-station work for two reasons: *firstly*, because it loads up the armatures of the alternators, causing heating and reducing the useful load that may be put upon each; because the power developed with a given E.M.F. is limited by the maximum current the conductors in the armature coils can carry. *Secondly*, owing to the watts lost in the cables and conductors through which the 'wattless current' flows. Although the current is wattless so far as any use that may be made of it is concerned, there still remains the drop of power due to ohmic resistance, the fall of pressure in a cable carrying a given current depending solely on the resistance, taking into account, of course, the reduction in useful area due to any so-called 'skin resistance' (§ 26).

Thus:—

$$\text{Pressure drop} = \text{resistance} \times \text{current}$$

$$\text{and watts lost in conductors} = \text{pressure drop} \times \text{current},$$

the 'current' being that measured on an ammeter connected to the cable in question, and therefore the virtual current.

In addition to the foregoing matters, a lag (or lead) in phase of the current sets up a troublesome reaction between the field-magnets and the armature coils, tending to weaken the former, and this necessitates an increase in the exciting current if the impressed virtual E.M.F. is to be maintained.

32. POWER IN ALTERNATING-CURRENT CIRCUITS (CONT.)

—The formula for the power in an alternating-current circuit is as follows :

$$\text{(True or effective) } P_W = \mathrm{E}^v\,\mathrm{C}^v \cos \lambda$$

where P_W stands for power (in watts), E^v for virtual electromotive force, C^v for virtual current, and λ for the angle of lag or lead.*

On reference to any table of cosines it will be seen that for an angle of no degrees the cosine value is unity, or 1. Thus, in the formula above, if the current and pressure are in phase—*i.e.* if there is no phase difference (angle of lag or lead)—the true or effective watts may be obtained by simply multiplying together the virtual volts and virtual amperes, as mentioned in the preceding paragraph.

Thus :—

$$\begin{aligned}\text{True or effective watts} &= E^v \times C^v \times \cos 0^\circ\\ &= E^v \times C^v \times 1\\ &= E^v \times C^v\end{aligned}$$

---

* λ = Greek l (*lambda*), used for lag or lead values. Cos λ signifies the cosine of any angle λ. The cosine of angle a (Fig. 33), for instance, is the ratio of the adjacent side BE to the hypotenuse BD, or $\frac{BE}{BD}$.

As the phase-difference increases, the cosine values decrease below unity, thus cos 10° = ·985, cos 30° = ·866, cos 80° = ·173, cos 90° = ·000; and the true watts become proportionately less than the apparent watts. Thus, supposing the phase difference $\lambda = 60°$, the true watts will only be half the apparent watts, for cos 60° = ·5. It will thus be seen how important it is to keep the phase difference as low as possible.

In practice, λ cannot be directly calculated with any degree of accuracy, for it varies with every variation in the conditions of the circuit, and also with the frequency. It can, of course, be calculated for any given case, but it is not a fixed or constant quantity. The true watts may be directly ascertained by means of a non-inductive wattmeter.*

The apparent or virtual watts put into a circuit feeding arc lamps or motors through transformers, as calculated from the indications of a voltmeter and ammeter at the station end, may be far in excess of the actual power conveyed to the lamps, motors, or other inductive apparatus—*i.e.* may give the idea that a far larger number of consuming devices are in circuit than is actually the case, owing to the excessive reactance in the transformer circuit.

The following record of actual observations furnishes

The cosine value of any angle is simply dependent on the angle itself, and may be obtained from tables. See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 104.

* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 147.

an instructive example. The virtual current passing in and out from an alternator was 44 amperes, and the pressure 2,050 volts. The exciting current for a corresponding non-inductive load would have been between 50 and 55 amperes, at about 80 volts; but this had to be increased to from 75 to 80 amperes in order to maintain the 2,050 volts pressure at the alternator terminals. By tests made with a wattmeter, which measures true power, it was found that the latter was only 56,000 watts.

Thus:—

$$\text{Apparent watts} = 2{,}050 \times 44$$
$$= 90{,}200$$

and $$\text{True watts} = 56{,}000$$

Consequently the ratio between the true and apparent watts, which is termed the *power factor*, was in this case $\frac{56{,}000}{90{,}200} = \cdot 62$.

To keep this power factor as near unity as possible is thus one of the chief problems in alternating-current distribution.

When transformers are feeding non-inductive circuits, such as glow lamps, the reactance due to the former is less than in the cases cited above, and is diminished as the non-inductive load is increased.

It is here that the question of the introduction of capacity (in the shape of condensers) to reduce the lag crops up; but, though most engineers are familiar with the theory of their application, it is as yet a moot point as to whether the cost and upkeep of the condensers, as well as the power lost in them, would not exceed in value the saving of power effected by their use (§ 6). The loss of power in a condenser is principally due to a phenomenon known as *dielectric hysteresis*, which is somewhat analogous to magnetic hysteresis. The rapidly alternating charges in a condenser connected up in an alternating-current circuit may be said to cause alternating polarisation of the dielectric, and consequent heating and loss of energy.

On the other hand, if the phase difference is due to excessive capacity in the circuit, the introduction of inductance would neutralise it.

33. Conclusion.—The kind of alternating current dealt with in this little book is that known as the *single-phase* or *monophase current*. There are other kinds of alternating current called *polyphase currents*, which may be roughly compared with two (*diphase*), three (*triphase*), or more simple alternating currents set up in distinct circuits, and lagging one behind the other. When such are properly applied to a specially wound gramme ring, or to the coils of a multipolar field magnet, they produce what is known as a *rotatory* or *rotating magnetic field*; and within such a field, a specially wound armature without *commutator* or *collector*, *i.e.* without any external electrical connection, will revolve.* Motors so constructed are called *polyphase asynchronous motors*, the term *asynchronous* signifying that the movement of the motor armature is not in unison with the frequency of the working currents; and polyphase currents thus

---

* See the Author's *Electric Lighting and Power Distribution*, Third Edition, vol. i. § 100.

possess great advantages over simple alternating currents for motive-power transmission as well as other work: for though a commutatorless motor can be made to work with a monophase or ordinary alternating current (*monophase asynchronous motor*), the field produced is oscillatory not rotatory, and the apparatus is less efficient. As in such motors it is difficult to say which part should be called the armature and which the field magnet, ambiguity is avoided by referring to the fixed portion as the *stator*, and to the moving portion as the *rotor*.

The conception of polyphase currents is a more difficult matter than is the case with monophase currents, and their study requires more mathematical knowledge.

The whole subject of alternating currents is very great, and leads up to vast possibilities of electrical development. This introductory book will have fulfilled its object if it helps the reader over the initial difficulties, and leads him to take up further and more serious study of the matter.

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