A SHORT COURSE IN THE

TESTING OF ELECTRICAL MACHINERY

FOR NON-ELECTRICAL STUDENTS

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111 ILLUSTRATIONS

FOURTH EDITION, REVISED AND ENLARGED

NEW YORK
D. VAN NOSTRAND COMPANY
EIGHT WARREN STREET
1921

PREFACE TO FOURTH EDITION

SINCE bringing out the last edition of this text, the engineering courses at Columbia have been put on a graduate basis; the amount of electrical work in the courses for non-electrical students has been materially increased, making it possible to carry out the laboratory work along broader lines than was formerly done. We have added certain experiments on batteries, illumination, measurement of electrical energy, etc., with the idea that the non-electrical engineer frequently has to pass judgment on these phases of electrical installations and should therefore have a passing knowledge of such features of electrical engineering.

We are glad to acknowledge indebtedness to our colleagues Prof. M. Arendt and Mr. W. A. Curry, who have given material assistance in the preparation of this edition.

J. H. M.
F. W. H.

August 1, 1921.

PREFACE TO FIRST EDITION

In presenting these brief notes the authors feel that an explanation of their object is necessary. At Columbia University practically all of the engineering students are required to take courses in the electrical laboratories, testing both direct-current and alternating-current machinery. Students in Mining, Mechanical, Metallurgical, Chemical, Civil Engineering, etc., do not have those courses in the theory of electrical machinery, which are really necessary for a proper comprehension of the machines with which they work in the laboratory; it is unreasonable to expect them to consult various text-books to prepare themselves on the theory involved in the tests, and it is with the intention of filling the needs of these men that the notes have been compiled.

Before giving specific directions regarding the test to be performed, a brief analysis of the characteristics of the machine is attempted; in so far as is possible in such a limited space the reasons for the behavior of the machine are given. It is, of course, realized that a complete analysis of the different types of machines is impossible and it is questionable whether a complete analysis would serve the purpose. It has been the intention of the writers to present the subject-matter in such a manner that the student not well versed in electrical theory can get the most out of it in the short time allotted to the electrical courses.

In some of the tests, methods are described which may not be strictly according to the standard practice; if a gain in simplicity and ease of performance is to be obtained by a sacrifice in accuracy of the test of a few tenths of a per cent, it is thought justifiable to use the simpler method of testing.

While the notes are being put into printed form specifically for our use, they may possibly be found of use in other schools where the conditions are similar to those at Columbia.

The authors wish to express their indebtedness to Professor Geo. F. Sever, who first developed the electrical laboratory work for the non-electrical students at Columbia, and whose original schedule of experiments served as a guide in arranging this work; also to Mr. F. L. Mason, who has rendered valuable assistance in the preparation of the book.

J. H. M.
F. W. H.

Columbia University,
September, 1911.

PREFACE TO THIRD EDITION

In bringing out the third edition of this manual we have thought it well to expand some of the experiments and to add one on the location of faults in direct-current generators and motors. We have also added many questions which, it is expected, the student will answer in writing his report. The questions have been so selected as to show the main ideas which should have been gained from the work in the laboratory.

J. H. M.
F. W. H.

February 1, 1915.

LIST OF D.C. EXPERIMENTS

1. "Fall of Potential" along a Conductor Carrying Current.
2. Measurement of Armature Circuit and Shunt Field Resistances.
3. The Shunt Generator; Preliminary Work with a Generator. Magnetization Curve; External Characteristic.
4. The Compound Generator; Armature Characteristic of a Shunt Generator; External Characteristic of a Compound Generator; Effect of Operating a Compound Generator at Speeds Higher or Lower than Rated Value.
5. The Shunt Motor; Speed Characteristics; Commercial Efficiency by Brake Test.
6. The Motor Starting Rheostat.
7. Efficiency of a Shunt Motor by the Stray Power Method.
8. The Series Motor.
9. Current-Torque Curves of Different Types of Motors.
10. Parallel Operation of Shunt Generators.
11. Parallel Operation of Compound Generators.
12. The Commutating Pole Motor and Generator.
13. Location of Faults in a Direct Current Motor or Generator.
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16. Illumination Laws and Measurements.

TESTING OF ELECTRICAL MACHINERY

DIRECT CURRENT TESTS

EXPERIMENT I

"Fall of Potential" along a Conductor Carrying Current. (*a*) If an electromotive force is impressed upon a circuit, as for instance a wire, a current of electricity will flow along it. The relation between the current, resistance and difference of potential between any two points on the conductor is given by Ohm's law, which expresses the equality of the impressed force and the reacting force. It is found that the reacting force varies directly with the current and this fact may be expressed by the equation,

$$E=IR$$

from which we obtain,

$$I=E/R, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where I=current flowing in amperes;

E=difference of potential in volts, between the two points considered;

R=resistance of the conductor in ohms, between the two points considered.

It is a fact that all conductors offer more or less resistance to the flow of an electric current and experiment shows that for any particular conductor, the resistance varies directly as its length and inversely as its area of cross-section. This may be expressed in the form of an equation as follows:

$$R=K\frac{l}{a}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where R = resistance of conductor in ohms;
l = length of conductor in feet;
a = area in circular mils;
K = resistance per mil foot of the material used; i.e., the resistance of a conductor one foot long and having a cross-sectional area of one circular mil.

If the value of R as given in Eq. (2) is substituted in Eq. (1) we have

$$I=\frac{E}{K\frac{l}{a}}=\frac{Ea}{Kl}, \qquad (3)$$

and

$$E=IK\frac{l}{a}. \qquad (4)$$

This states that when the other factors remain constant, the "drop" in potential varies directly with the current and the length of the conductor and inversely with the area of cross-section. The drop also varies with the material.

It is also evident if Eq. (1) is written in the form

$$R=\frac{E}{I}, \qquad (5)$$

that the resistance of a conductor is readily determined if the current flowing through it and the drop in potential across it are known.

The apparatus to be used in verifying the laws stated above should consist of a board, upon which are mounted and connected in series, equal lengths of wire (preferably 48 inches) of copper, aluminum, iron and German silver, all of equal cross-section. Connect the wire board as shown in Fig. 1. Determine the safe current-carrying capacity of the German silver wire and be sure that the variable resistance, lamp board, and ammeter can safely carry this current. The voltmeter should have a capacity on one range of about 15 volts with another range lower than this.

With only one lamp in the lamp board and all the resistance in the variable rheostat cut out, close the switch and note if the ammeter deflects in the proper way. If not, open the switch and reverse the ammeter connections. Then cut in enough additional lamps in the board, so that the current will be slightly greater than $\frac{1}{5}$ of the safe current value for the German silver wire. Insert enough resistance in the variable rheostat so that exactly $\frac{1}{5}$ of the maximum permissible current is flowing. Using the highest range upon the voltmeter, place one lead to one end of the copper wire and tap the other voltmeter lead on the 6-inch mark upon the wire. If the throw of the needle is in the proper direction, the free lead may be fastened to the wire; if not, the

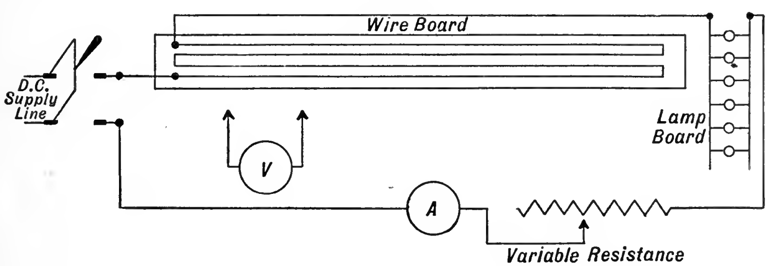


FIG. 1

leads are to be reversed *at the wire. Never reverse or disconnect voltmeter leads at the meter, while the other ends of the leads are attached to live terminals; a short circuit is likely to result. Always reverse or disconnect the leads at the point where they are attached to the live terminals.* Great precaution must also be taken with low-reading voltmeters, as they are easily burnt out. To determine an unknown low voltage, a range somewhat above the line voltage should first be tried and a reading taken; lower ranges can then be tried until the proper one has been determined.

Having determined the proper range upon the voltmeter and adjusted the variable resistance so that the current flowing is exactly the desired value, read the voltmeter. Move the voltmeter leads to include 12 inches of wire and repeat. Continue this operation until the drop over the entire length of copper wire has been determined and then do the same with the remaining three wires. Raise the current to $\frac{3}{5}$ and finally to the full value of the current-carrying capacity of the system and measure the fall in potential along each wire. Record readings in neatly tabulated form and calculate the resistance of each wire for each value of current. Calculate how much power was used in each wire for each value of current. Determine the average value of the resistance per mil foot for each material and with the value obtained calculate the resistance of 000 feet of No. 10 B. & S. wire, obtaining the diameter of No. 10 wire from a wire table.

(*b*) Determine the hot and cold resistance, total watts and economy for a 50- and a 100-watt Gem or metallized filament lamp, and for a 25-watt Mazda or tungsten lamp.

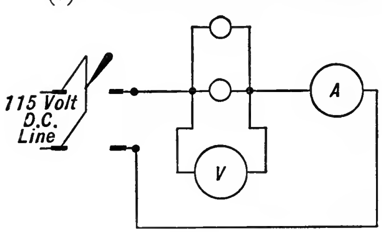


FIG. 2

The filament used in Gem lamps is of carbon which has undergone various heat treatments, causing it to assume some of the properties of metals, the most important being a positive resistance temperature coefficient. Carbon has a negative coefficient, or, its resistance decreases with rise in temperature. In metallized filament lamps the hot resistance will be found somewhat greater than the cold resistance and the same applies, but to a more marked degree, in the case of tungsten.

To determine the hot resistance of the lamps, connect them as in Fig. 2, to a source of E.M.F. of about 115 volts, in series with an ammeter of about 2 amperes range. No series resistance is required, as the lamps themselves are of high enough resistance to withstand the full line voltage. Using a voltmeter with a range of 150 volts, determine the voltage across the lamp burning. Remove the voltmeter and read the ammeter. Do not read the ammeter with the voltmeter connected across the lamp, as the current indicated by the ammeter will be the sum of the lamp and voltmeter currents and not the lamp current alone. Take a set of readings for each lamp and record them in a log as shown in Table I.

TABLE I

Type of Lamp.	Candle Power.	Volts.	Amperes.	Watts.	Economy or Watts per Candle Power.	Resistance.	
						Hot by Drop in Potential	Cold by Wheatstone Bridge.

Determine the cold resistance of the lamps by means of a Wheatstone bridge.

In calculating economy or watts per candle power, assume that the lamp gives its rated candle power at the voltage used. Values of candle power of the lamps used will be furnished by instructors. The economy serves as a measure of the efficiency of a lamp, in that a lamp is usually rated as using so many watts per candle power; a lamp using 1.2 watts per candle power is evidently more efficient as a light producer than one using 3 watts per candle power.

Curves. (*a*) Plot the results obtained for each wire on one sheet of cross-section paper, plotting voltmeter readings as ordinates and lengths as abscissæ.

Conclusions. How does drop in potential along a wire vary? Why are the curves straight lines? What might cause them to be slightly concave upward? Which metal is the better conductor and which best adapted for use as resistance wire in rheostats and why? Why did the wires expand during the experiment? How do the values for resistance per mil foot and for the resistance for 1000 feet of No. 10 B. & S. wire compare with values obtained from wire tables? How do you explain the difference in the hot and cold resistances of the lamps used? How do the efficiencies of the different types of lamps compare? Explain briefly the principle and operation of the Wheatstone bridge.

EXPERIMENT II

Measurement of Armature Circuit and Shunt Field Resistances. (*a*) The resistance of an armature circuit is made up of the resistance of the conductors upon the armature, the brushes, the brush contacts, and the cables leading from the brushes to the machine terminals. In a well-designed motor or generator, the armature circuit resistance is made as low as is consistent with the size of the machine, in order to cut down the amount of energy dissipated as heat. The rate of production of heat in the armature is given by the formula, watts $= I^2R$. A motor or a generator is designed to carry a certain maximum value of armature current and this then fixes the value for I, so that to keep the amount of heat generated in the armature low, the resistance must be made as small as is commercially practical.

The armature conductors being always of copper, their resistance will be independent of the current except for heating. The same applies to the machine leads, the resistance of which is very small. The brush contact resistance is the resistance of the surface contact between the carbon brushes and the commutator. This resistance is quite appreciable and decreases with increase of current strength; it decreases as the mechanical pressure between the brush and the commutator increases. The resistance of the brushes themselves is insignificant.

Determine the full load armature current of the machine, whose armature circuit resistance is to be measured, from its name-plate data; connect the armature in series with an ammeter, lamp board and a variable resistance, all of suitable current carrying capacity, as shown in Fig. 3. Close the line switch and adjust the current to $\frac{1}{8}$ of the full-load value.

Using first the highest range of the voltmeter, attach the leads to the two terminals of the machine (corresponding to position 1 in Fig. 3) and read the meter. If the reading is within the next lower range, detach the leads *from the machine terminals* and shift to the lower range. When a suitable range has been found upon the voltmeter, so that the deflection is a large one, read simultaneously ammeter and voltmeter and record the

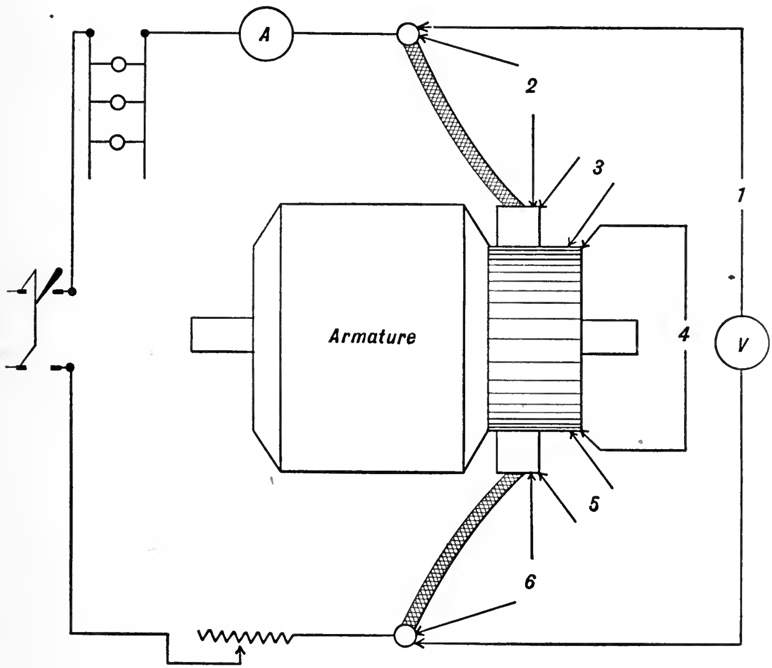


Fig. 3

readings in a log as in Table II. From the readings taken with the voltmeter leads attached as in position 1, the resistance of the entire armature circuit can be calculated. Leave one of the voltmeter leads upon one of the machine terminals and starting from the one employed, trace the cable which leads to the machine. Find the brush to which this cable is attached and connect the other voltmeter lead to some convenient place upon it (position 2). After having adjusted the current to its proper value read the voltmeter. From this reading the resistance of one of the machine leads can be determined. Then shift the voltmeter leads successively to positions 3, 4, 5, and 6, reading the meters as before. These readings should be taken as rapidly as possible, so that the armature shall not heat up too much. Repeat this operation, using 2/3 and full-load armature current, respectively. The sum of readings 2, 3, 4, 5, and 6 entered in column 7 of the log should equal the values in column 1, the measured drop of the entire circuit. Calculate the values of resistance and tabulate in a form similar to Table II.

TABLE II

Amperes.	Volts.							Difference between 1 and 7.
	1	2	3	4	5	6	7	
	Across entire Armature. Circuit.	Across ends of one Machine Lead.	Across one Brush Contact	Across Armature.	Across second Brush Contact.	Across ends of second Machine Lead.	Sum of Drops 2, 3, 4, 5 and 6.	

Caution. Great caution must be exercised in obtaining the voltage across the various parts. In order to obtain large readings upon the voltmeter it will be necessary to shift from one low reading range to another, *so that it must constantly be borne in mind that a voltmeter needle is easily bent or the instrument entirely burnt out, if a high potential is applied to a low range.*

To determine brush drop, connect one voltmeter lead to the place upon the brush or brush stud used in determining the drop across the machine leads and hold the other lead on the commutator bar directly under the brush; do not touch the terminals of the voltmeter leads against the brushes. When determining the drop across the armature winding hold the voltmeter leads to commutator segments which are under brushes of opposite polarity, again being careful not to touch the terminal on the commutator, against the brush while reading the voltmeter.

Do not permit the armature to rotate, as a counter electromotive force is generated which decreases the current and causes an apparent increase in the resistance of the armature.

Caution. When it becomes necessary to open the armature circuit be sure that the voltmeter leads have been entirely removed before the switch is opened. A large amount of magnetic energy is stored up in the armature while current is flowing and when the circuit is opened this energy must be dissipated. If a voltmeter is connected across the armature terminals a high protential will be applied to it, due to the self-induction of the armature. This is quite likely to bend the needle of the voltmeter and may even burn it out. Therefore never suddenly open a circuit containing much self-induction while a voltmeter is connected across any part of it.

(*b*) The function of a shunt field is to provide a certain number of ampere-turns for the magnetic circuit and this can be accomplished either by using a small number of turns carrying a comparatively large current, or a large number of turns with a small current flowing through them. Generally a large number of turns is preferred, as this gives a high field resistance and a comparatively small consumption of energy in the field coils. A shunt field is always so built that it may be safely placed across a line of the same voltage for which the machine was designed.

It must be remembered that a shunt field possesses considerable self-induction, so that when a difference of potential is applied to it, the current does not immediately assume its final value, but builds up slowly. This is due to the counter-electromotive force of self-induction which is set up while the current is increasing. This "building up" of the current can be seen very nicely by watching the ammeter as the line switch is closed.

Connect the shunt field whose resistance is to be measured, in series with an ammeter of proper capacity, to a source of E.M.F. equal to that for which it was designed; the connections to be as shown in Fig. 4. Close the line switch and using a voltmeter of the proper range, determine the difference of potential between the ends of the field. Remove the voltmeter and determine the current value. Then open the circuit slowly, drawing out the arc; *be sure the voltmeter is disconnected.*

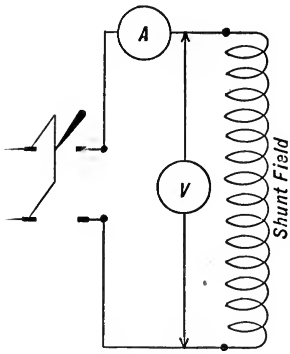


FIG. 4

Also determine the resistance of the field, using a Wheatstone bridge.

Conclusions. Explain why armature resistances are made low and shunt field resistances high. How do the resistances of the various parts of the armature circuit vary with current? Why is it unsatisfactory to determine the armature circuit resistance with the ordinary Wheatstone bridge. Why should an inductive circuit never be opened if a voltmeter is connected across any portion of it?

EXPERIMENT III

The Shunt Generator. (*a*) Preliminary Work with a Generator; (*b*) Magnetization Curve of a Shunt Generator; (*c*) External Characteristic of the Shunt Generator.

(*a*) The student should first familiarize himself with the component parts of the machine assigned and look over their construction and relation to one another, in order to get a general idea of the generator. The following table of data and dimensions is then to be completely filled out.

General

Type of generator.......shunt or compound	Current....................
	K. W. Output................
Rated voltage................	Speed ....

Armature

Type............ring or drum	Active length ....
Number of sections..........	Circumference in feet........
Conductors per section.......	Peripheral speed in ft. per min.
Total number of conductors. ..	

Commutator

Active length.	Average voltage between bars .
Total length..................	Width of bars.. ....
Circumference in feet........	Width of insulation ....
Peripheral speed in ft. per min..	Kind of brushes.............
Total number of bars........	Brush area per set..........
Number of bars between brushes of opposite polarity........	Current density in brushes, in amperes per sq. in ....

Fields

Number of main poles........	Pole width ....
Number of commutating poles..	Pole length ....
Pole arc in degrees	Width of pole shoe ....

A shunt generator can readily be distinguished from a compound generator by examination of the field coils. A shunt field is wound of relatively small wire and there will be only two terminals on each field spool. A compound generator has a series winding of large wire or copper strip in addition to its shunt winding, so that each field spool will have two large additional taps for the series field current. The remainder of the general data can be determined from the name plate.

The type of armature can generally be determined by examining the back connections. A ring winding is one in which the wire is wound around an annular ring, so that there are conductors both on the outside and the inside of the ring. In a drum winding all of the conductors are upon the other periphery. An armature section can be defined as that part of the winding, which starts at one commutator bar and ends at another. The number of sections upon the armature can sometimes be determined from the back connections, the number of slots and the connections to the commutator. The number of sections will never be less than the number of commutator bars and will generally be some multiple or sub-multiple of the number of slots. If the manufacturer's data is at hand the number of sections can be taken therefrom and then verified. The number of conductors per section will probably have to be taken from the manufacturer's winding data. The active length of the armature will be equal to the width of the pole shoe (i.e., the length of the pole shoe parallel to the shaft) plus twice the length of the air gap.

The active length of the commutator can be regarded as the distance occupied by the brushes plus the spaces between them, measured parallel to the shaft. A commutator is always made longer than this to permit clearance and end play. In determining the current density of the brushes, remember that brush sets always operate in pairs. In a bi-polar generator each brush set carries the total current of the machine. The pole width is the distance parallel to the shaft. The pole length is measured out radially.

Before a generator is to be operated, certain conditions should be noted, particularly in a new machine or one which has not been run for some time. The things to be noted are as follows:

(1) Amount of oil in the bearings or cups. With self-oiling bearings it is advisible to note whether the oil rings turn easily and dip into oil. This can be readily seen by turning the rings over by hand.

(2) Condition of the brushes and commutator. The commutator should be clean and fairly bright. If it is not, it can be polished while revolving with fine sandpaper on a flat wooden block or a polishing stone. Do not use emery. The brushes should make good contact over their whole bearing surface.

(3) Brush Pressure. This should be from one and a half to two pounds per square inch of contact surface.

(4) The armature should turn easily, either by hand in the case of a small machine or by means of a lever in a large one. If the armature turns hard, either the bearings are in bad condition or the alignment of the shaft in the bearings is not good.

(*b*) A generator is a device which transforms mechanical energy into electrical energy. Its operation is based upon the fact that when a conductor is moved in a magnetic field so as to cut lines of force, an E.M.F. is induced in it. In a generator a number of copper wires or bars are mounted upon a cylindrical iron core, and this armature, when rotated in a magnetic field, generates a voltage. The armature inductors are properly interconnected, so as to add their individual E.M.Fs. and are also connected to the commutator which rectifies the alternating voltages induced in them.

The fundamental equation of the generator can be written as follows:

$$E_g = \frac{\phi \times N \times n \times 2p}{10^8 \times 60 \times c}, \quad \dots \dots \quad (6)$$

where E_g is the voltage generated by the armature;

ϕ = the flux per pole in lines of force;

N = R.P.M.

n = total number of inductors upon the armature;

p = number of pairs of poles;

c = number of circuits in parallel upon the armature.

The derivation follows if we remember that when an inductor cuts 10^8 lines of force per second, an E.M.F. of one volt is induced between its ends.

The magnetic field of a generator is produced by the ampere-turns of the field windings according to the formula,

$$\text{Magnetomotive force} = .4\pi \times \text{ampere-turns},$$

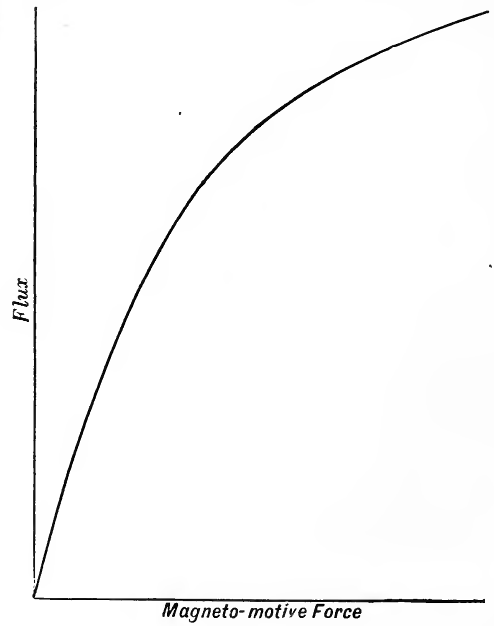


FIG. 5

and this magnetomotive force acting over the reluctance of the magnetic circuit produces a flux according to the relation

$$\text{flux} = \frac{\text{M.M.F.}}{\text{reluctance}}.$$

The curve showing the relation between flux and M.M.F. is shown in Fig. 5; it is seen that at low values of M.M.F. a small increase in M.M.F. produces quite a large increase in flux. As the field becomes stronger the flux curve begins to bend over more and more, so that for large additions of M.M.F. there is only a small increase in the flux; when in this state the iron is said to be saturated.

In the case of a generator, in determining the magnetization or saturation curve, we make use of the fact that magnetomotive force is directly proportional to the field amperes, since the number of field turns is constant. Furthermore, in Eq. (6), if the speed is a constant quantity, the generated voltage will be a measure of the flux, all the other quantities being constants. The magnetization curve of the generator may then be plotted between generated volts and field current.

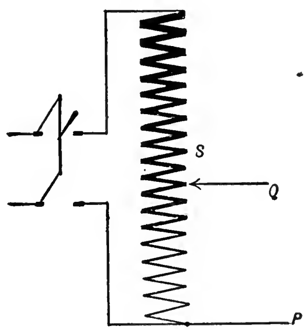


Fig. 6

It is preferable that the field of the generator be separately excited, and a very convenient method for doing this is the so-called potentiometer method. This consists of a rheostat, with a sliding contact, placed across the D.C. line as shown in Fig. 6. By adjusting the slider *S*, any desired voltage can be had across the leads *PQ*, from zero up to the value of the supply voltage. If the leads *PQ* are applied to a field it is possible to vary the field current gradually from *zero to its maximum value.*

Rheostats are usually made of tapering sizes of wire (shown diagrammatically in Fig. 6), in which case it is necessary that the field be put in parallel with the fine wire end. The coarse wire will then carry the field current plus the current flowing through that portion of the resistance which is in parallel with the field.

The advantage of the potentiometer method may be seen from the following numerical example. The shunt field of a generator is to be separately excited from a 250-volt line. The resistance of the field is 100 ohms and an external resistance of 150 ohms is available. Using the resistance in series with the field, it is possible to vary the current from 2.5 amperes to 1 ampere as a minimum; if values below 1 ampere are desired, a larger external resistance is necessary. Used, however, as a potentiometer, the current may be varied from 2.5 to zero amperes.

Excite the field of the machine to be used, from a source of E.M.F. greater than the rated voltage of the machine, using potentiometer connection as is shown in Fig. 7. (Note resistance of rheostat used on log.) For a 115-volt generator, excite the field from a 230-volt line, etc. With the line switch open, rotate the machine at its rated speed by means of a prime mover whose speed can be held constant; place a voltmeter of suitable range across the brushes of the machine. With no current flowing through the field of the machine, it will be found that a small voltage is generated. This is due to a small amount of residual magnetism retained from a former excitation.

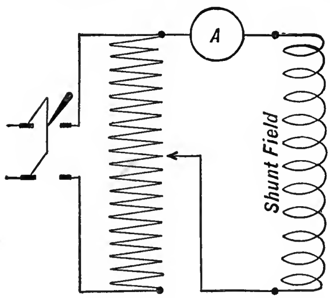


FIG. 7

Now close the line switch and send a small current through the field of the generator, making sure that its direction is such as to increase the voltmeter reading. Then keeping the speed of the machine constant, take about 10 readings, raising the voltage 50 per cent above its rated value. Then decrease the value of current in similar steps until it is again zero. It will be found

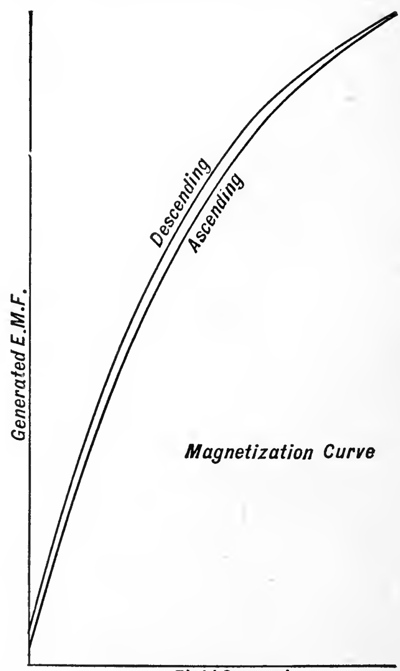


FIG. 8

that the descending curve is higher than the ascending, or in other words that the same field current gives a higher generated voltage descending than ascending. This is due to hysteresis or the retentiveness of the magnetic path. The curve obtained is shown in Fig. 8.

Caution. Because of hysteresis, great care must be taken when on the ascending curve, to always bring the magnetizing current up to the value at which a reading is to be taken. If the desired value should be exceeded and the current subsequently reduced to it, the readings obtained would lie on the descending curve. In case the desired value of field current is exceeded, adjust the current to the proper value, open the field circuit slowly for an instant and then let the current build up again. The opposite applies to the descending curve.

After obtaining the readings for the magnetization curve, determine the shunt field resistance, using the same connections as before and measuring the voltage across the field *at the machine.*

(*c*) A shunt generator, as its name implies, is one in which the field is shunted or connected directly across the armature. Thus a part of the armature current is diverted from the external circuit and sent through the field. As has been seen before, the resistance of the shunt field is made high in order that only a small percentage of the current output of the generator may be used in this part of the machine: the power expended in the field circuit is lost as heat, and being a constant loss, every effort is made to reduce it to as low a value as is practically possible.

It was mentioned in part (*a*) that even with no field current a small flux due to residual magnetism traverses the armature, which the conductors cut as they rotate. If the shunt field is connected across the brushes, the small E.M.F. generated by the armature, causes a small current to flow through the field winding, which strengthens the residual field. This increased field induces a higher E.M.F. in the armature, which in turn causes more field current, so there results a stronger field, and so on until the excitation reaches its proper value. This process is called "building up." It is quite evident that if there is no residual magnetism present, as may sometimes occur, that the machine cannot "build up" any voltage. In this case the field must be excited by some exterior source of power. Another possibility of trouble is reversed field connections, so that whatever voltage is generated due to residual magnetism, causes current to flow through the field coils in such a direction as to weaken the residual magnetism instead of strengthening it. To test for this, open the field and determine the voltage due to residual magnetism. Then close the field and notice if the voltmeter drops toward zero. In this case reverse the field connections. If there is a short circuit in the external circuit the machine will not build up, nor can it if the field connections are open. If the residual magnetism is weak, increasing the pressure of the brushes will often start a machine to build up its voltage.

The external characteristic of a shunt generator is the curve which shows the relation between terminal voltage and external current. If we have a generator rotating at rated speed and allow it a definite field current, it will generate a certain E.M.F. If the external circuit is closed through a resistance, a current will flow through the armature and the external circuit, depending upon the value of the voltage generated and the resistance of the external circuit. It has been seen before that when current flows through an armature, there is a drop of potential, so that some of the voltage induced by the generator will be used up in the armature and the remainder in the load circuit. We may write this in the form of an equation as follows:

$$E_g = E_t + I_a R_a, \quad \dots\dots\dots \quad (7)$$

where E_g = voltage generated by the machine;
E_t = terminal voltage;
I_a = current flowing through the armature;
R_a = resistance of the armature circuit.

As more and more load is placed upon the machine the terminal voltage is decreased due to the increased IR drop in the armature. In addition to this there is also armature reaction to be taken into account, the effect of this being generally to weaken the field and thus reduce the generated voltage. Furthermore, the shunt field, being also connected across the terminals of the machine, receives less and less current due to the terminal voltage decreasing which still further weakens the flux. It should be carefully noted that the decrease in shunt field current, is a result of

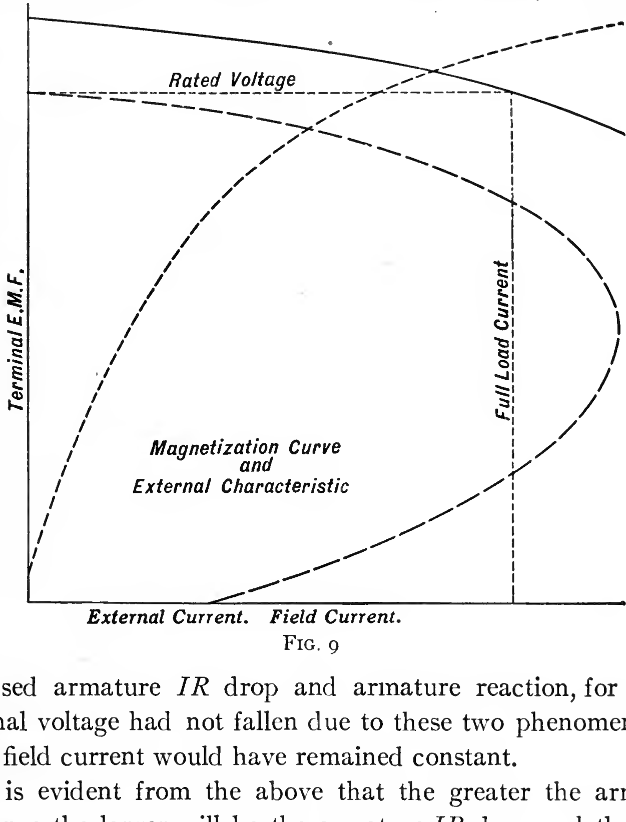


Fig. 9

increased armature *IR* drop and armature reaction, for if the terminal voltage had not fallen due to these two phenomena, the shunt field current would have remained constant.

It is evident from the above that the greater the armature resistance the larger will be the armature *IR* drop and the more the voltage will fall off with the load; armature reaction should also be kept as small as possible.

As the external resistance is decreased more and more, a point is reached where the external current no longer increases but actually decreases. If the external resistance is still further decreased the current continues to decrease until when dead short circuit is reached there is only a small current flowing. The E.M.F. generated in the armature under such short circuit is due to the residual flux and it is nearly all used up as *IR* drop in the armature, the terminal voltage being practically zero. The reasons for the curve bending back on itself can be seen by comparing the curve with the magnetization curve as in Fig. 9. The machine with no external current flowing is operating at a point upon the saturated portion of the curve. When the field weakens a little due to the addition of load as stated before, the point of operation is then lower down, but as the field is still somewhat saturated the change in flux is not great. However, when the machine drops down to the straight portion of the magnetization curve, where a small change in field current causes a large decrease in flux, then the generated and terminal voltages fall away quite rapidly and the external current decreases.

That the external characteristic bends back on itself may further be seen if we consider the equation

$$I_e = \frac{E_t}{R_e}$$

where I_e = current flowing through external circuit;

E_t = terminal voltage as before;

R_e = resistance of the external circuit.

Both R_e and E_t are decreasing quantities throughout the determination of the external characteristic and whether I_e increases or decreases depends upon their relative rates of decrease. The operator causes R_e to decrease as he chooses by adding load to the machine, but the rate of decrease of E_t is determined from Eq. (7) and the shape of the magnetization curve. At first as R_e is decreased, E_t does not decrease relatively as much and the external current increases. This continues, E_t decreasing at a relatively increasing rate, until finally, the machine having reached the bend in the magnetization curve, E_t decreases faster than R_e and I_e begins to decrease.

To determine the external characteristic, the machine should be so adjusted that when it is supplying full load current its terminal voltage is at its rated value. However, if this were done, the armature current would reach an excessive value before the curve would turn back on itself, and it is therefore advisable to obtain a curve of this peculiar form by starting with the machine at its *rated* voltage at *no* load. Such external characteristic is illustrated by the broken curve in Fig. 9.

According to modern practice nearly all large generators and most small ones are equipped with commutating poles, by whose aid, sparking at the commutator and the necessity for brush shifting are done away with. The presence of commutating poles may to some extent alter the shape of the external characteristic so that it is preferable to use a generator not so equipped to determine this curve.

Connect the machine as indicated in Fig. 10, using an ammeter of the proper range in the field and one in the external circuit whose range will equal twice the rated full load current of the machine.

Adjust the machine to normal voltage at full load and rated speed and shift the brushes to the position giving best commutation. Without altering the field rheostat remove the load, and after making certain that the speed is still at its rated value read the voltmeter. The per cent rise in voltage determines the regulation of the machine, as the regulation of a generator is given by the equation.

$$\text{Regulation} = \frac{\text{no load voltage} - \text{full load voltage}}{\text{full load voltage}}.$$

Shift the brushes to give no sparking and then lower the voltage of the generator at no load to its rated value, and after noting that the speed is at its proper value read the meters. (If the generator used is equipped with commutating poles, it will not be necessary to shift the brushes if they were properly set to start.) Then keeping the speed constant and without altering the field resistance or shifting brushes, continue adding load in the form of lamps or water rheostats in equal increments, each time taking a reading upon all the meters. Continue this until the voltage is low enough for the machine to be completely short circuited. Record readings and calculate the armature *IR* drop as indicated in Table III.

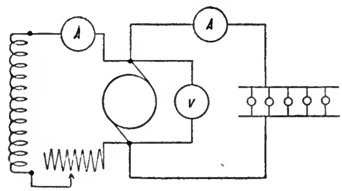


FIG. 10

TABLE III

Speed.	Terminal E.M.F.	Armature Current.	Field Current	Armature *IR* Drop

After this test (using a generator not provided with commutating poles), bring the machine to rated voltage at rated speed with no load upon it, adjusting the brushes to give best commutation. Then add full load and shift the brushes forward until the point of best commutation is again reached: watch the voltmeter very carefully while this is being done. Then shift the brushes further forward and then backward beyond the no-load neutral point, again noting the voltmeter and also sparking.

Finally measure the armature resistance for several values of current from zero to the maximum value used. Plot a curve between armature current and armature resistance and use this curve in calculating *IR* drop in table.

Curves. Plot the magnetization curve of the machine from the results obtained; plot the external characteristic on the same sheet, using same scale for E.M.F.

Conclusions. What are the advantages of the potentiometer method for separately exciting a field? In determining the magnetization curve, if the rheostat used had been connected in series with the field, what would the lowest obtainable value of current have been? How much resistance in series with the shunt field would have been necessary to obtain the lowest value of field current you recorded? What does the magnetization curve show? Why are the ascending and descending curves not coincident? What purpose does residual magnetism serve? For what reasons might a generator refuse to build up and what action is necessary to remedy the trouble? What is the regulation in per cent of the machine tested? Explain why the terminal voltage of a generator tends to fall with increase of load. Why should the armature resistance of a generator be made low? Explain briefly the principles upon which armature reaction and sparking depend. Why does the presence of commutating poles eliminate sparking and the necessity of shifting brushes.

EXPERIMENT IV

The Compound Generator. (*a*) Armature Characteristic of a Shunt Generator. (*b*) External Characteristic of a Compound Generator. (*c*) Effect of Operating a Compound Generator at Speeds Higher or Lower than Rated Value.

(*a*) We have seen that when a shunt generator is loaded, the terminal voltage falls if no attempt is made to regulate it, the decrease being due to *IR* drop in the armature and armature reaction. As a result of these, the shunt field current is reduced, causing a still further decrease in voltage. Referring to the equation $E_g = E_t - IR_a$ it is evident that if the terminal voltage E_t is to be maintained constant while IR_a is increasing, the value of E_g must be increased. Referring to Eq. (6) it will be seen that either the speed or the field flux might be increased and the generated voltage thereby raised. Increasing the field flux is the more feasible, as the prime movers used for driving generators are built to maintain a constant speed. Then as load is added to the generator, sufficient additional flux must be provided in order to raise the generated voltage enough to compensate for armature *IR* drop and armature reaction. In order to provide more flux, more shunt field current is necessary, so that the no-load shunt field current will be smaller than the full-load field current. There must then be some external resistance in series with the shunt field at no load, which can be cut out and the shunt field current thereby increased as load is increased.

The armature characteristic is the curve showing the relation between the external and the shunt field currents, when the terminal voltage is maintained constant by shunt field regulation. The curve is usually concave upward (as is shown in Fig. 11) due to the fact that the increase in flux per unit increase of the shunt field current, as indicated by the magnetization curve, decreases as the iron approaches saturation. Accordingly there is needed a greater increase in shunt field current to compensate for a given value of armature *IR* drop and armature reaction at high loads than at light loads.

Since the number of turns upon the shunt field is constant,

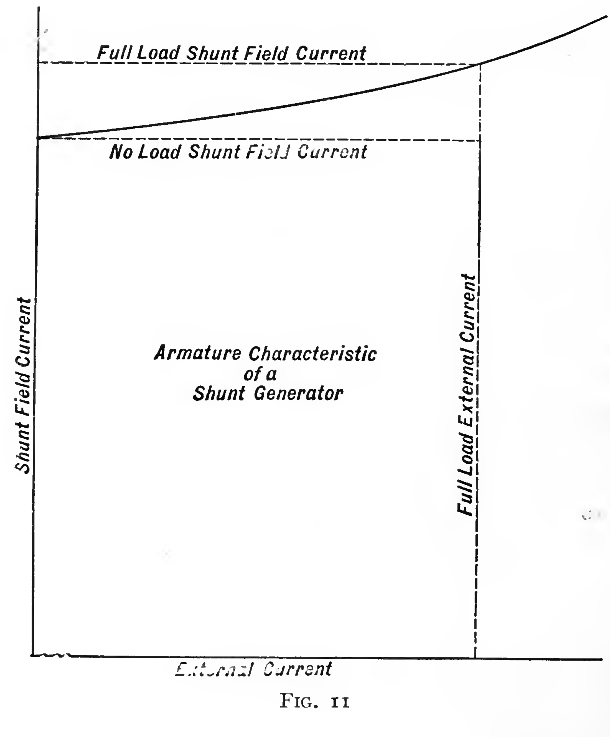


FIG. 11

and the number of shunt ampere turns therefore always proportional to the shunt field current, we can then determine the per cent increase in the number of ampere turns from no load to full load.

Connect the generator to be tested as in Fig. 10 and start at rated voltage and speed with no load upon the machine. Then add load, maintaining rated speed and adjust the shunt field resistance so that for each addition of load the voltage is brought back to its rated value. Take eight readings up to 25 per cent overload. Use log as in Table III.

(*b*) It was pointed out in Exp. III that a shunt generator, when no attempt at regulation was made, decreased its terminal voltage with increase of load. However, if sufficient flux was added to compensate for the factors causing the decrease, then the terminal voltage remained constant. In part (*a*) it was seen that the necessary increase in field ampere-turns could be obtained by decreasing the resistance of the shunt field circuit. A very simple way of causing an increase in the field ampere-turns is to employ the external current, which causes the terminal voltage to fall, by simply passing it through the series field winding which consists of several turns of large wire. Such a machine is called a compound generator. The series field carries all or a fixed per cent of the current output of the machine and is then in series with the external circuit. The shunt field provides the correct no-load flux of the machine, while the series field compensates for the loss of voltage due to armature reaction, *IR* drop in the armature, and *IR* drop in the series field itself. If the number of series turns is more than sufficient to compensate for all the losses of E.M.F. then the terminal E.M.F. will rise with increase of load current. In lighting systems and isolated plants the overcompounding, as it is termed, is about 2 to 3 per cent, while in railway work the generators are usually 10 per cent overcompounded, the E.M.F. rising from perhaps 500 volts at no load to 550 volts at full load. This regulation is entirely automatic and almost instantaneous. Generally machines are built with more than enough series turns, and then a portion of the external current is shunted off by means of a German silver shunt, so that by varying the resistance of the shunt a wide degree of compounding can be obtained.

From the data obtained in part (*a*) the number of series turns necessary to convert the machine there used to a compound generator, can be calculated if the number of turns upon the shunt field are given, as we then know the actual increase in the ampere-turns from no load to full load. By dividing the increase in ampere-turns by the value of the full-load external current we obtain the minimum number of series turns that the machine requires.

It will be found that the external characteristic of a compound generator is somewhat convex upward, this being due to the shape of that portion of the magnetization curve upon which the machine is operated.

In studying the compound generator it is seen that there are two different field currents, one circulating through a winding of a large number of turns of fine wire, the other through a winding of a few turns of large wire or strip, so that there must then be devised some way of expressing one in terms of the other. This is possible if we know the ratio of series to shunt turns, and this ratio can be experimentally determined as follows: The series field of the machine is first separately excited from some outside source of power and a current sent through it, equal to the full load external current of the machine. Then with the machine rotating at rated speed the voltage across the armature is determined. There being no current through the armature, generated and terminal voltages are the same. Then in turn, the shunt field is separately excited and a current is sent through it of such a value that, with the machine again rotating at rated speed, the terminal voltage is the same as before.

In both cases the armature cut the same number of lines of force, since it was rotating at the same speed and generating the same voltage. The number of ampere-turns upon the field must therefore have been identical in both cases, so that we may write

$$\phi = \frac{.4\pi n_1 I_1}{\text{reluctance}} = \frac{.4\pi n_2 I_2}{\text{reluctance}},$$

where n_1 = number of shunt turns;
n_2 = number of series turns;
I_1 = shunt field current;
I_2 = series field current.

Eliminating constants we have

$$\frac{I_1}{I_2} = \frac{n_2}{n_1} = K,$$

which states that

$$\text{Equivalent shunt field current} = \text{series field current} \times \frac{\text{series turns}}{\text{shunt turns}},$$

or

$$\text{Equivalent shunt field current} = \text{series field current} \times K.$$

In case the series field has a German silver shunt and the actual ratio of turns is desired, it will be necessary to determine the actual current flowing through the series field. Where the value of K is to be used in getting the total magnetizing current, it is better in determining K, to assume that all of the external

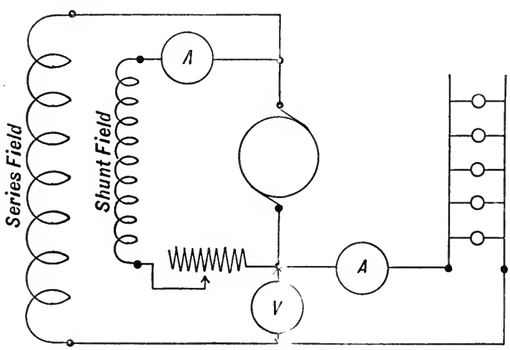


FIG. 12

current flows through the series field. The value thus obtained will be less than the actual value, but it makes calculations easier, since to obtain total magnetizing current we need only multiply the external current by K to obtain the shunt current equivalent to the series field current.

Thus for any load condition we may add to the shunt field current, the corresponding series field current multiplied by K and obtain the total magnetizing current expressed in terms of the shunt field current. If the same generator was used for both parts (*a*) and (*b*) then a curve plotted between external current and total magnetizing current from the results of part (*b*) should be very nearly the same as the armature characteristic of part (*a*).

Connect up the machine as in Fig. 12 and operating it at rated speed, adjust the shunt field resistance to give rated no load voltage. Then with no further adjustment than to keep the speed constant, add load to the machine. Read external and shunt field currents and terminal E.M.F. taking ten readings from no load to 25 per cent overload. Use a log as shown in table IV.

TABLE IV

Terminal Volts.	External Current.	Shunt Field Current.	Shunt Field Current Equivalent to Series Field Current.	Total Magnetizing Current.	Speed.
1	2	3	4	5	6
			(2) ×"K"	3+4	

(*c*) It is of considerable importance that a compound generator be operated at rated speed if it is to compound as intended. If a flat compounded generator is operated at a speed higher than rated, but with rated voltage at no load, it will be found that it will overcompound as load is added. If it had been operated at lower than rated speed, it would have undercompounded.

We have seen from Eq. (6) that $E_g = k\phi N$, so that at rated speed there is necessary at no load a certain value of flux. This is shown in Fig. 13, *oc* being the value of the shunt field current and *oi* the value of the flux produced. As load is added to the machine the series field provides a certain additional number of ampere-turns shown by the distance *cd*. The machine thus operates between the points *p* and *q* on the magnetization curve, the flux added being represented by the dstance *ij*. This amount of flux is sufficient to compensate for the loss of E.M.F. due to the addition of load, so that the machine is flat compounded, as shown in the full line curve in Fig. 14. If the machine is to be operated at a speed higher than rated, it follows that if the armature is to generate the same no-load voltage, the same amount of flux must be cut per second, so that if the speed is raised, less flux is necessary. Under these conditions a smaller shunt field current, shown as *oa*, is sufficient, so that the machine begins operating at the point *m* on the curve, the value of the flux being *og*.

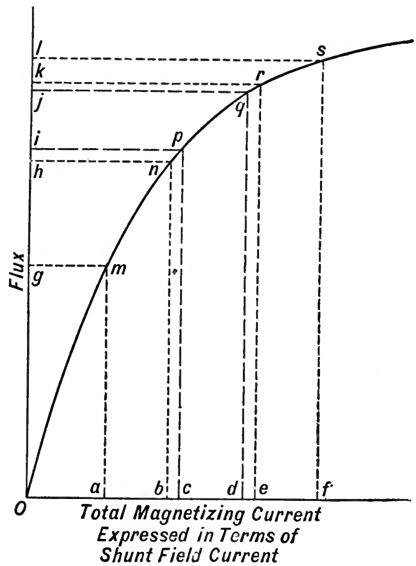


FIG. 13

When full load is put upon the machine, the series field provides the same addition of ampere-turns as before, so that the distance *ab* is equal to *cd*. The flux thereby added is shown as *gh*, which is more than *ij* (the amount just necessary to compensate for loss of voltage) which causes the machine to overcompound as shown in Fig. 14. By similar reasoning it will be seen that operating below rated speed requires more no-load shunt field current, but the magnetic circuit is then more highly saturated so that the series field is unable to provide sufficient flux to compensate for the losses in potential and the machine undercompounds.

Operate the machine with the same connections as in part (*b*) at speeds 15 or 20 per cent above and below rated value, beginning at the rated value of terminal voltage. Take about eight readings up to full load.

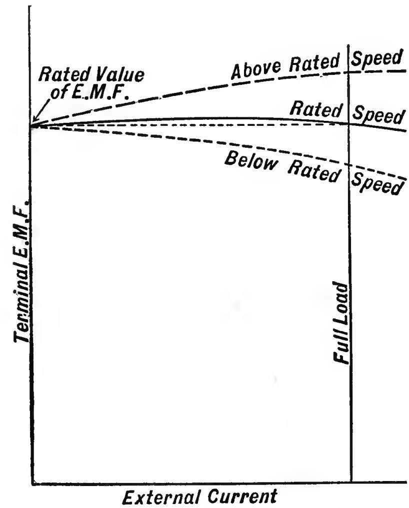


FIG. 14

Determine the value of *K* for the machine as indicated in part (*b*). The connections are shown in Fig. 15.

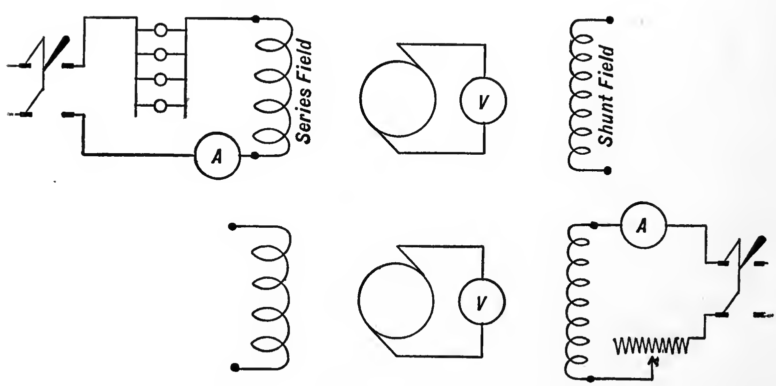


FIG. 15

Curves. Plot the armature characteristic and to the same set of co-ordinates, plot a curve between external current and total magnetizing current as obtained in part (*b*). To another set of co-ordinates plot the three compound characteristics as obtained in parts (*b*) and (*c*).

Conclusions. What is the increase in ampere-turns from no load to full load in per cent of the full load value, in the shunt generator operating at rated speed? If the number of shunt field turns can be obtained, calculate the number of series field turns necessary to make the machine flat compounded with all of the external current passing through the series field. Why should the resistance of a series field be made low? Explain why a flat compounded generator overcompounds or under-compounds, when operated at higher or lower than rated speeds respectively, if started at rated no-load voltage. Would you consider the operation of a shunt generator satisfactory for commercial work if the load is widely varying and constant terminal voltage is desired? Does the compound generator meet the difficulties? Explain why.

EXPERIMENT V

The Shunt Motor. (*a*) Speed Characteristics. (*b*) Commercial Efficiency by Brake Test.

From a structural standpoint the shunt motor and the shunt generator are identical and it will also be seen that both depend upon the same phenomena for their operation. In fact any direct-current dynamo-electric machine that can be used as a generator can also be used as a motor, the only point of difference being in their function and application. A generator has mechanical energy supplied to its shaft and this energy is converted into electrical energy by the rotation of the armature in the magnetic field. In the case of the motor, electrical energy is supplied to its field and armature and the machine converts it into mechanical form at the shaft.

Motors are usually classed according to their field windings, these being known as shunt, series, and compound; these types correspond exactly with those in the generator.

The operation of a motor involves two fundamental phenomena. The first is, that when a conductor carrying current is placed in a magnetic field, a force is developed which tends to move the conductor in a direction at right angles to itself and to the magnetic flux. This force is directly proportional to both the strength of the field and the current flowing in the conductor. The direction in which the conductor moves (for obviously it can sweep across the field in either of two ways) depends upon the direction of the current in the conductor and the direction of the magnetic flux.

In a motor we have a number of conductors distributed around the periphery of the armature, and when the latter is placed in a magnetic field, some of the conductors develop a torque when current flows through them and move at right angles to the field, thereby rotating the armature. As they move out of the field, others take their places and in turn also move out, so that the torque is continuous and the armature keeps on rotating.

The second phenomenon is the same as that upon which the operation of a generator depends, namely, that when a conductor, whether carrying current or not, is moved in a magnetic field so as to cut lines of force, an electromotive force is generated in it.

In the case of the generator, as soon as current flows in the windings of the armature, a torque is produced which tends to move the conductors in a direction opposite to that in which the arnature rotates, due to the fact that the conductors are carrying current and are placed in a magnetic field. That is, the current, which flows through the conductors as a result of their cutting the magnetic field, causes a torque in the direction opposite to that in which they are moving. It is this counter torque which the prime mover must overcome in order to continue the rotation of the armature.

In the motor, when current is sent through the armature winding, a reaction takes place between the armature conductors and the magnetic field and the armature rotates. As soon as it begins to rotate, due to the fact that the conductors are cutting the lines of force of the field, an E.M.F. is generated, which is in the opposite direction to that impressed upon the armature. This is called the "counter" E.M.F. of the motor and evidently it cannot become equal to, or greater than the impressed E.M.F., so long as the machine is operating as a motor, for then no current would flow and the armature would cease rotating.

It follows then, that the generated E.M.F. of the generator and the counter E.M.F. of the motor are the same and that the terminal E.M.F. of the generator becomes the impressed E.M.F. of the motor. In Eq. (7) ($E_g=E_t+IR_a$), we saw that while the machine was delivering current and IR therefore positive, that E_g was greater than E_t, while if no current flowed, E_g and E_t would be equal. If the machine operates as a motor and takes current (which for the same direction of rotation could flow in the reverse direction) IR would be negative. Under these conditions E_g is called the counter E.M.F. and is evidently less than E_t. We may then write

$$e = E_t - IR, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where e = C.E.M.F.

By transposition we also have

$$E_t = e + IR, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and

$$I = \frac{E_t - e}{R_a}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The latter form is really Ohm's law for a motor and it indicates that the armature current is caused to flow by an effective E.M.F., which is equal to the difference between the impressed and the counter E.M.F.'s.

Since the C.E.M.F. of a motor is the same as the generated E.M.F. of a generator, then Eq. (6) is also that for the C.E.M.F. of a motor, so that we have

$$e = \frac{\phi \cdot N \cdot n \cdot 2p}{10^8 \cdot 60 \cdot c} = K\phi N, \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

which indicates that the C.E.M.F. depends upon the flux and the speed.

The shunt motor, as stated before, has its field and armature connected in parallel across the supply circuit. Since the resistance of the shunt field is constant except for temperature changes, the field current and therefore the flux will depend upon the line difference of potential. This usually has a constant value and as a result, the flux, so far as it depends upon the field current, will remain constant, i.e., independent of load.

With this fact in mind, let us now consider what happens when load is placed upon the armature. This means that the armature must increase its torque or turning effort and to effect this, there must be a greater force exerted between the armature inductors and the field flux. This force is proportional to the product of field flux and armature current, so that if it is to be increased there must be an increase in the armature current, the field flux being constant. Now consider Eq. (10), in which E_t and R_a are constant. If I_a is to increase, e must decrease, and in order that this may be, since ϕ is constant, the speed must fall. This brings us to the first operating characteristic of the shunt motor, namely, that as the load is increased, the speed falls. Thus, when additional load is put upon the motor, the machine at that instant not developing the required torque, begins to slow up a trifle. This causes the C.E.M.F. to decrease, more current passes through the armature and a greater torque is developed. This continues until the motor exerts the required torque, the speed becoming constant at a value a little below what it was before. In a well-designed shunt motor the decrease in speed from no load to full load is, however, very small, so that the shunt motor is often called a constant-speed machine. From Eq. (8) it is evident that if R_a is high, the drop in speed will be large, so that to obtain good speed regulation with load, the armature resistance must be low. Substitution of some actual values in Eq. (9) will give an idea of the relative changes of C.E.M.F. and armature current from no load to full load. A 5 h.p., 110-volt shunt motor would require an armature current of about 40 amperes at full load and about 4 amperes at no load. The armature circuit resistance of such a motor would be about 0.25 ohm. Using no load values in Eq. (9) would give

$$110=109+4\times 0.25$$

and at full load

$$110=100+40\times 0.25.$$

With a small change of 9 volts in the C.E.M.F. the armature current rose from 4 to 40 amperes, which is a considerable change.

Let us now consider what happens when resistance is inserted into the armature circuit. When current flows through the resistance there will be an IR drop across it, so that the E.M.F. applied to the armature terminals will be the difference between the line E.M.F. and the IR drop across the variable resistance. Then

$$E_t-IR_{v.r.}=e+IR_a. \quad \ldots \ldots \quad (12)$$

For this equation to be satisfied, e must decrease, but since $e=K\phi N$, in which ϕ is constant, the speed must fall. This in one sense, is equivalent to changing the armature resistance, as will be seen if we rewrite Eq. (12) in the form

$$E_t = e + I(R_a + R_{.vr.}).$$

The effect of adding resistance to the shunt field circuit is just the reverse. The first effect produced is a decrease in the shunt field current, which in turn decreases the flux and the C.E.M.F. This permits more armature current to flow and the extra torque developed accelerates the motor until the C.E.M.F. has built up to such a value that normal armature current is again flowing. If the armature current has nearly the same value in both cases (i.e., before and after resistance was added to the field) then the value of the C.E.M.F. must be nearly the same for both cases and in order to satisfy this condition for a decrease in flux, there must be a corresponding increase in the speed. To operate the motor at a higher speed requires a slight increase in torque, so that with the weaker field the armature current must increase enough to cause the motor to exert a little greater torque than before. This will, however, require only a slight change in the C.E.M.F. as was noted before. The practical limit to weakening the field is imposed by sparking at the brushes, due to the fact that with the weakened field, armature reaction is able to distort the field to such an extent that there is no commutating flux. The absolute limit to field weakening is complete open circuit in the shunt field. If this accidentally occurs, the machine will tend to speed up to a dangerous value, the high speed being necessary to generate the proper value of C.E.M.F., since only residual flux is present. Meanwhile it also draws an excessive value of current from the line.

When the brushes are shifted in a motor not equipped with commutating poles, as in the generator, armature reaction is intensified. For a backward shift, due to the creation of more back ampere-turns, part of the main field flux is neutralized and, as above, the speed rises. Furthermore, the effect of shifting brushes is to decrease the effective number of inductors upon the armature. In Figs. 16 and 17 is shown a motor armature in which the inductors marked with a cross carry current away from the observer, those marked with a dot toward the observer.

We have seen that when the conductors upon the armature of a motor revolve in the magnetic field, there is generated in each an E.M.F. which is in the opposite direction to that impressed upon the armature. This generated E.M.F. was called the counter E.M.F. *Considering only the C.E.M.Fs.* in the case of the conductors to the left of the line *aa* in Fig. 16, the ends toward the observer are positive with respect to the ends away from the observer. In those to the right of *aa'*, the observer is looking at the negative end of the conductor. In an armature

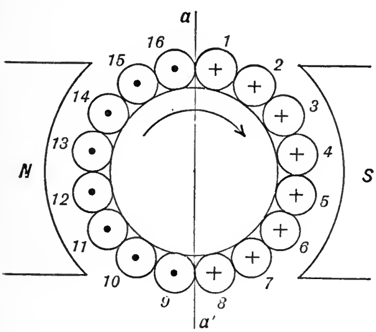


Fig. 16

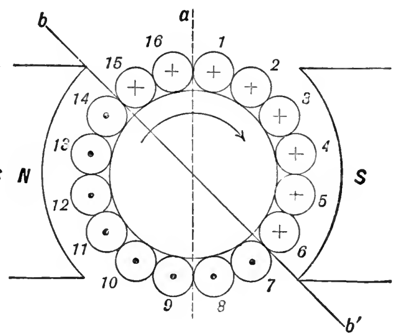


Fig. 17

the individual conductors are always so connected that the positive end of one of the right-hand conductors is joined to the negative end of a conductor on the left of *aa'*. Thus all of the conductors are joined to add their individual C.E.M.Fs.

If the brushes are now shifted backwards to the position *bb'*, as shown in Fig. 17, the current in conductors 7, 8, 15 and 16 is reversed, but as these conductors are still cutting the flux as before, the upper ends of 7 and 8 will still be negative and those of 15 and 16 positive with respect to the lower ends. Since the upper end of each conductor above *bb'* is joined to the upper end of some conductor below *bb'*, then some of the conductors are connected in the improper order, i.e., the positive ends of some of the conductors are joined to a positive end of another. The C.E.M.Fs. of some of the conductors thus oppose those generated in others, and the effect is equivalent to decreasing the effective number of conductors. Since $e=K'\phi Nn$ (where n is the effective number of conductors) it follows that if e is to remain at its proper value, the speed must increase.

We have seen before that the effect of additional load is to cause the speed of a shunt motor to decrease. Increase of armature current is also accompanied by greater armature reaction, whose effect, as we have just seen, is to decrease the effective flux and thereby increase the speed. It might then be argued, that if armature reaction were made great enough, a constant speed shunt motor might be designed. Whereas this is possible, it is never done, armature reaction being kept as low as possible to obtain good commutation. Besides, the drop in speed in a shunt motor, from no load to full load, being only a few per cent., is of no great commercial importance.

In order to change the direction of rotation in a motor the relation of armature current to field flux must be changed. This involves reversing either the armature or the field current. If both are reversed, their relation remains the same and the armature continues to rotate in the same direction as before.

Connect the shunt motor to be used as in Fig. 18, choosing

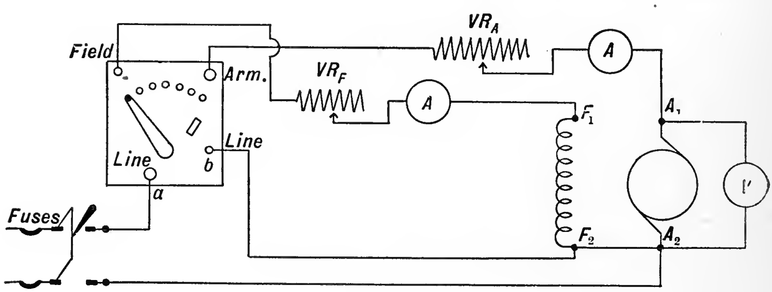


FIG. 18

ammeters and variable rheostats of suitable current capacity. The terminals of the starting box will generally be marked as in the diagram and they should be connected as indicated. The starting box shown has four terminals, of which two are marked "line"; one of these will be a large terminal (marked "a" in the diagram), the other is a small terminal (marked "*b*"). Many starting boxes are provided with only three terminals, and in this case, line terminal *b* is the one omitted and the connection *b*, F_2, is left out.

With all of the resistance cut out of both rheostats, close the line switch and *slowly* move the handle of the starting box as far as it can go. If the starting box is properly connected the handle will remain in this position.

(1) With the machine running free, adjust the brushes by shifting backward and forward, to obtain the minimum speed; note that at this point the sparking is a minimum. It is known as the no-load neutral point.

(2) Shift the brushes forward a small amount, note speed and sparking and read the meters. Again move them forward an equal amount and repeat. Continue this until either the speed rises 25 per cent or the sparking becomes bad. Repeat, moving the brushes backward.

NOTE: If the machine assigned is provided with commutating poles, perform 1 and 2 upon another machine.

(3) With the brushes on the neutral point and no load on the motor, insert resistance into the shunt field circuit by means of VR_f. Do not raise the speed more than 25 per cent above the normal value. Carefully determine speeds and read all meters. Take from 8 to 10 readings, recording in a log as in Table V. Put load on the motor by means of a brake and repeat, holding the armature current constant at one-half rated value by adjusting the brake tension.

TABLE V

Armature Volts.	Armature Amperes.	Field Amperes.	Speed.	Armature *IR* Drop.	C.E.M.F.

(4) With no load on the motor insert resistance into the armature circuit by means of VR_A (VR_F should be all cut out), again noting speed variations and reading all meters. Repeat,

holding the armature current constant at one-half rated value, by means of a brake.

(5) Investigate the methods of reversing the direction of rotation of the armature.

(*b*) The rating of a motor is usually given in horse-power, and is the actual or available horse-power at the motor pulley. To determine the horse-power output of a motor, we must know the pull F, which the motor is capable of exerting at the periphery of the pulley, and also L, the radius of the pulley. In one revolution the point of application moves a distance $2\pi L$ with respect to the pulley, and in one minute, if N expresses the R.P.M., it moves a distance $2\pi LN$. The work done in foot-pounds per minute is then $2\pi FLN$, and since 33,000 foot-pounds per minute is equivalent to one horse-power we have

$$\text{H.P.} = \frac{2\pi LFN}{33{,}000} = \frac{TN}{5250}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where L is expressed in feet, and T is the torque in pound-feet.

The efficiency of a motor is the ratio of the power which the motor gives out in mechanical form, to that which it receives in electrical form. The most direct way of getting the efficiency is to measure both; to get the mechanical output a brake is most commonly used.

The principle of a mechanical brake is that mechanical energy is transformed into heat by friction. One of the simplest forms of brakes is one in which a leather or canvas belt is wrapped partly around the pulley, as shown in Fig. 19. The belt is suspended from two spring balances, one of which is suspended from a hook in some form of frame, the other being hung from a threaded rod which passes through the frame and engages a handwheel. To adjust the brake, it is first necessary to allow the belt to hang loose, when, due to the weight of the belt there will be a small pull upon both balances. This must be noted and subtracted from all subsequent readings. Any load can now be put upon the motor by increasing the tension of the belt, which causes greater friction. In order that the pulley shall not get too hot, it is generally of the water-cooled type, i.e., built to hold water in the inside of its rim. The pull exerted by the motor is the difference between the net readings of the spring balances. (A steelyard may be substituted for balance S_1.)

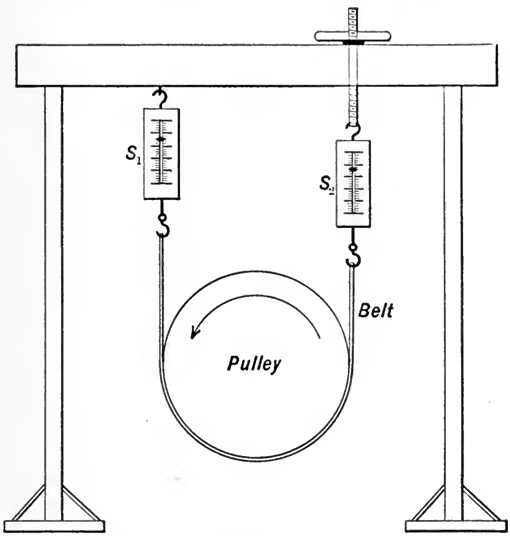


Fig. 19

Another form of brake which is very commonly used is known as the Prony brake. A good form of it, as shown in Fig. 20, consists of a beam of wood hollowed out at one end to fit the pulley. Around the pulley are placed two thin iron straps on the inside of which are placed small blocks of wood. One end of each strap is fixed and the other ends are attached to a threaded rod which passes through the beam and can be moved up or down by means of a nut or threaded handle. The tension of the brake can thus be varied at will.

The brake described above has the effect of increasing the radius of the pulley, as the force is measured in a direction perpendicular to a line passing through the center of the shaft or pulley. In the

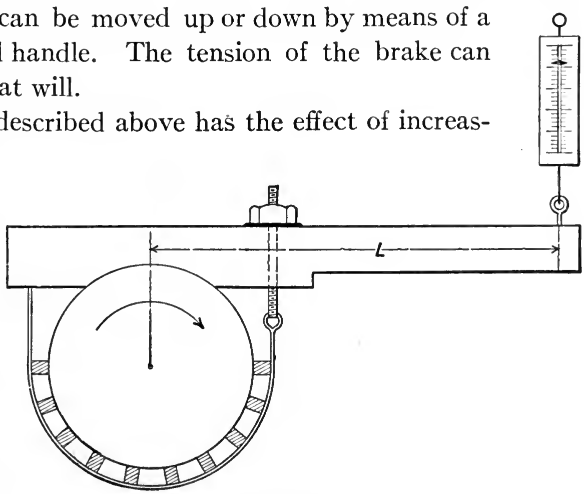


Fig. 20

form of brake described above it is rather difficult to do this, as the line from the center of the pulley to the point of application of the force is to a certain extent imaginary. Considering Fig. 21, we have that the torque is equal to the product of F and L. We have, however, that

$$L' = L \cos \theta \quad \text{or} \quad L = \frac{L'}{\cos \theta}.$$

Now $F = F' \cos \theta$. It follows then that

$$F \times L = \frac{L'}{\cos \theta} \times F' \cos \theta = L' \times F'.$$

If the arm of the brake is held horizontally, the torque of the

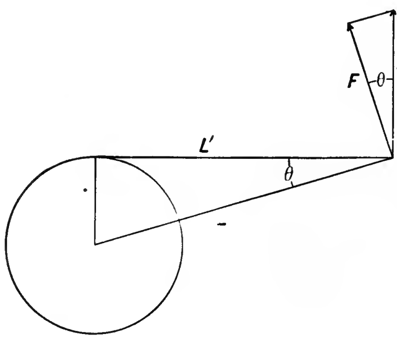


FIG. 21

motor will be given by the length of the lever arm multiplied by the pull indicated by a spring balance pulling in a direction perpendicular to the brake arm. In order to determine the pull exerted by the brake itself, clamp it fast to the pulley and slowly raise and lower the brake, taking readings upon the spring balance. The average of these two readings gives the pull due to gravity of the brake. Remember to hold the spring balance perpendicularly to the brake arm when raising or lowering it.

In Fig 22 are shown the characteristic curves of a shunt motor. It will be seen that the efficiency, at first, rises very rapidly with increasing H.P. output, then slowly bends over, becomes horizontal and falls on overload. This is due to the fact that the losses of the machine are at the start nearly constant, but increase more and more rapidly until on overload they increase faster than the output. This is principally due to the armature copper loss, which varies as the square of the armature current. The same factors cause the curve plotted between H.P. output and amperes input, to become concave upward on overload.

To determine the commercial efficiency of the motor to be tested, connect it up as in part (*a*), omitting the two variable rheostats. Determine the full load armature current and operate the motor, first with no load upon it and then with $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$, $\frac{4}{4}$ and $\frac{5}{4}$ full load armature current. Read all three meters and the two spring balances and determine the speed for each setting. Record readings in a log as shown in Table VI.

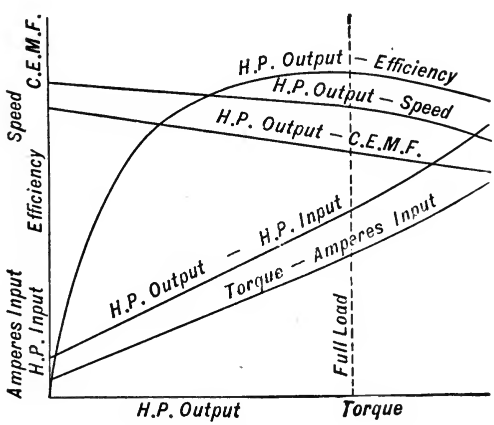


FIG. 22

Measure the armature circuit resistance for the same range of currents as used above. Use the values here determined in the calculations for both parts (*a*) and (*b*).

Curves.—(*a*) Plot a curve between field current and speed from the results of run 3. Upon the same sheet of cross-section paper plot a curve between armature E.M.F. and speed from the results of run 4. Plot speed as abscissa in both cases.

(*b*) Upon a second sheet of cross-section paper plot a set of curves as indicated in Fig. 22. Plot a curve between armature resistance and armature current upon a separate sheet.

TABLE VI

A Volts.	*B* Armature Amperes.	*C* Field Amperes.	*D* Total Amperes.	*E* C.E.M.F.	*F* Spring Balance S_1	*G* Spring Balance S_2
			$B+C$		Initial Reading=	Initial Reading=

H Net Pull.	*I* Torque.	*J* Watts Input	*K* H.P. Input.	*L* H.P. Output.	*M* Per cent Efficiency.	*N* R.P.M.
		$A \times D$				

Note.—When using Prony Brake omit column *G*.

Conclusions.—What are the principles upon which motor operation depends? How can the speed of a shunt motor be increased above its rated value? How can it be lowered from its rated value? Give the reasons for these results. What are the disadvantages of each method? Why is the curve between field current and speed concave upward?

Explain the form of the load characteristics. Why does the speed of a shunt motor fall off slightly from no load to full load? Why must the armature resistance be made low? What is the speed regulation, in per cent, of the motor tested? What is the effect, on speed regulation, of resistance in series with the armature?

EXPERIMENT VI

The Motor Starting Rheostat. We have seen that when current flows through an armature that there is an IR drop, which when multiplied by the current gives I^2R, the rate of production of heat. If at ordinary temperatures the armature is unable to radiate this heat as fast as it is produced, it may rise to a temperature of 100° C. or more, at which values of temperature the various kinds of insulation upon the armature will be damaged. Accordingly the current capacity of a machine is taken as that value, which, with continuous operation will not cause the temperature of the armature to rise more than 50° C. above a room temperature of 40° C.* A machine is, however, usually capable of carrying a large current for short intervals, say 150 per cent of its full load value for half an hour. It might also be possible for a motor to take an instantaneous current of many times its rated value without undue injury, but such a current value would be *beyond the range of the protective apparatus*, such as fuses and circuit breakers. These protect against comparatively small overloads which if continuously applied would burn out the machine.

When the armature of a motor is at rest and an E.M.F. is applied to its terminals, there is only the resistance reaction to balance the applied voltage, so that a current will flow through the armature according to the relation.

$$I_a=\frac{E_a}{R_a},$$

where I_a=armature current;

E_a=voltage impressed across the armature;

R_a=armature resistance.

The armature resistance being very low, it follows that if the value of E_a were that of the line upon which the motor is intended to operate, the armature current would be excessive.

* The matter of temperature ratings of electrical machinery is a complicated one. See Standardization Rules of the A.I.E.E. and of the Electric Power Club.

The most natural method of preventing an abnormal current is to insert resistance in series with the armature, so that we have

$$I_a=\frac{E_t}{R_a+R_x},$$

where I_a and R_a are the same as before;

E_t=voltage of supply circuit;

R_x=external resistance in series with armature.

Let us leave this discussion for a time and consider the conditions which a motor must fulfill in order to properly start a load. In most cases a motor at starting, must exert its full load value of torque and in many cases a value greater than this. This means that the resisting torque of a load during starting of the motor, is equal to or somewhat greater than when running. The question of acceleration is also of considerable importance, for while desirable that the starting-up period be reasonably short, it must not be so short, as to demand such a value of torque which might cause a shaft to be bent or a belt to slip. It is usually found that if a motor is capable of exerting a torque of 100 to 150 per cent of its full load value, that the rate of acceleration is of the proper value.

The torque or turning effort of a motor depends only upon the current through the armature and upon the field flux, and is entirely independent of speed. It follows from this that the value of the field current should be a maximum, as then we can obtain any value of torque within the range of the motor, with minimum armature current. A shunt motor is nearly always so operated (i.e., with its field connected directly across the line) and then when full load current flows through the armature the motor exerts its full load torque. If we desire twice the full load value of torque we must supply double the armature current.

Therefore, to properly start a shunt motor we must connect its field directly across the supply line, so as to obtain maximum value of flux and then connect the armature to the supply line in series with an external resistance of such a value, that an armature current equal to 100 to 150 per cent of the full load rating of the machine will flow.

The resistance in series with the armature also serves another purpose, namely, that of reducing the voltage applied to the armature. The effect of this (as we have seen in the previous experiment) is to reduce the speed. As soon then as the armature, with resistance in series is connected to the line, the current rises to 100 to 150 per cent of the full load value. This reacting with the field flux produces a torque which starts the armature rotating. As soon as it starts to rotate, a C.E.M.F.

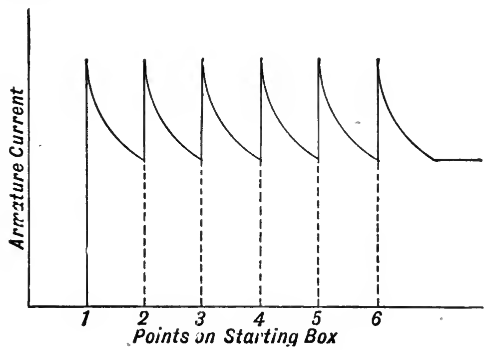


FIG. 23

is generated, which in turn reduces the current to a smaller value and the motor continues to rotate at a speed somewhat below its rated value. If now a little of the starting resistance is taken out, there will be another increase of the current, more torque will be exerted and the speed will rise to a higher value. The sudden increase in current each time the starting resistance is reduced, is occasioned by the fact that the voltage across the armature is suddenly increased, whereas the C.E.M.F. at that instant is at the value fixed by previous conditions. Finally when all of the starting resistance has been taken out, the motor is operating at full speed directly upon the line. The variations of the armature current during starting under full load are shown in Fig. 23.

Motor-starting rheostats are made up in many different forms; a rather completely equipped form is shown in Fig. 24. The starting handle is shown in a position cutting out part of the resistance. Current enters let us say at the terminal *L* and flows around a solenoid *B*, through a switch-blade contact *C*, along the movable arm *D* to the movable arm *E*. The current then divides, part going through the resistances r_3, r_4, r_5 to the terminal *A*, which is connected to the armature. The remainder of the current goes through the resistances r_1, r_2, to the terminal *F*, which is connected to the field. These currents unite at *M*, flowing back to the line on a common conductor.

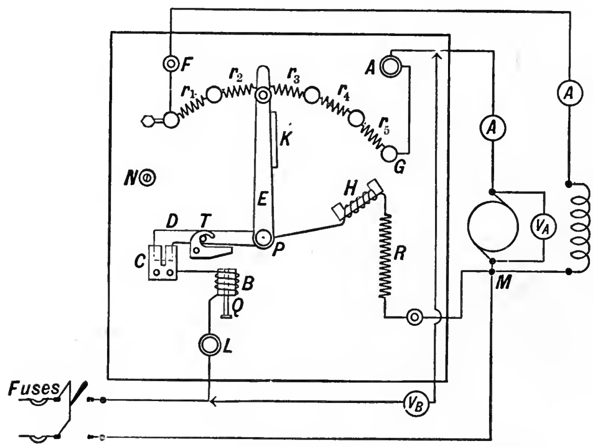


FIG. 24

When the motor is standing still, the main switch is open and the arm *E* of the starting rheostat is over to the left against the stop *N*, being held there by a spiral spring *P* at the pivot of the arms. To start the motor, the line switch is first closed and the arm *E* slowly moved over to the right against the tension of the spring *P*, until it is on the last notch. Here the arm is held by the attraction of an electromagnet *H* for the iron keeper *K* upon the arm. This device is commonly called the " no-voltage " release. The electromagnet is energized by current flowing from *P* and through the high resistance *R*, this circuit being thus connected directly across the supply line. When the main switch is opened or the line potential fails, the solenoid

H is demagnetized and the starting arm swings back to the starting position, automatically protecting the motor for the next starting or from a big inrush current if the line potential were again applied.

The other automatic device is the overload release, which is essentially a circuit breaker. A solenoid *B* is placed in series with the main circuit and when the motor current momentarily exceeds a certain limit, the plunger *Q* is attracted upward and strikes a trigger *T*. This releases the arm *D*, which swings in

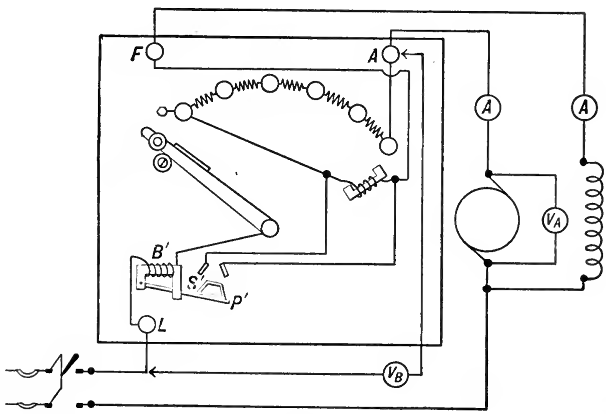


FIG. 25

toward *E*, due to the action of the spring *P*. The circuit is thus automatically opened at *C*. The lever *D* cannot be reset without moving the arm *E* back beyond its starting position.

In a majority of the starting rheostats in use, the overload device is not used, the line fuses being relied upon to open the circuit in case of overload. The advantage of having the overload release, is that it is easily reset, whereas it takes time to put in new fuses.

Another form of starting rheostat is shown in Fig. 25, in which it will be seen that the winding of the no-voltage release is in series with the field, instead of being connected directly across the line as in Fig. 24. This is an excellent arrangement, as it guards against accidental opening of the field. There is the disadvantage that a certain size starting box cannot be used on all motors of the same size and voltage, inasmuch as the value of the field current may not be the same for the various different motors. The manufacturer of the motor can decide upon any value of field current he chooses, as field excitation is only a matter of ampere-turns. Thus in one motor the field current may not be high enough to give the electromagnet sufficient excitation to hold the starting arm, in another it may be so large as to cause the winding of the magnet to heat.

The type of overload release shown on Fig. 25 is also different from that in Fig. 24. In this case the arm P' is provided with a small piece of copper strip S', bent as shown. When P' is attracted due to an overload current flowing through the solenoid B', the copper strip makes contact with two complementary strips of copper and thus short circuits the winding of the no-voltage release. As a result the latter becomes de-energized and permits the starting arm to swing back to the starting position. The trouble with this device, though cheaper to manufacture, is that the auxiliary contacts are liable to be bent or become dirty and thus inoperative. The form of overload release shown in Fig. 24 is more positive in its action and more reliable.

For this experiment, a starting-box is necessary which will permit a motor to be operated at full load current at the various notches for short intervals without dangerous overheating. Considerable energy is transformed into heat in the box under these conditions and most types will be injured if so operated. There are, however, a few excellent types upon the market in which the resistances are imbedded in sand with no soldered connections and which are absolutely fireproof.

Connect the motor to be used in studying the operation of the starting box assigned, as in Figs. 24 or 25. The ammeter to be used in the armature circuit must have a range equal to double the full load armature current of the motor. The two voltmeters should have a range a little larger than the line voltage. Provide a slip of paper for each meter upon which the readings can be jotted down, as there will not be time to record them in the log. Three men are really needed for rapid work, one to manipulate the starting lever and read one voltmeter and the field ammeter, the second to read the remaining meters and the third to take speed.

With no load upon the motor close the line switch and put the starting lever upon the first notch of the rheostat. At the same time the maximum throw upon the armature ammeter must be noted and immediately recorded. As soon as the motor has reached steady speed, as determined by a tachometer, a reading upon all the meters is to be taken. Then the starting lever is to be moved to the second notch, the maximum reading upon the armature ammeter, the speed and all the steady values are again to be recorded. This is continued until the running position has been reached.

Then put a brake upon the motor and with the motor running at full speed tighten the brake until the armature current is about 80 per cent full load value. Then without changing the tension of the brake stop the motor and proceed as before.

It is imperative that the readings be taken rapidly, else the box will heat excessively.

After the second run, determine the armature resistance for several values of current, covering the range recorded in the test.

TABLE VII

1	2	3	4	5	6	7	8	9
Armature E.M.F. V_A	Box E.M.F. V_B	Line E.M.F.	Armature Current.		Field Current.	C.E.M.F	Speed.	Box Resistance.
			Maximum.	Steady.				
		1 + 2						

Record readings in a log as in Table VII, using steady values of armature current to calculate C.E.M.F. and box resistance.

Curves. Plot a curve between armature current and notches on starting box as indicated in Fig. 23, for both no load and full load runs. Also plot curves for both runs between speeds (abscissa) and C.E.M.F.

Conclusions. Why is a starting rheostat necessary? Why is it essential to provide maximum value of field current at the first point? Why should a motor be started slowly? How do armature and field currents vary during starting? Why cannot the usual type of starting box be used for continuous operation with the lever upon any of the starting notches? What determines the steady speed and armature current for each notch on the starting rheostat?

EXPERIMENT VII

Efficiency of a Shunt Motor by the Stray Power Method. The electrical input to a motor is not all converted into mechanical energy, some of it going to waste in various ways. Accordingly we may write that

$$\text{Input} = \text{Output} + \text{Losses}, \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and also

$$\text{Commercial Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}}. \quad . \quad . \quad (15)$$

The losses in any motor or generator can be divided as follows:

- Losses
  - Copper
    - Copper loss in armature
    - Copper loss in fields
  - Stray Power
    - Friction or Mechanical losses
      - Bearing Friction
      - Air friction or windage
      - Brush friction
    - Iron or Core losses
      - Hysteresis loss
      - Eddy current loss.

Upon consideration of the copper losses, it is evident that if we know the resistance of the armature circuit we can immediately compute the I^2R loss for any value of current. This is true for a current actually measured or assumed and the same applies to the fields.

The friction losses will vary directly with the speed within the limits between which the machine is operated. The hysteresis loss, however, varies directly as the speed and the 1.6 power of the magnetic density in the armature iron. The eddy current loss varies as the square of both the speed and the magnetic induction.

In the shunt motor as commercially operated two factors are considered constant, namely, the impressed E.M.F. and the shunt field current. *Let us, for the moment, neglect the effect of armature reaction upon the flux and therefore consider the latter as being constant under all conditions of load.*

When the load upon the motor was increased, we found that there was a decrease in C.E.M.F. and a slight drop in speed. From the equation $e=K\phi N$ it follows that if the flux is considered constant, the C.E.M.F. is directly proportional to the speed.

The equation for the armature current of a shunt motor is, as we have seen,

$$I_a=\frac{E_t-e}{R},$$

so that, knowing the resistance of the armature, we are able to calculate the value of the C.E.M.F. for any value of armature current. Nor does it make any difference whether this value of armature current is one actually obtained in practice or one *assumed.* Then if we know the value of the speed and C.E.M.F. at some value of armature current, we can calculate the C.E.M.F. at any other armature current and by proportion obtain the speed. That is, we predict the speed at which the motor would run if it had a certain value of armature current. We can thus forecast the speed load curve of a shunt motor provided that we know the armature resistance and the speed at some one value of armature current.

Consider then that we know the values of armature and field currents and speed when the motor is running free, with rated voltage applied to both armature and field. From the name-plate of the motor we can find what the manufacturer intended the full load armature current should be. From this full-load value of the armature current, we can calculate the value of the full load C.E.M.F. and by proportion obtain the full load speed of the machine, using the relation

C.E.M.F. at no load : C.E.M.F. at full load = Speed at no load : Speed at full load

The full load speed will of course be lower than the no load speed.

Knowing the full load armature current we also know the complete power input, that being the sum of the armature and field currents multiplied by the terminal E.M.F. As we know the value of armature and field resistances, we can readily determine what the armature and field copper losses will be. So that the only other losses that so far we do not know, are the stray power losses.

When a motor is operating at no load, that is, running free, the entire input is used in overcoming losses in the machine itself. If the known copper losses be subtracted from the input, we have left the stray power loss at no load, at a particular speed and the rated value of field current. Similarly we could determine the stray power loss at any other speed and field current.

Suppose we knew the full load speed of the machine and were to operate the motor with no load upon it, at this value (which is of course lower than the no load value) and at rated value of field current. We could then calculate the stray power loss of the machine, when running at its *full load speed and rated field current but with no load upon it.*

The effect of armature reaction, proportional to load current and brush position, is to modify somewhat the stray power loss. If we neglect this effect, however, it is possible to obtain full load stray power or stray power at any fractional load, without actually loading the motor. If, e.g., the full load speed is known, then full load stray power may be obtained with the machine running free by measuring armature input, with normal field and sufficient impressed E.M.F. to give full load speed. Stray power loss is then obtained by subtracting the armature copper loss from the armature input. Then knowing all the losses and the total input, we can readily determine the commercial efficiency.

It is, however, necessary that we consider what effect load does have upon the value of the stray power losses. As soon as armature current flows we have armature reaction, the effect of which is generally to weaken the main field. This tends to raise the speed, of the motor, or in other words the actual speed load curve is slightly higher than the predicted curve. As a result of these conditions the value of stray power will be slightly different from those determined with no load upon the machine. However, the difference is small and inasmuch as stray power itself is a small per cent of the total input, the error is negligible.

The advantages of the method, however, more than counterbalance this, for being a prediction method there is a great saving in power. Waste of power is unavoidable in a brake test and even at times prohibitive, as the necessary power may not be available. Then again the losses are measured by means of electrical instruments which are very accurate, very much more so than the forms of brakes used, which are also difficult to operate.

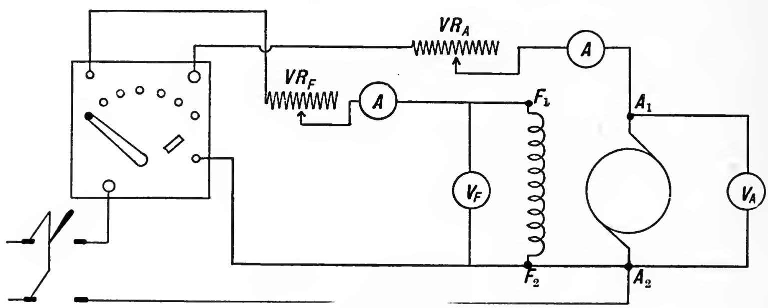


FIG. 26

The method is therefore preferable in most cases, particularly where the division of the losses into separate components is desired.

Before operating the motor to be tested first detemine the resistance of the armature circuit for 8 values of current between a very low value (2 or 3 per cent of rated value) and 150 per cent full load current, and plot the values as a curve.

Connect the motor as in Fig. 26, the source of power being preferably a laboratory generator whose terminal voltage is under control. With both VR_A and VR_F both out, operate the motor with rated voltage impressed across both field and armature. Let the machine operate for about 15 minutes and then measure speed and both field and armature currents *very* carefully.

Determine the full load armature current of the machine from its name-plate and calculate the C.E.M.F. for 25, 37.5, 50, 75, 100, 125, and 150 per cent full load currents. Then calculate the C.E.M.F. when running light and with the speed there found, determine by proportion the speeds corresponding to the armature currents assumed above.

Then operate the machine at rated field current and at the calculated speeds and read all meters. A good method of pro-

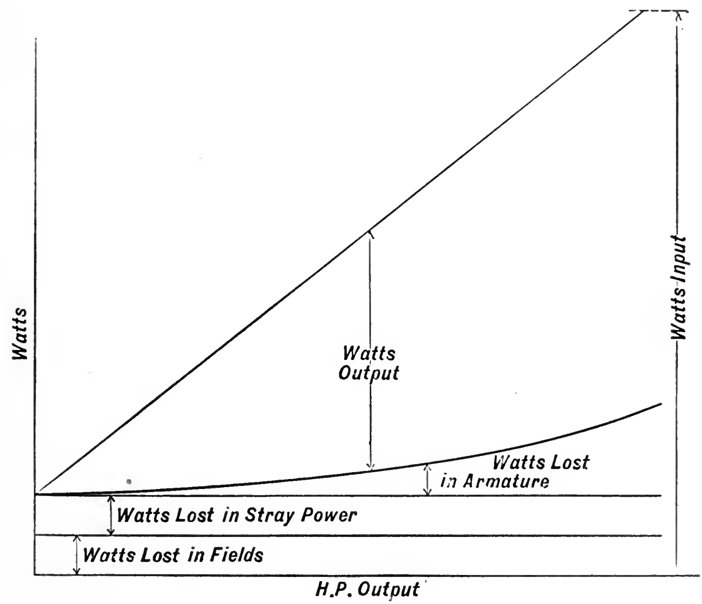


FIG. 27

cedure is to set the value of the supply line a few volts above the rated value of the machine. Then insert resistance into the field circuit by means of VR_F until rated value of field current is flowing. Then decrease the speed of the machine to the desired value by inserting resistance into the armature circuit by means of VR_A.

In the log, as shown in Table VIII, part *a* is for the operation at no load to determine the stray power loss corresponding to each load speed. All of the columns in part *b* are to be calculated or assumed except column 9, which is taken from part *a*.

TABLE VIII

a Machine Running Light

A	B	C	D	E	F	G	H	I	J	K	L
R.P.M. (Calculated).	Armature Current (Running Light).	Field Current (Constant).	Volts across Armature.	Volts across Field.	Watts Input to Armature.	Watts Input to Field.	Total Watts Input.	Armature I^2R Loss.	Watts Lost in Field.	Total Copper Loss.	Stray Power Loss.
					$B \times D$	$C \times E$	$F+G$	$B^2 \times Ra$	G	$I+J$	$H - K$

b, Predicted Operation under Load

1	2	3	4	5	6	7	8	9	10	11	12	13
R.P.M. Calculated.	Rated Line Volts. Constant).	Armature Current. (Assumed Values.)	Field Current. (Constant).	Total Current.	Watts Input	Watts Lost in Armature.	Watts Lost in Field	Stray Power Loss.	Total Losses Output.	Watts Output.	H.P. Output,	Per cent Efficiency
				$3+4$	2×5	$3^2 \times Ra$	2×4	L	$7+8+9$	$6-10$	$\frac{11}{746}$	$\frac{11}{6} \times 100$

Curves. Plot the loss curves determined for the machine, as shown in Fig. 27; also plot the curves of calculated efficiency and speed, using same scale for abscissa as for the loss curves. If this experiment is performed on the same machine as was previously tested by brake (Ex. 5), plot the efficiency and speed curves obtained by brake on same curve sheet as those obtained by this method.

Conclusions. What is the assumption upon which the stray power method of determining the commercial efficiency of a shunt motor is based? What are the advantages of the method? How do the losses vary from no load to full load? Why does the efficiency at first rise and then fall? How much would the full load efficiency as determined in this test be changed, if the no load stray power value, operating at rated voltage across the armature and field were used, instead of that obtained by operating at the calculated full load speed?

EXPERIMENT VIII.

Series Motor. In the series motor, the field winding is placed in series with the armature and carries the whole armature current, and this fact causes its characteristics to be entirely different from those of the shunt motor.

The equation for the current in a series motor is as follows:

$$I_a=\frac{E_t-e}{R_a+R_{se}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

in which all of the terms are the same as before and R_{se} is the resistance of the series field.

As in the case of the shunt motor, for the series motor to increase its armature current, there must be a decrease in the C.E.M.F. In the shunt motor, where, except for armature reaction the field flux was constant, this was brought about by a slight decrease in speed. In the series motor we have a variable flux, for evidently, if the armature current increases, there will be an increase in flux.

It has been shown that for any motor $e=K\phi N$, and that the armature current can only increase as a result of a decrease in e. The increase in armature current at the same time brings about an increase in ϕ, so that if the C.E.M.F. is to fall, there must be a large decrease in speed. In the shunt motor the flux is constant and as load increases the speed falls only enough to cause a decrease in e. In the series motor, in addition to this, the speed must fall enough to counteract the large increase in flux. It would appear then from the equation $e=K\phi N$ that inasmuch as e only changes a small amount, that the speed load curve of a series motor is nearly an equilateral hyperbola. This is not quite the case, due to the fact that the iron of the field becomes saturated. When the point is reached where an increase in armature current causes only a small increase in flux, then the speed does not fall as much as before. The speed load curve of a series motor is shown in Fig. 28. It is evident from the curve that the speed changes very materially in going from no load to full load. A very dangerous condition is, however, reached when there is no load upon the motor, for under these conditions the machine takes very little current from the line

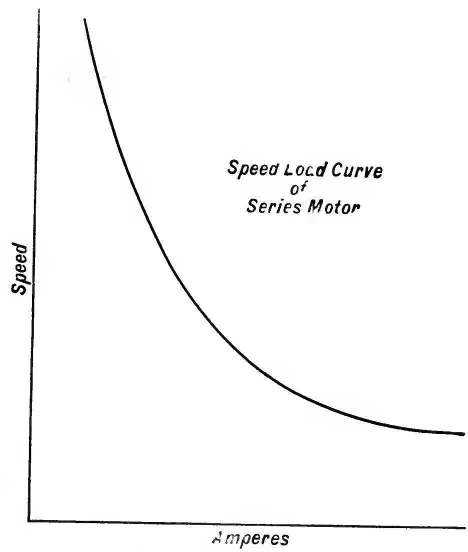


FIG. 28

and hence must have a high value of C.E.M.F. This is accompanied by a weak field and hence a dangerously high speed. For this reason a series motor is always direct connected to its load either by a coupling or through gears or chains, unless a speed limit device is attached. In the latter case, if the motor speed rises above a certain point it is automatically disconnected from the line.

The torque of any motor may be expressed by the formula $T=K\phi I_a$ and in applying this to the shunt motor we have seen that inasmuch as ϕ was nearly constant, that T varied almost directly with I_a. In the series motor ϕ is, however, not constant, but varies with I_a. Starting with light load upon the motor we have with an increase of I_a an almost equal increase of ϕ. The machine under these conditions is operating upon the straight portion of the magnetization curve, so that the torque varies

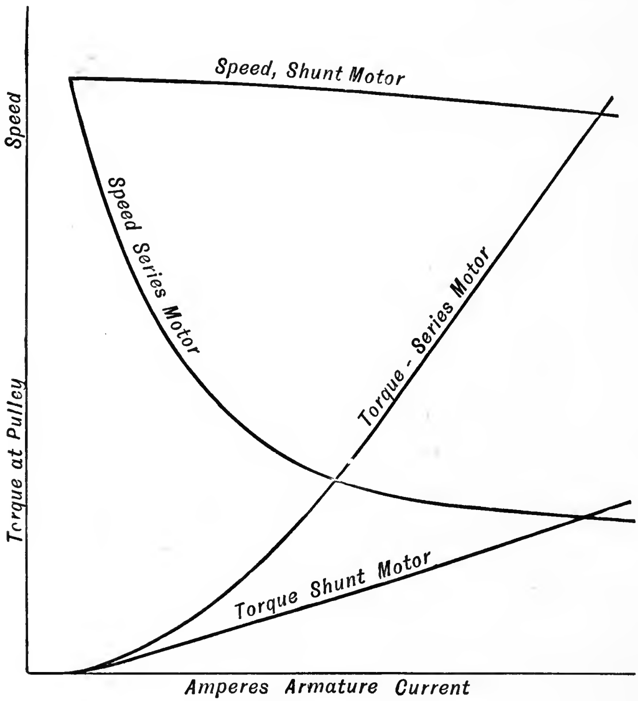


Fig. 29

as I_a^2; at the same time the motor is operating at a high speed. As the armature current increases and the saturated portion of the magnetization curve is reached, the increase in flux is no longer proportional to the current increase, so that finally the torque increases directly as the armature current.

The fact that the series motor exerts its maximum torque at stand-still, (that being the point where the current is greatest for a given armature voltage) constitutes one of its greatest advantages. In Fig. 29 are given curves of torque and speed plotted against *amperes armature current* for a shunt and a series motor of the same full load rating. The speeds of both motors are the same at light loads, but at full load the speed of the series motor is very much less than that of the shunt machine.

Now since horse-power output is proportional to the product of torque and speed, i.e., H.P. output $=KTN$, it follows that in the series motor, due to its lower speed, the torque will be much greater at full load than that of the shunt motor. To exert the same torque a much larger shunt motor would be necessary.

The series motor is thus particularly valuable for work where

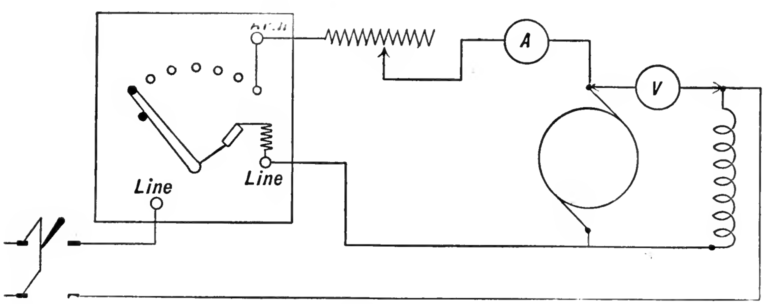


FIG. 30

a load is to be frequently started and a great starting torque is desired, as in traction service, hoists, cranes, etc. When the required torque is large the motor operates at a low speed, but where a light torque is necessary it operates at a high speed.

If the impressed voltage of the motor is decreased, the motor speed will fall and it will be found that the speed varies almost directly with the impressed voltage.

The resistances of the armature and series field are always made low for reasons of efficiency. The question of regulation is of no importance as the series motor has of itself a widely varying speed characteristic.

(1) Determine the resistance of the armature and series field, taking readings up to 150 per cent full load armature current.

(2) Connect the motor as in Fig. 30, choosing an ammeter and

a variable resistance with a capacity of about double the rated current of the motor. Start the motor and reduce the voltage across the armature to one-half of its rated value. Then starting with a very small load (no load if possible) take a reading of current and speed; then gradually increase the load by means of a brake, keeping the voltage constant at half rated value. Take eight readings up to 50 per cent overload current. If a constant potential line of one-half the rated motor voltage is available, it serves the purpose better than the use of a variable resistance. Record readings as in Table IX.

TABLE IX

E.M.F. across Motor.	Current.	Speed.	C.E.M.F.

(3) Impressing full voltage upon the motor, adjust the load until the motor takes about $\frac{2}{3}$ of its rated current. Read speed and voltage. Then decrease the voltage across the armature by about 10 per cent and adjust the current to the same value as before by means of the brake and take a set of readings. Continue to decrease the armature voltage, keeping the armature current constant until 6 or 8 readings have been taken.

(4) With rated voltage impressed upon the motor make a complete brake test up to 50 per cent overload current. If the motor is equipped with a speed limit device, allow the motor to run free and determine the speed, current, and voltage, just at the instant the speed limit device disconnects the motor from the line. If no speed limit device is provided, adjust the brake until the motor operates at 300 per cent of its *rated full load speed. Do not permit it to rotate faster than this value.*

Record readings in a form similar to Table VI.

Curves.—Plot a curve between current and the sum of the series field and armature resistances. Upon a second sheet, plot a curve between speed as ordinate and armature current from the results of run 2, and a curve between speed and impressed voltage from the results of run 3. Upon the same sheet, from the readings of run 4, plot a speed-current curve, a torque-current and an efficiency-current curve, the current being plotted as absicssa in each case.

Conclusions. Explain why the speed of a series motor varies more widely than that of a shunt motor and why a series motor of the same horse-power rating as a shunt motor, exerts a greater full load torque. Why is the series motor better adapted to frequent starting of heavy loads than the shunt motor? Why is the torque curve concave upward at the lower end and straight at its upper end? What is the effect of lowering the terminal voltage of a series motor? Why should a series motor never be belt connected to its load?

EXPERIMENT IX

Current-Torque Curves of Different Types of Motors. This experiment is intended to show the value of the torque exerted by different types of motors with various values of armature and field currents, for purposes of comparison.

We have seen that when current flows through the armature windings of a motor whose fields are excited, there is a torque exerted, which tends to rotate the armature. The value of the torque depends upon the strength of the field and upon the value of the armature current, i.e., $T=K\phi I$.

In the case of the shunt motor we have a constant field current and if the flux remains constant we would expect that the torque would vary directly as the armature current and that a curve expressing their relation, would be a straight line. In this case the torque per ampere (i.e., the value of torque divided by the current) would be constant. This is, however, not quite the case, inasmuch as armature reaction distorts and reduces the flux so that the torque per ampere decreases with the higher values of armature current. For the same armature current and a varying field current, we do not get a straight line relation unless we are operating upon the straight portion of the magnetization curve. As the saturated portion of the curve is reached the torque does not increase as rapidly for a given increase of field current.

If to the shunt motor, a series winding is added and so connected that its M.M.F. is added to that of the shunt field, we get a cumulative compound motor. The shunt field current in this case again remains constant and the series field current increases, being the same as the armature current. The result is an increasing flux as the armature current increases, so that the torque per ampere is greater than when only a shunt winding is used. If the machine is very much compounded, that is, if the series turns furnish a large percentage of the M.M.F. at full load, the curve between torque and current will be slightly concave upward.

In the case of the series motor, we of course have the same current flowing through both field and armature. When operating upon the straight portion of the magnetization curve, the flux is proportional to the current, so that the torque varies as the current squared:

$$T=K\phi I=KI^2.$$

Under these conditions the curve between torque and current is concave upward. As the field approaches saturation the curve gradually straightens out until at the end it becomes straight.

We are now in a position to compare the behavior of the shunt and series motor. Let us assume that we have a shunt and a series motor, each of about 5 horse-power and both having the same full load efficiency and therefore about the same full load armature current. Let us further assume that the shunt motor has a full load speed of about 1200 R. P. M. and that the series motor has the same speed at its lightest permissible load; the full load speed of the latter would then be about 500 or 600 R. P. M. The light load speeds of the two motors would thus be the same, which fact is shown in Fig. 29. Since output is proportional to the product of speed and torque, the torque exerted by both motors is about the same at light load. At full load, however, the series motor must exert double the torque of the shunt motor, as its speed is about half that of the latter. It follows that the pole pieces and armature of the series motor must be larger than those of the shunt motor to provide and accommodate the extra flux, so that the series motor is generally larger than the equivalent shunt motor.

This again brings out the great advantage of the series motor, namely, that it can exert a much greater torque at higher loads than the shunt motor for the same value of armature current.

The compound motor, as we have seen, increases its torque somewhat with load, with a greater decrease in speed than the shunt motor, but not as much as in the case of the series motor.

It is very valuable for running certain types of machine tools, as punch presses, power shears, etc., which are always provided with a heavy flywheel, the energy necessary for the actual operation of the tool, that is, say, shearing metal, etc., coming from the energy stored in the flywheel. The motor slowing up, immediately develops a strong torque and accelerates the flywheel. It is evident that the compound motor is able to accelerate the flywheel and bring it up to speed in a shorter interval of time than the shunt motor. There is also the great advantage that a relatively small motor is necessary to operate such machines provided with a heavy flywheel, since the time the machine is doing work is only a small per cent of the time it is running. In the time when the machine is running free the motor is able to store energy in the flywheel.

In order to determine the torque exerted by a motor when standing still, some form of Prony brake is clamped fast upon its pulley, as is shown in Fig. 20. When current flows through the armature and fields, let us suppose that the torque is so exerted as to tend to revolve the armature in a clockwise direction. If the brake arm be slowly moved upward against the torque of the motor, we are then, first, lifting the brake; second, overcoming the friction of the bearings; and third, overcoming the torque of the motor. This can be written as an equation as follows:

$$W_{up} \times L = T + w + f,$$

where W_{up} = the reading upon the spring balance when the brake moves the pulley against the torque of the armature;

T = torque exerted by armature;

w = torque due to weight of brake;

f = torque due to bearing friction;

L = length of brake arm.

Where the brake is allowed to descend, the motor torque and the weight of the brake overcome the friction so that

$$W_{down} \times L = T + w - f;$$

adding the two equations we have

$$T + w = \left(\frac{W_{\text{up}} + W_{\text{down}}}{2}\right)L,$$

which eliminates friction. To determine w, the weight of the brake, open the current in both armature and field and slowly raise and lower the brake, taking readings on the spring balance. The average of these two readings gives the pull due to gravity of the brake arm itself, which we have called w.

The compound motor to be used should be connected as in Fig. 31, the shunt field being separately excited by the poten-

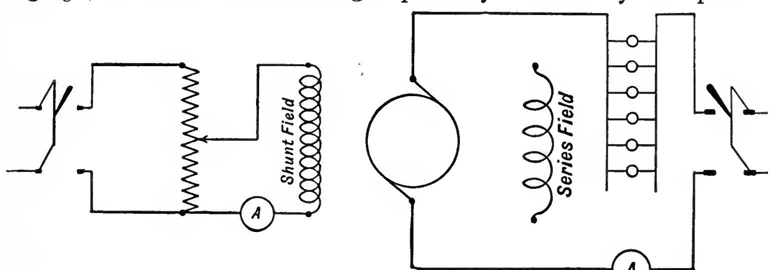


FIG. 31

tiometer method and the series winding open. The machine is thus in reality a shunt motor. By means of the variable resistance, set the value of shunt field current a trifle lower than one-half its rated value and then vary the armature current from zero up to 150 per cent full load value in about 8 steps, by varying the number of lamps burning in the lamp board, taking torque and current readings as previously noted. Keep the shunt field current constant throughout. Then raise the shunt field current to a value double that used in the first run and proceed as before. For a third run, set the armature current at its full load value and keep it constant. Then vary the shunt field current from zero to its rated value. Take readings as before. For a fourth run connect the series field in series with the armature as in Fig. 32, making the machine a cumulative compound motor. Vary the current through series field and armature as before with the shunt field current as in second run. Take the same readings as before.

To determine the curves for the series motor it is preferable to use a machine of the same voltage and H.P. output as the compound motor already tested, in order that proper comparisons can be made. Pass the same current through both armature and field as shown in Fig. 33.

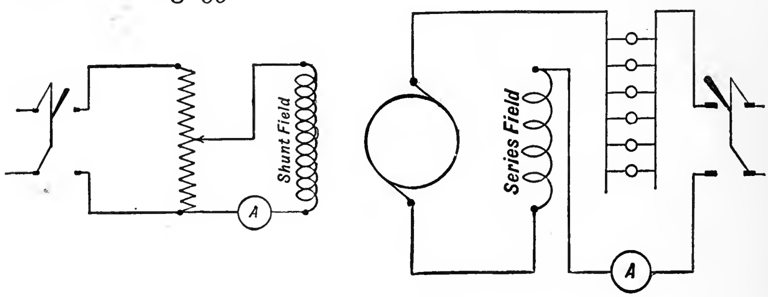


FIG. 32

Curves.—For runs 1, 2, 4, and 5 plot curves between armature current as abscissa and torque and torque per ampere armature current as ordinates. For run 3 use field current as abscissa. Plot corresponding curves on the same sheet of cross-section paper.

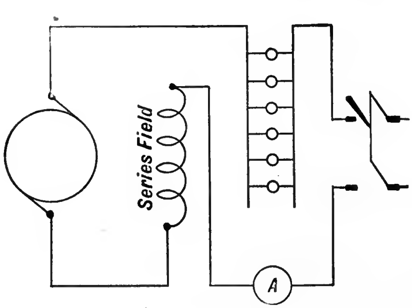


FIG. 33

Conclusions. Why are the current-torque curves for the shunt motor straight lines? Why is it concave upward at the start for the series motor? Why does torque per ampere decrease in the shunt motor and not on the compound and series motors? From the data obtained compare the action of the three types of motors. In run 4, what tests can be made to determine whether the series field is properly connected to make the machine a cumulative compound motor?

EXPERIMENT X

Parallel Operation of Shunt Generators. In many lighting and power systems the load which the station is required to carry is much greater than the capacity of the largest direct current generator which is manufactured. It therefore becomes necessary to operate several generators on the same feeder system to supply the load. Even when the load could be carried by one large unit, it is many times preferable to install two or more smaller units to carry the load, because of the increased security against possible accident. If the load is all carried by one machine and even a minor accident happens to this machine, the station is obliged to shut down for repairs. If two or more machines are used to supply load, one of them may be shut down for repairs and the others, overloaded perhaps for a short time, will satisfactorily supply the station load. Besides, it is more efficient to operate a small machine at full load than a larger one at light load.

There are two possible schemes for connecting D.C. machines together so that they supply power to a common bus, in series or in parallel.

If they are connected in series, the voltage of the line depends upon how many machines are operating; while this type of service has been used for very special purposes, it is not feasible to use such a system for the ordinary purposes of furnishing current for light and motors. For such purposes a constant potential system is required and obviously a number of D.C. machines operating in series, their number depending upon the load, could not satisfy this requirement. Also the possible current output of such a series system is the rating of the smallest machine used.

If, however, several machines, each of the voltage required by the system, are operated in parallel in the same system, the latter will be essentially a constant potential one and the possible current output of the station depends only upon how many machines are connected to the system. The current capacity of the station is equal to the combined capacity of all the machines connected to the buses.

Although shunt wound generators are not used very much for station work, compound wound generators serving the purpose so much better, it is necessary to examine the parallel operation of shunt generators, so that the more difficult case of compound

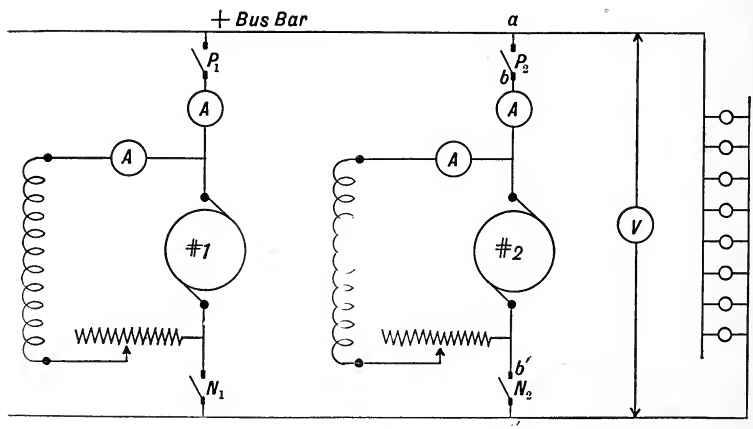


Fig. 34

generators may be understood. (The operation of compound generators in parallel will be considered in the next experiment.)

The analysis of the question may be most easily made by supposing first that one machine (say No. 1) is already connected to a load, and that whatever manipulation is carried out with the second machine (No. 2), the bus-bar voltage will be assumed constant. This latter will not generally be the case, but makes the first analysis simpler.

Consider the machines connected as in Fig. 34. Generator

No. 1 is supplying load and it is desired to connect machine No. 2 to the bus bars and divide the load between them.

Let E = voltage between bus bars;
E_g = generated voltge of No. 2;
R_a = armature resistance of No. 2;
I_2 = armature current of No. 2.

Now if the voltage E_g is exactly equal and opposite to E, it is evident that when P_2 and N_2 are closed no current will flow through the armature circuit of No. 2.

We have shown previously that

$$I_2 = \frac{E - E_g}{R_a},$$

which is also written

$$E = E_g + I_2 R_a. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

If when the switches P_2 and N_2 are closed, $E_g = E$, it is quite evident from the above equation, that no current will flow through the armature of machine No. 2. But if E_g is not equal to E then current will flow upon closing the switches, the *magnitude* of the current being determined by the difference in E_g and E, and the *direction* of the current depending upon whether E_g is greater or less than E. If E_g is greater than E, current will flow in the same direction as E_g tends to make it flow; i.e., the machine acts as a generator. If E_g is less than E then the line E.M.F. forces current to flow through the armature of No. 2 *against* its generated E.M.F. and No. 2 acts as a shunt motor, drawing power *from* the line instead of furnishing power to it.

If switches N_2 and P_2 are closed when E_g is not nearly equal and opposite to E, then an excessive current will necessarily flow so that the equation may be satisfied. This rush of current disturbs the line voltage, may blow fuses and circuit breakers and even injure the machine. It is always advisable, therefore, to have E_g as nearly equal to E as possible.

It has been mentioned that E_g must be opposite to E; this is sometimes expressed by saying that the machines must be connected in the proper polarity. That this is a very necessary condition is almost self-evident.

Suppose that E_g were not opposite to E. As soon as switches P_2 and N_2 are closed, both E and E_g would tend to force current in the same direction, through the circuit composed of the two armatures and the bus-bars. As the resistance of this circuit is extremely low, the conditions would be one similar to a dead short circuit on each machine. To test for polarity N_2 may be closed and a voltmeter of range at least twice the voltage of the machines, connected across switch P_2. If machine No. 2 is connected with proper polarity, the voltmeter reading will be $E-E_g$; if improperly connected, the voltmeter will read $E+E_g$.

Another way of testing for polarity is to connect a voltmeter (one of range equal to machine voltage only is necessary) to the points aa' and then transfer the voltmeter leads, *without interchanging them* to the points bb'. If the voltmeter deflects the same way in both cases the polarity is correct; if not, the connections of machine No. 2 to the bus-bar switches must be reversed or else the generator must be forced to build up in the opposite direction.

The question of division of load between the two machines is now to be analyzed. When the bus-bars voltage is supposed constant and the load current is taken as constant, it is a very simple matter to see from Eq. (17) that the current, I_2, depends directly upon the value of E_g. If E_g is increased while E remains constant I_2 must increase. The output of machine No. 2 depends directly upon the value of its generated voltage.

If machine No. 2 has been brought up to rated speed, its voltage adjusted to be equal to the line voltage and the polarity test satisfied, N_2 and P_2 may be closed and no current will flow through its armature. If now its generated voltage is increased, by decreasing the resistance of the shunt field circuit, it will begin to deliver current to the line, the amount depending upon how much E_g is increased. The division of load between two shunt generators is thus always at the command of the operator; by proper field adjustment the load may be shifted from one machine to the other at will.

If the load is once equally divided, the question arises whether the division will remain equal as the load varies. This is an important point to investigate, as it is very desirable that after the machines are once adjusted for proper load division, the division should not change as the load fluctuates. If the load is once properly divided (proportionate to the relative capacities of the machines) the division will only be automatically maintained if the external characteristics of the two machines are coincident throughout the range of operation.

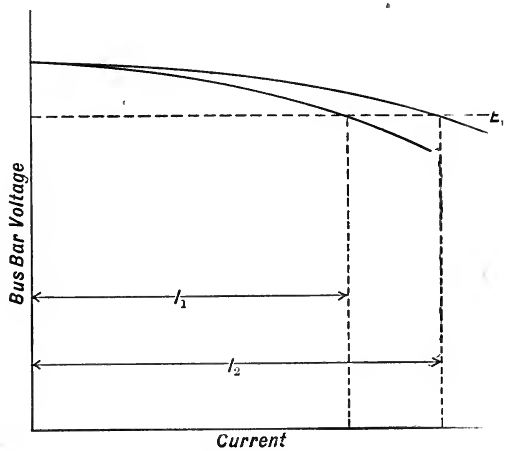


FIG. 35

Suppose the load to be zero and the voltages of the two machines adjusted to be equal. The supposed external characteristics of the machines are given in Fig. 35. Now as the machines are connected to a common bus, *their terminal voltages must always be equal.* But it is seen that if the two machines are to have the same voltage with a certain load (I_1+I_2) that machine No. 1 must be furnishing current I_1 and machine No. 2 current I_2. So that from this figure it is seen that as the load varies, (field rheostats left in fixed position) the division of load will change, the amount of change depending upon how far the external characteristics separate.

If the bus-bar voltage is allowed to vary as the load changes the division of load between the two machines will change in exactly the same manner as shown in the previous analysis, but the effects noted will not take place to the same degree. In Eq. (17) E will generally decrease as load is increased and this will tend to make machine No. 2 take more load for a given E_g than if E remained constant.

Connect the shunt generators to be operated in parallel as in Fig. 34. Attach one of the machines to the bus-bars and load it with lamps. Then bring the second machine up to speed, build up its voltage to that of the bars, and having made certain that the terminals of the machine will be properly connected as regards polarity, close the line switches. Strengthen the field of the incoming machine until it takes half of the load and then weaken the field of the first machine until it is supplying no current. Then further weaken the field of the first machine until it operates as a motor. This fact will be indicated by the armature ammeter reversing. Note that the shunt field current continues to flow in the same direction. Then bring the current in the first machine to zero and disconnect it from the bars. Continue this procedure until sufficient practice has been had, in putting machines on and off the bars and in throwing the load back and forth.

(*a*). Bring both generators in parallel upon the bars at rated voltage with no armature current in either machine. Then add load in equal steps up to the full load value of each machine, keeping it equally divided between the two machines, voltage constant at rated value and speeds constant. Read all meters, recording readings in a log as in table X.

(*b*). Starting as before with rated voltage and no load upon either machine, add load to the system but allow the total current to divide between the machines as it will. Permit the voltage to vary, but keep speeds constant at rated value.

After run *b*, with about half load on each machine, investigate the effect of shifting the brushes of one machine forward and backward. Be careful not to shift too far if the machines are equipped with commutating poles.

Curves. Upon one sheet of cross-section paper plot three

TABLE X

	Generator No. 1.				Generator No. 2.				Totals.	
1	2	3	4	5	6	7	8	9	10	11
System E.M.F.	External Current.	Field Current.	R.P.M.	K.W. Output.	External Current.	Field Current.	R.P.M.	K.W. Output.	Load Current.	K.W. Output.
				1 × 2				1 × 6	2 + 6	1 × 10

curves (one for run *a* and two for run *b*), between terminal E.M.F.'s (ordinate) and individual external currents. Also plot four curves (two for each run) between shunt field currents (ordinates) and individual external currents.

Conclusions. What precautions must be taken in connecting shunt generators for parallel operation? Why, if left without adjustment, do the machines not divide the load in proportion to their rated outputs? Why is the parallel operation of shunt generators rather impractical from a commercial standpoint? Explain the form of the curves obtained. Explain the effects of shifting the brushes of one of two shunt generators operating in parallel.

EXPERIMENT XI

Parallel Operation of Compound Generators. The parallel operation of compound generators is in many respects similar to the operation of shunt generators; there are, however, a few added precautions to be noted before they may be connected to the same bus-bars.

In Fig. 36 are shown the connections of two compound generators intended for parallel operation. Let us again consider

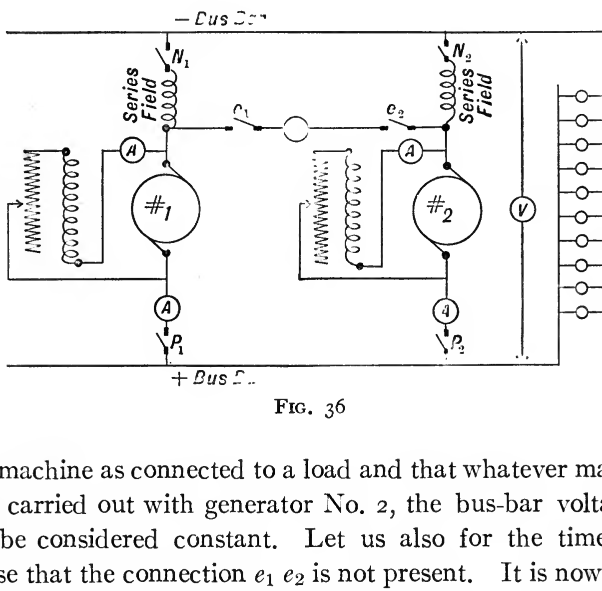


FIG. 36

No. 1 machine as connected to a load and that whatever manipulation is carried out with generator No. 2, the bus-bar voltage will again be considered constant. Let us also for the time being, suppose that the connection e_1 e_2 is not present. It is now desired to connect machine No. 2 to the same bus-bars, in order to have it share the load. The same precautions as to polarity and voltage must also apply in this case as in the operation of shunt generators except that if the second generator comes in with its polarity opposite to that of the bus-bars, its residual magnetism must be reversed so that it will build up with the proper polarity. Reversing the machine connections at the bus-bars will result in a short circuit when the equalizer switches are closed and reversing the armature connections alone will make the machine act as a differential generator. Accordingly let us bring up the voltage of generator No. 2 to the same value as that of the bus-bars and close the switches N_2 and P_2. The generator may then be made to assume load as before by strengthening its field.

The machines are, however, now operating under a condition of unstable equilibrium. Let us suppose that the speed of No. 1 machine were momentarily raised and its generated voltage thereby raised for an instant. This would immediately mean that it would take a slightly greater load, depriving No. 2 of some. The additional current flowing through the series field of the first machine would cause its generated voltage to rise still higher while that of No. 2 would be decreased. This action is likely to continue until No. 1 is supplying all of the load and No. 2

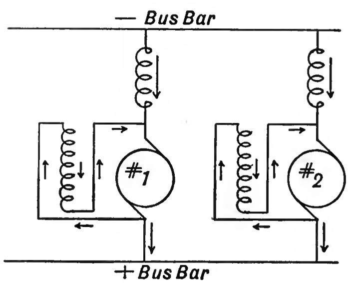


FIG. 37

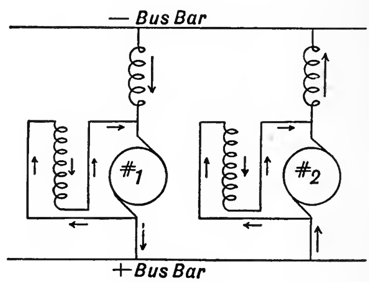


FIG. 38

none of it, and it is also likely that the generated voltage of No. 2 would drop below the voltage of the buses so that the latter would take current from the bus-bars and operate as a motor. This follows as before if we consider the equation $E = E_g - IR$.

We have seen that in the case of shunt generators in parallel, no danger would result if one machine operated as a motor. In the case of compound generators this action, with the conditions as assumed, is really dangerous. In Fig. 37 are shown two compound generators operating in parallel, both acting as generators. The current through the armature and series field flows from the negative to the positive bus as indicated by the long arrows, while the shunt field currents flow from the positive to the negative terminals of the machine as indicated by the short arrows. As the machines are compound wound generators, the M.M.F.'s of the shunt and series fields are added and the arrows point in the same direction to indicate this fact. When No. 2 machine operates as a motor (Fig. 58), the current in its armature and series field reverses flowing from the positive to the negative bus. The current through its shunt field, however, does not reverse but flows as before, so that the M.M..F.'s of the two fields are opposed, which results in the net flux of the machine being reduced.

This in turn results in two things. First, a machine whose field is weakened tends to increase its speed; this is somewhat difficult in this case, since the machine then tends to drive its prime mover, and it is generally unable to accelerate it very much. The second result of the weakened field, is an actual decrease in generated E.M.F. or what it really is, since the machine is operating as a motor, a decreased C.E.M.F. This is due to the fact that the machine cannot raise its speed fast enough, and, besides, the action is cumulative. For if the C.E.M.F. is slightly decreased, more current flows through the series field and armature, which makes the series field stronger and the net flux weaker. Thus the more current the machine takes the more its field is weakened and so on. This goes on so rapidly that the speed has no chance to catch up and keep the C.E.M.F. up to the required value, the net result being that No. 2 forms a short circuit for No. 1, blowing fuses and circuit breakers and disturbing the system. Often the inrush current into No. 2 will be so great as to cause the series field to become so strong that it overpowers the shunt field and actually reverses the polarity of the residual magnetism of the machine.

To prevent this action and make the parallel operation of compound generators stable, a connection e_1e_2, termed the "equalizing" bus-bar, is employed, and it will be noticed that it joins the machines between their armatures and series fields. This connection prevents the reversal of the current through the series field of the machine operating as a motor, which is readily seen if we suppose switches E_1 and E_2 closed and machine No. 2 operating as a motor. Its armature current then flows from the positive bus, but when it arrives at the point x it has a choice of either passing on through the series field of No. 2 along the negative bus and through the series field of No. 1, or flowing directly along the equalizer connection. As this latter is always of very low resistance, the current will take this path. Machine No. 2 is thus in reality operating as a shunt motor, which we have seen is not accompanied by any dangerous conditions.

As the equalizer is of very low resistance, the IR drop of the two series fields must under all conditions be equal. If the load of No. 1 increases, the IR drop of series field No. 1 tends to increase, but this can only increase if a corresponding increase in the drop of series field No. 2 takes place and this means more current through the series field of No. 2. If, therefore, No. 1 tends to increase its load and so raise its voltage, No. 2 will also raise its voltage due to the action of the increased current through its series field, which flows through the equalizer connection from No. 1. The division of the load between the two machines thus tends to remain more or less constant. It follows from the above that the resistances of the two series fields must be inversely proportional to the full load current outputs of the two machines, for if this is not so, the series field currents would not be of their proper values when the armature currents are correct. It is also necessary that the two machines have the same characteristics, that is, each must have the same degree of compounding when running separately. If they differ in this respect, the machines will not share the load equally.

The sequence of closing switches when putting machines upon the bus-bars is also very important. Again consider machine No. 1 supplying current to a load. When it becomes necessary to parallel No. 2, we might first bring it up to the bus voltage by shunt field regulation and then close E_2 and N_2. Current would then flow through the series field of No. 2, and raise its generated voltage somewhat above that of the bus-bars. This would require further shunt field regulation, so that it is better to first close switches N_2 and E_2 and then when the machine has been brought up to the bus-bar voltage by shunt field regulation, P_2 can be closed.

TABLE XI

1	Generator No. 1.				6	Generator No. 2.				Totals.	
	2	3	4	5		7	8	9	10	11	12
System E.M.F.	External Current.	Shunt Field Current.	R.P.M.	K.W. Output.	Equalizer Current.	External Current.	Shunt Field Current.	R.P.M.	K.W. Output.	Load Current.	K.W. Output.

Switch P_2 must never be closed unless the machine is up to voltage and must always be the last one thrown in.

Load is then put upon the machine by strengthening its shunt field. To remove No. 2 machine from the bus-bars, first reduce its armature current to zero by means of shunt field regulation and then open switch P_2 and then N_2 and E_2. Always open P_2 first. The prime mover of No. 2 can then be stopped and the machine shut down.

Operate the machines with the equalizer in, as was done in Ex. 10, bringing a machine upon the bus-bars, transferring the load from one machine to another and removing one machine. Also cause one machine to operate as a motor and note results.

Make two tests, taking about twelve readings in each run, including a no-load setting, and recording readings in a log as in Table XI.

(*a*) Start with the machines in parallel, but with no load upon either and gradually increase the load up to rated value, keeping system E.M.F., and speed constant at rated value and current equally divided between the two machines.

(*b*) Start as before and add load and keep only speeds constant. Allow terminal E.M.F. to vary and the load to divide as it will.

After run (*b*) with half load on each machine, note the effect of shifting brushes. Do not shift too far, if the machines are equipped with commutating poles.

Curves. Plot three curves (one for run *a* and two for run *b*) between system E.M.F. (ordinates) and individual external currents. Upon the same sheet of cross-section plot four curves (two for each run) between shunt field currents and individual external current.

Conclusions.—Explain what is likely to happen if compound generators are operated without an equalizer connection. What are the functions of the equalizer connection and how does it carry them out? What is the proper sequence of closing switches and why is this sequence absolutely necessary? Is the parallel operation of compound generators entirely satisfactory? If, with the generators connected as in Fig. 36, test shows that the polarity of the incoming machine is opposite to that of the bus-bars, what must be done?

EXPERIMENT XII

Commutating Pole Motor and Generator. In motors and generators not equipped with commutating poles, commutation is improved by brush shifting. As a coil on the armature is commutated, its current must reverse, or die down to zero and build up in the reverse direction. In order that there shall be no sparking the rate of change of the current must be such that the current has built up to its final value when the brush and commutator bar separate. However, due to the fact that the coil being commutated possesses some self-induction, the changing current generates a counter E.M.F. which opposes the change. As a result the current may not have built up to its final value when brush and bar part company and a spark is formed.

If during commutation, while the changing current generates a counter E.M.F. of self-induction, the coil can be made to cut flux and generate a voltage equal and opposite to the C.E.M.F. of self-induction, commutation will be satisfactory. This, as was noted, is accomplished by moving the brushes. Since the direction of the E.M.F. required to overcome the C.E.M.F. of self-induction must be in the same direction as that of the final current, it follows that the brushes must be shifted forward in the generator and backward in the motor.

To express the conditions just stated we may write

$$L\frac{dI}{dt} = N\frac{d\phi_c}{dt}, \quad \ldots \ldots \ldots \quad (18)$$

where L = coefficient of self-induction of the coil being commutated;

I = armature current per coil;

ϕ_c = flux cut by short-circuited coil under pole tip;

t = time of commutation;

N = number of turns in the coil.

Evidently as the load on the machine varies, the current I will change and therefore the value of the left-hand term of the expression. In order to maintain equality and hence good commutation, the value of flux ϕ_c, which the coil cuts must be changed, and as this depends upon the position of the brushes, there is a different position of the brushes for each load. In small motors this is not attempted, the brushes being set to that position which gives the best average commutation. The limitation of the method on overloads is the fact that armature reaction causes distortion of the flux and weakening the very pole tip toward which the brushes are shifted and under which the commutating flux is sought. This limitation was particularly noted in Exp. V., when the method of raising the speed of a shunt motor by field weakening was investigated. As the field flux is reduced, armature reaction, which is the effect of armature M.M.F. on field M.M.F., is able to cause greater distortion than when the field is normal.

By the use of commutating poles the same result is obtained. While the method of shifting brushes moves the short-circuited coil to the necessary commutating flux, the commutating pole brings the flux to the coil. From Eq. (18) it is evident that, to perform its function, the flux from the commutating pole must always be proportional to the armature current, and for this reason the commutating pole is excited by putting its winding in series with the armature. It is also so designed that up to fair overload it will not become saturated.

It should be noted that whereas the commutating pole neutralizes the M.M.F. of the armature in the immediate region where its flux enters and leaves the armature, complete neutralization of the armature M.M.F. is not possible by the use of commutating poles, inasmuch as the space distribution of the armature and commutating pole M.M.Fs. are entirely different.

In Fig. 39 is shown the flux distribution in a commutating pole machine for a given load. As the amount of flux from the commutating poles is proportional to the load, the flux distribution throughout the machine will be different for each load. It may be seen that the commutating poles do not prevent the flux from crowding into the main pole tips. This does practically no harm; the principal thing to obtain is the proper field for commutation in the turns short-circuited, which, for normal operation, should be directly under the commutating poles.

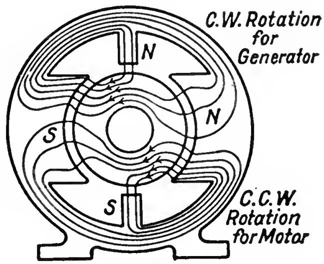


FIG. 39

In Fig. 40 the armature of a commutating pole generator is shown with the brushes in the proper position. Under the main and commutating poles voltages are generated in the various conductors, being indicated by dots and crosses inside the conductors. The currents the conductors are carrying under load are indicated by dots and crosses outside. A dot indicates a voltage or

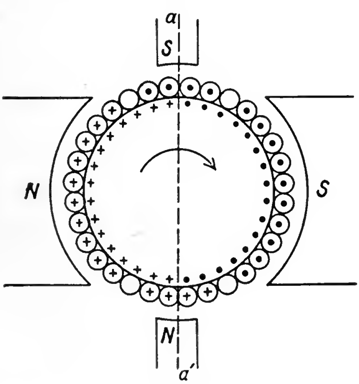


FIG. 40

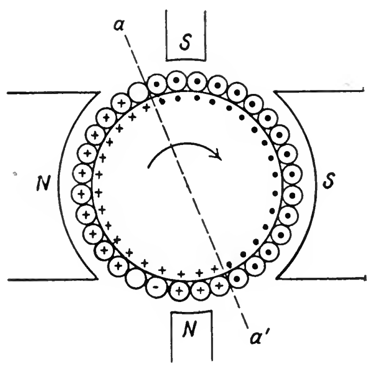


FIG. 41

current toward the observer. It is customary to make the width of the commutating poles slightly greater than the distance moved over by a slot while the coils in it are undergoing commutation. Even if voltages are induced under the commutating poles by conductors before and after they are short-circuited by the brushes, their effects neutralize. Whatever voltage is induced under a north commutating pole on one side of the line of brushes a,a', is equal and opposite to that induced under the south commutating pole.

If now the brushes are shifted backward in the generator, as indicated in Fig. 41, the effect is to cause a certain amount of compounding. One way of regarding it is that on the same side of the brush line there is a series field pole of the same polarity as the main pole. As load increases, the commutating pole is strengthened and the voltage tends to rise. A better way of considering the action is that the voltages induced under the commutating poles, are now no longer used to oppose the C.E.M.Fs. of self-induction in the short-circuited coil since shifting the brushes has moved this coil out from under the commutating pole. The voltages are then added to those induced under the main poles, causing more or less compounding depending on how far the short-circuited turn has been moved. Only a very slight forward shift of the brushes will change the amount of compounding of a generator to a considerable degree. The function of the commutating poles being to improve commutation brush shifting is never relied upon to effect compounding, for it is evident that if the brushes are shifted from the neutral point, commutation will suffer.

For a forward shift of the brushes the reverse takes place, for the voltages induced under the commutating poles will now be opposite to those induced under the main poles on the same side of the brush line and the voltage of the generator will fall off rapidly with load.

In commutating pole motors, shifting brushes affects the speed. In Figs. 42 and 43 are shown the armature of a shunt motor in which the direction of the C.E.M.Fs. is indicated by dots and crosses inside the conductors and the direction of the currents by dots and crosses outside. Whatever voltages are generated under the commutating poles when the brushes are shifted, will be added or subtracted from the C.E.M.Fs. generated under the main poles. In Fig. 42 the brushes are shifted forward, so that as load is added, more conductors generating C.E.M.F., the speed will fall more than that determined by the required IR drop. In other words, the machine has the speed characteristic of a compound motor. We may also regard the action as in the generator, as the addition of a series field on the same side of the brush line, the flux increasing with load. Or we may consider that the effective number of armature conductors has been increased (page 37).

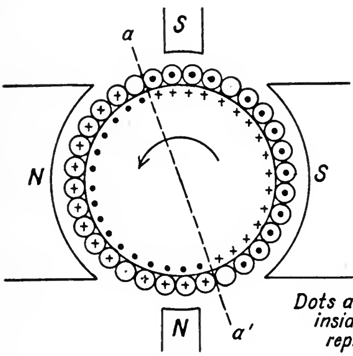
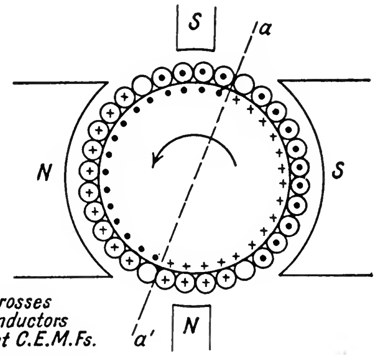


FIG. 42



Dots and Crosses inside conductors represent C.E.M.Fs.

FIG. 43

With a backward shift of the brushes (Fig. 43) a shunt motor will have the speed characteristic of a differential motor, the speed remaining nearly constant or even increasing with load. With any but a slight shift backward, particularly with weak fields, the motor is in a state of unstable equilibrium. If a sudden surge of armature current occurs, the effects of the commutating poles will cause considerable reduction of the C.E.M.F. which will cause further increase in the armature current. Meanwhile the speed will rapidly increase and the machine is apt to run away. The behavior under these conditions is analogous to the operation of compound generators in parallel without any equalizer connection.

It is therefore inadvisable to shift the brushes of commutating pole motors. Commutation will be impaired and if differential or compound speed characteristics are desired, it is better to obtain them by using series fields. Furthermore in the case of motors which are operated in either direction of rotation, if the brushes are not on the neutral point, the motors will have a different speed in one direction than in the other for the same load. In fact this is one method of determining the proper position for the brushes.

The use of commutating poles also makes possible the variation of the speed of a shunt motor through wide limits by field weakening. In the shunt motor without commutating poles, it was pointed out (page 36) that the practical limit to weakening the field is imposed by sparking at the brushes, due to the fact that with the weakened field, armature reaction is able to distort the field to such an extent that there is no commutating flux. We saw in Eq. (18) that so long as the commutating flux (ϕ_c), supplied now by the commutating poles, is proportional to the armature current, commutation will remain satisfactory. It was also stated that even though the main flux is distorted by the use of commutating poles, no great practical harm results. So as the speed is varied by field weakening, commutation will still remain good, for while the C.E.M.F. of self-induction increases as the time of commutation is reduced, the rate of cutting of the commutating flux is also increased by the higher speed.

There results the "adjustable speed" shunt motor, in which the speed is adjusted by shunt field current variation, the motor once adjusted having the speed characteristic of an ordinary shunt machine with variation of load. Adjustable speed motors are built for ranges of speed of from 2 to 1 to as high as 6 to 1. In a 4 to 1 speed motor the highest speed permissible is four times the lowest value. Such motors are usually provided with special starting rheostats which are a combination of an ordinary starting rheostat and a field rheostat.

A type of starting rheostat for an adjustable speed motor is shown in Fig. 44. A peg *B*, inserted into a flat metal disc *D*, is forced by the tension of a spiral spring at the pivot *P*, up against the main arm *C*, which in turn is forced up against the spring stop *S*. When arm *C* is grasped by the handle *H* and moved upward to the right, it pushes against peg *B*, forcing the disc *D* around. When arm *C* approaches the end of its travel, peg *B* comes up against a latch *L* rigidly attached to arm *E* which is pivoted at *V*. As *B* continues to move, it pushes arm *E* around so that it rotates in a counter-clockwise direction until the keeper *T* comes up against the no-voltage release *R*, which when excited holds the keeper *T*. While arm *E* rotated, the

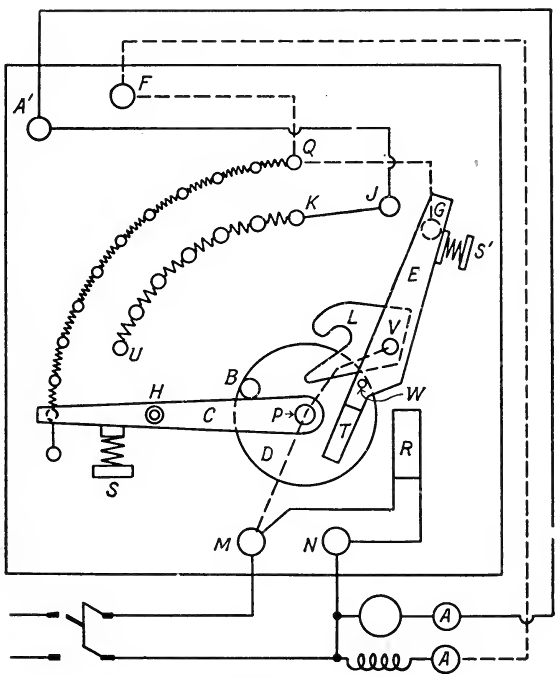


FIG. 44

finger of latch *L* swung around so as to grasp peg *B*, so that the no-voltage release also holds the disc *D* in position. Tension is now removed from arm *C* and it can be moved back and forth over the outer series of resistance buttons at will, remaining wherever left. Whenever the no-voltage release lets go, spring tension at pivot *V* and also at *P*, force arm *E* and the disc to rotate clockwise and counter-clockwise, respectively. In the course of its travel peg *B* strikes arm *C*, forcing it up against stop S. At the same time a second peg W comes up against the under side of latch L, forcing arm E against its stop S'.

When the main switch is closed the shunt field circuit is made, current flowing in at terminal M, to pivot P, pivot V, over arm E to button G, button Q, terminal F, through the field and back to the line. If arm C is now moved up to make contact with button U, current flows from pivot P to button U through the starting resistance to button K, to button J to terminal A' and through the armature. The motor having full field strength starts to rotate. As the arm continues upward, more and more of the starting resistance is cut out. When arm C pushes arm E around, it will be seen that E is now making contact with button J instead of G. The armature current will now flow from P to V, over arm E to J, the starting resistance being thereby short-circuited. Field current now flows over arm C to button Q and as arm C is moved backward over the outer series of buttons, more resistance is inserted into the field.

If the experiment is to be performed on a compound generator, determine its compound characteristic with its brushes in the proper position and also for a forward and a backward shift of the brushes. Also determine the external characteristic as a shunt generator with the brushes in the proper position and also with them shifted backwards. It is advisable that the amount of brush shift be determined by an instructor.

When performing the experiment on an adjustable speed motor, operate it with the commutating field properly connected and also with it reversed. Do this at a fairly high speed with about full load. With the commutating field correctly connected and the brushes properly set, make a brake test at the lowest speed for which the machine is intended, taking all data necessary to obtain its speed load characteristic and efficiency. Repeat in a second run starting at an intermediate speed and in a third run at the highest speed permissible. Have the brushes shifted forward by an instructor and make a fourth run starting at the same intermediate speed used in run 2. Have the brushes shifted backward by an instructor and make a fifth run starting again as in run 2.

Caution. Because of the possible danger that the machine may run away, it is advisable that each member of the squad knows how to quickly and conveniently shut the machine down if it starts to run away.

Curves. Plot on one sheet, curves of efficiency, speed and torque against horse-power output from the results of runs 1, 2 and 3. On a second sheet plot curves between speed and H.P. output from the results of runs 3, 4 and 5.

Conclusions. Explain how commutating poles improve commutation. What happens if the commutating pole winding is incorrectly connected? What is the result of shifting brushes in commutating pole machines? Why is it inadvisable to move the brushes of such machines from the proper neutral position? Can machines be designed to operate successfully with only half as many commutating poles as main poles? If in the parallel operation of generators equipped with commutating poles, one machine operates as a motor, is its commutating field properly connected for motor operation? Why? For what types of service are adjustable speed motors adapted?

EXPERIMENT XIII

Location of Faults in a Direct Current Motor or Generator. The location of the following faults in direct current motors and generators are to be investigated:

a. Open turn in armature.
b. Short-circuited turn in armature.
c. Ground in field windings.
d. Ground in armature winding.

a. Open Circuit in Armature. Commercial armature windings so far as commutator connections are concerned, are of two types. In large machines, separate commutator risers are em-

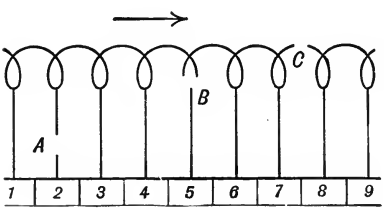


FIG. 45

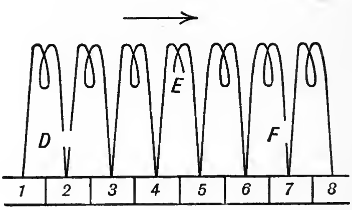


FIG. 46

ployed which are tapped into the winding at the outer periphery of the armature as in Fig. 45. In smaller machines the ends of the coils themselves are carried down into the commutator bars as in Fig. 46. In the first type of winding there are three ways in which the windings may open up. The commutator riser only may break as in *A*, a break may occur which both opens the winding proper and completely disconnects it from the riser as in *B*, or only the winding may open up, say at the back of the armature, as in *C*.

Break *A* will show no decided symptoms, if the brushes are wide enough to cover *more* than one commutator bar and the end of the broken commutator riser attached to the winding does not make contact with the risers on either side. If it does, a short-circuited turn results which will be treated later. If the brush does not cover more than one commutator bar, sparking will result, for it is evident that when the brush is entirely on bar 2 no current can pass to the winding. A moment before while the brush was still touching bar 3 (supposing the armature as moving from left to right), current was flowing, and this current is broken when the brush leaves bar 3. A pronounced arc occurs, due to the self-induction of the armature winding, which causes blackening and pitting of bar 3. In both cases *B* and *C* sparking will result. When in a bi-polar machine the break in the winding is between brushes, current flows around the other armature circuit, and when the break passes under a brush and is thus transferred to the other side of the armature a spark results, due to the breaking of the current and the self-induction of the winding. The spark will only occur when brush and bar 6 (case *B*) separate, causing this bar to blacken and pit.

In generators sparking and failure to generate are the important symptoms. In motors besides sparking there will also be found absence of proper starting torque under load or a tendency to turn over in a jerky manner.

A very simple method of locating an open armature coil is to connect several dry cells across the brushes. A voltmeter with a range somewhat greater than the open-circuit voltage of the cells is then successively touched to adjoining commutator bars. When touched to bars on the side of the armature, where the winding is not open, the voltmeter reading will be quite small, but on the side where the winding is open, the entire voltage of the cells will be found across the bars between which the break occurs.

The remedy for an open coil is to find it and close it by splicing in a piece of suitable wire. It is better, if time will allow, to put in an entirely new coil. Temporary repairs, however, can be made at the commutator by electrically connecting commutator bars 4, 5, and 6 (case *B*, Fig. 45), by soldering or screwing on a copper strap. Case *C* is repaired by joining bars 7 and 8.

The latter method of making a machine operative should only be used where it is absolutely necessary to keep it in operation, Proper repairs should be made at the first opportunity. Care must, however, be taken, not to short-circuit any of the other coils.

b. Short-circuited Coil. In both motors and generators a short-circuited armature coil will, as it rotates, cut the field flux and therefore generate voltage, which will cause a current to circulate in the coil. This current will prove excessive and if left flowing for any length of time will heat up and finally burn out the coil, the heated insulation giving out a bad odor. Due to the power expended in heating the coil a motor will draw a larger current and a generator require more driving power than usual.

A short-circuited coil is often easily located by feeling the armature all over, particularly at the back, after operating one or two minutes and noting the hottest coil. It may also be located at the commutator by the method given above for detecting an open coil, using dry cells and a voltmeter. It is evident that the resistance of a short-circuited coil is less than the resistance of a normal coil, so that the reading of the voltmeter across the commutator bars to which the short-circuited coil is attached will be very small.

To repair a short-circuit in an armature, first see whether the trouble is due to solder or copper dust between commutator bars or risers, in which case remove it. If the difficulty is in the coil itself, the best practice is to put in a new one. Temporary repairs may be made by opening the coil within the short-circuited portion and then bridging the commutator as for an open coil.

c and d. Grounds. A ground in a machine is defined as an electrical connection between the windings and the iron portion of the machine, that is, the frame, armature laminations, etc. They are due to worn or damaged insulation, so that the copper wires or conductors come in contact with the iron of the machine. It is evident that a ground may also be of high or low resistance, depending on how good the contact is between the windings and the iron.

If a machine is grounded it is essential that the ground be removed by finding it and repairing the worn or damaged insulation. While the machine is grounded, danger to the attendants exists, due to the liability of shocks, and if the system is grounded elsewhere, local heating with the attendant loss of power due to stray currents may result.

Tests for Grounds. In general, to tell whether a machine is grounded, a very simple test can be made. A voltmeter or an incandescent lamp is placed in series with a source of E.M.F. and the free ends applied, one to the frame or shaft of the machine and the other to one of the armature or field terminals. If the voltmeter deflects appreciably or the lamp lights up, a ground exists. The magnitude of the voltmeter deflection and the degree to which the lamp lights up will be an indication of the resistance of the ground circuit, for the greater the voltmeter deflection and the brighter the lamp, the less the resistance of the ground circuit.

This test is usually sufficient for field windings, inasmuch as grounds can occur only where the field spools touch the iron, so that the exact spot can usually be located by examination of the spool.

To locate the exact coil in an armature which is grounded the apparatus may be arranged as in Fig. 47. In this figure *A* and *B* are the brushes which are connected by a buzzer *S* or some other device which makes and breaks the current, in series with a battery. *T* is a telephone receiver, one end of which is permanently grounded. *G* is the ground which is to be located.

If the positive end of the battery is connected to brush *A*, then the latter will be at a higher potential than *B*, and since the difference in potential between *A* and *B* is applied to one-half of the winding, it follows that brush *A* is at higher potential than the ground *G*, and that the latter is similarly at higher potential than brush *B*. In general it is customary to consider the ground as being at zero potential, so that it follows that A is above the potential of the ground or at positive potential and B is below the ground potential or at negative potential.

If now the free end of the telephone receiver T is successively touched to each commutator bar in the upper half of the armature in Fig. 47, it will be silent or nearly so only when touched to the particular bars to which the grounded coil is connected. When touching any other commutator bar the telephone receiver will sound, owing to the pulsating current set up in it by the

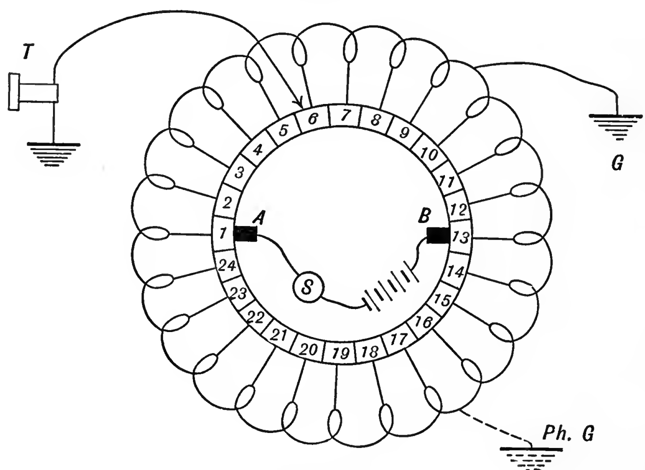


FIG. 47

pulsating difference of potential between the bar touched and the ground.

It will, however, be seen that the same difference of potential exists across the lower half of the winding, and since A is above and B is below the ground potential, a point will be found *in the lower half of the winding* (Fig. 47) which is at the same potential as the ground and at which the telephone will be silent. This point is called the phantom ground, Ph. G. Or with the telephone receiver tapped to bar 16, the difference in potential from bar 16 to brush B will be equal and opposite to that from bar 10 to brush B and the telephone will therefore be silent.

Two commutator bars have thus been found at which the telephone receiver is silent, one of these being the real and the other being the phantom ground. In order to distinguish between them, the armature is rotated a few degrees as in Fig. 48. The real ground must necessarily be found at the same place, but the phantom ground will now be located somewhere else, since the relative potential of A and B with respect to the ground is now different. In Fig. 47 the phantom ground is shown between bars 16 and 17 and in Fig. 48 between bars 1 and 24.

In multipolar machines the procedure is the same, except that the armature should be converted to a two-circuit winding. This is readily done by slipping paper between all the brushes and the

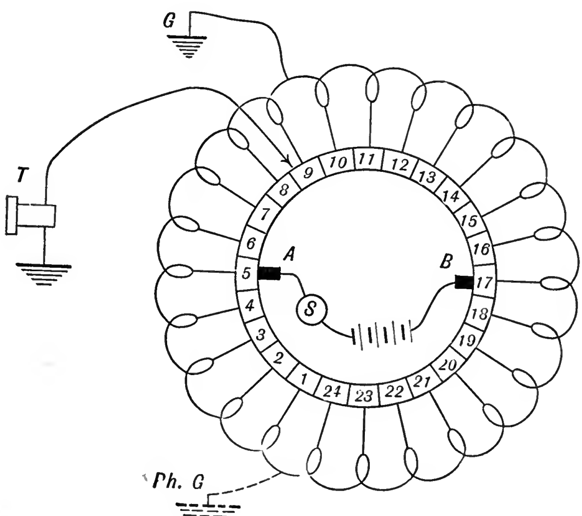


FIG. 48

commutator and slipping the leads from the battery between the paper and the commutator at two diametrically opposite sets of brushes.

Buzzer S may be omitted, in which case the free end of the telephone circuit must be tapped on the various bars. Each time a contact is made the telephone will sound. A voltmeter may also be substituted for the telephone receiver.

Method. First test the faulty machine for open armature coils by operating it as a motor with its shunt field separately excited and its armature in series with a lamp board. With a rather weak field, throw in enough lamps to make the armature rotate slowly. If sparking occurs and you consider it due to an open coil, locate the bars at which it occurs and verify by using the method outlined, using dry cells and a voltmeter. If an open coil exists, bridge the proper commutator bars after consulting an instructor. Then operate again for one minute, stop and examine the armature for a heated coil. Continue several times and make certain if a short-circuited turn exists by using the voltmeter and dry cells.

Finally test the fields and armature for grounds by the lamp or voltmeter method and if the armature is found to be grounded locate the commutator bars at which it exists.

Do not rip off any canvas covering or insulation in order to find just where the fault exists, unless specifically directed.

Conclusions. Explain what is meant by grounds, open and short-circuited armature coils. Give symptoms and remedies for them. What specific temporary repairs can be made for cases *D*, *E*, and *F* in Fig. 46? Explain why a phantom ground exists in Figs. 47 and 48.

EXPERIMENT XIV

The Direct Current Watt-hour Meter.—In connection with the supply and sale of electrical energy, it is necessary to have some form of meter which will record the total amount of energy used. Whereas power, the rate at which energy is delivered, is measured in watts or kilowatts, energy is measured in watt-hours or kilowatt-hours, the watt-hour being defined as the total or integrated amount of energy supplied in one hour to a circuit, in which the steady or average rate at which energy is expended is 1 watt. A kilowatt-hour is then 1000 watt-hours.

Watt-hour meters as they are properly called are often referred to as "integrating watt-meters." Although the meter does integrate the amount of energy supplied to a circuit over a period of time, the term "watt-hour" meter is preferred, as it indicates the unit in which the instrument registers. The term "recording watt-meter," as applied to a watt-hour meter is incorrect, as this term really indicates a meter which makes a continuous record by means of a pen or other device, of the instantaneous watts on a sheet of paper, film, etc., the same as a recording voltmeter or ammeter.

A watt-hour meter consists essentially of (1) a small electric motor so constructed that its torque is proportional to the power taken by the load, (2) a brake system, so designed that the opposing torque is proportional to the speed of the rotating shaft and (3) a system of gears with numbered dials for registering the number of revolutions of the motor shaft.

When the speed of the rotating shaft is steady the driving torque must be just equal to the retarding torque. With the driving torque proportional to the power taken by the load and the opposing torque of the brake system proportional to the speed of rotation of the shaft, the speed of the shaft is proportional to the driving torque and hence to the power. Therefore the total number of revolutions which the shaft makes during any interval is proportional to the total energy during this interval, whether the power is steady or variable. Or, each revolution of the shaft represents a certain number of watt-hours of electrical energy having passed through the meter.

There are two common types of direct current watt-hour meters. The more common, invented by Elihu Thompson, has for its driving element a motor having fields and an armature with a small commutator. The second type employs what is known as a mercury motor.

In the Thompson or "commutating" type of watt-hour meter, the fields of its driving motor are placed in series with the load and therefore carry the load current. Obviously these will be of very low resistance and as no iron is used in the construction of the motor, the flux set up by the field coils is directly proportional to the load current. The armature is placed directly across the line and its current, which is reduced to a very small value by the use of a high resistance, is directly proportional to the E.M.F. of the supply line. Since the torque generated by a motor is proportional to the product of field strength and armature current, we have in the watt-hour meter, that the torque of its motor is proportional to the power passing through the meter.

The total resistance of the armature circuit is about 2500 ohms for 110-voltmeters, about 5000 ohms for 220 voltmeters, etc. The resistance of the armature itself is about 1200 ohms for all voltages, so that about 1300 ohms resistance in series with the armature must be provided for 110 volt watt-hour meters, 3800 ohms for 220 volt meters, etc. Bearing in mind that no iron is employed in the construction of the driving motor, it is evident, with such high values of armature resistance and the very low values of armature speeds used (25 to 50 R.P.M. at full load), that the C.E.M.F. generated in the armature is insignificant, the entire voltage impressed being used up as IR drop. This can also be shown by test; the armature of a certain 5 ampere, 110 volt watt-hour meter was found to take

0.045 ampere with 110 volts impressed on its armature circuit and a load current of 5 amperes was passing through its fields. When the armature was blocked so that it could not rotate, no change in the armature current could be observed on the ammeter.

The loss of power in the potential circuit, from the values of resistance given, will be seen to be about 5 watts for 110 voltmeters, 10 watts for 220 voltmeters, etc. The loss of power in the current coils is about 5 watts for a 5-ampere meter and increases with the current capacity of the meter.

The brake system of all modern types of watt-hour meters consists of a disc of aluminum mounted on the armature spindle. One or more permanent magnets are so arranged that the disc rotates between their poles. As the disc rotates, eddy currents are generated in the disc, producing a drag on the disc. The strength of the eddy currents generated depends directly upon the speed of the disc, since the strength of the permanent magnets is constant, so that the force between the eddy currents and the field of the magnets, and hence the drag on the disc, is directly proportional to the speed.

In Fig. 49 is shown the general form of a direct current watt-hour meter of the commutator type. The armature A, made in spherical form, is mounted on a vertical steel spindle which is supported at the top by a guide bearing and at the bottom by either a pivot and jewel, or ball and jewel, bearing. In the first type of lower bearing, the spindle terminates in a pivot which is supported by a jewel, while in the latter a jewel attached to the lower end of the spindle rests on a steel ball which in turn is supported by a second jewel. The jewels used are selected sapphires and diamonds. The main fields, fixed in position, are designated FF and the disc D is shown at the bottom, rotating between the poles of the magnets MM. The potential circuit, shown in broken lines, starts at terminal x passes successively through the compensating field C (taken up later), the armature, the fixed resistance R and ends at terminal y. In some meters all the necessary resistance in series with the armature is contained in the compensating field and no extra fixed resistance R is necessary.

It is evident from the preceding description that a certain amount of friction, due to the brushes on the commutator, the gear train, and the bearings, is present and approximately independent of any variations of the load. Brush friction, which is

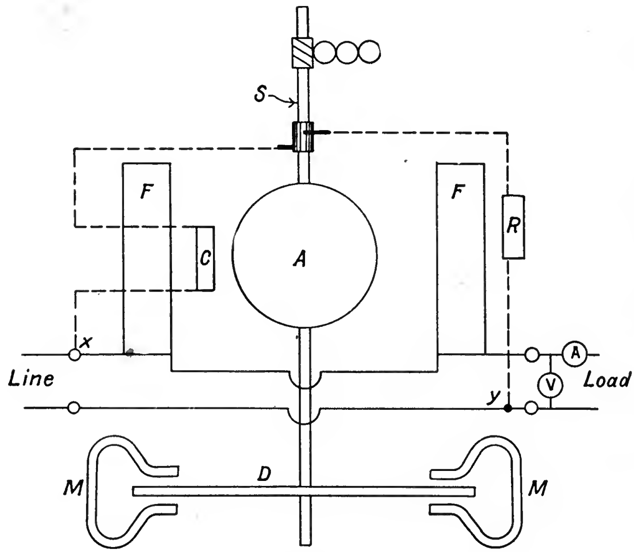


FIG. 49

more or less variable with time, is by far the most important. At light loads friction represents a larger percentage of the total driving torque than at heavy loads. It is thus desirable that the torque exerted by the driving motor be as high as practicable in order to reduce the percentage of driving torque necessary to overcome any change in friction. This results in a so-called "high torque" meter.

In order to reduce friction to a minimum, the commutator is made extremely small (about one-tenth inch in diameter) and in order that its surface remain smooth it is generally made of pure silver and the brushes silver-tipped to prevent oxidation.

To compensate for friction, all watt-hour meters have a compensating device, connected across the line so that the excitation is independent of the load on the meter. In the direct current commutator watt-hour meter, it consists of an auxiliary field coil, capable of being moved toward or away from the armature and clamped in the correct position. The strength of the compensating field is constant, but by varying its position with respect to the armature, enough of its flux passes through the armature to create a torque which will just balance friction, so that the meter is just on the point of starting at no load. Evidently if the compensating field is too close to the armature, more torque than necessary will result and the meter will "creep" or rotate slowly without any load current through its main fields, and for loads below 10 per cent, it will register "fast" or too high.

At higher loads the effect of the compensating field becomes more and more negligible compared to the main field and in order to control the speed of the disc under such loads, the position of the permanent magnets is changed. If they are moved in toward the center of the disc, the speed of the disc will increase for a given load, in order to maintain the same rate of cutting of the flux from the permanent magnets. If the magnets are moved out from the center of the disc, the reverse is true.

Several other factors affect the accuracy of watt-hour meters and their permanency of calibration. Variation of voltage will slightly affect the strength of the compensating field. Due to overloads and short-circuits, the magnetization of the permanents magnets is apt to be diminished, resulting in a fast meter. Wear of the bearings, brushes, commutator, etc., will cause the friction in a meter to change with time and vibration, vermin and possible corrosion due to dampness and fumes, are apt to interfere with its operation. It therefore becomes advisable to periodically inspect and test meters in order to keep them in proper condition. For meters in ordinary service, one or two routine tests per year is sufficient.

All modern watt-hour meters register in kilowatt-hours. In smaller sizes this reading is determined directly from the dials, while in the larger sizes a "dial" constant, usually some multiple of ten, must be applied to the dial reading to get kilowatt-hours. Dial constants are always clearly indicated.

In testing watt-hours the two common methods used are either a voltmeter and ammeter or a rotating standard watt-hour meter. In the former method a certain amount of power from a constant source of voltage is passed through the meter to be tested for a definite time and the number of revolutions of the meter counted in that time. The power is obtained from voltmeter and ammeter readings, the instruments being connected as in Fig. 49, and the time is determined by means of a stop-watch.

Since power is equal to watt-seconds per second or watt-hours times 3600 divided by seconds, we have that the average power as registered by the watt-hour meter is

$$P=\frac{RK3600}{t}, \qquad (19)$$

where R is the number of revolutions of the disc in t seconds and K, the meter "disc" constant, represents the watt-hours per revolution of the meter. In many types of meters, the disc constant is marked on the disc itself and usually expressed as above in watt-hours per revolution. Sometimes the constant is given in watt-seconds per revolution, in which case the term 3600 in the expression above is not necessary. In some direct current watt-hour meters made by the Westinghouse Electric and Manufacturing Co., the disc constant, expressed in watt-seconds per revolution, is obtained by multiplying the product of the rated voltage and current of the meter by 2.4.

The accuracy of the watt-hour meter under test is then the ratio (usually expressed in per cent) of the power as registered by the meter to the power as measured by the standard ammeter and voltmeter.

Whenever the load or voltage fluctuations are such as to make it difficult to average the ammeter and voltmeter readings or if only one tester is available, the ammeter-voltmeter method of testing is not used, a portable standard rotating watt-hour meter being substituted. In such a standard a finger, rotating over a dial, is attached directly to the spindle, the dial being readable to 0.01 revolution. With the current coils of the standard in series and its potential coils in parallel with those of the meter under test, it is only necessary to compare the number of revolutions made by the standard during a given time with the number made by the meter under test. The average powers indicated by the meter under test (t) and the standard (s) are

$$P_t = \frac{K_t N_t 3600}{t} \quad \text{and} \quad P_s = \frac{K_s N_s 3600}{t},$$

and the accuracy of the meter under test

$$\frac{P_t 100}{P_s} = \frac{K_t N_t 100}{K_s N_s}. \qquad (20)$$

In order that the disc constants of both meters be the same as often as possible, standard watt-hour meters are made with a number of different current and potential capacities.

Standard meters are started and stopped by either making and breaking the potential circuit or else throwing the register in and out of gear by an electrically operated clutch.

In the mercury flotation type of watt-hour meter, advantage is taken of the principle that when a pivoted metallic disc carrying current is placed under the influence of a magnetic field, the disc will rotate.

Fig. 50 shows the essentials of a direct current watt-hour meter of this type. A copper armature disc D, slotted radiallly to guide the current and supported on a spindle S, is enclosed in a suitable chamber B, made of moulded insulating material partially filled with mercury. Current is led in and out of the mercury chamber by means of the copper lugs L which are set diameterically opposite each other. The current passes from one lug through the comparatively high-resistance mercury to the edge of the low-resistance copper disc, across the disc to the mercury and out from the other lug. The field magnet *Y* is built up of steel laminations and carries the two windings *SW* and *CW*. The magnetic circuit is completed by the circular ring *Z* made up of steel ribbon and placed over the mercury chamber.

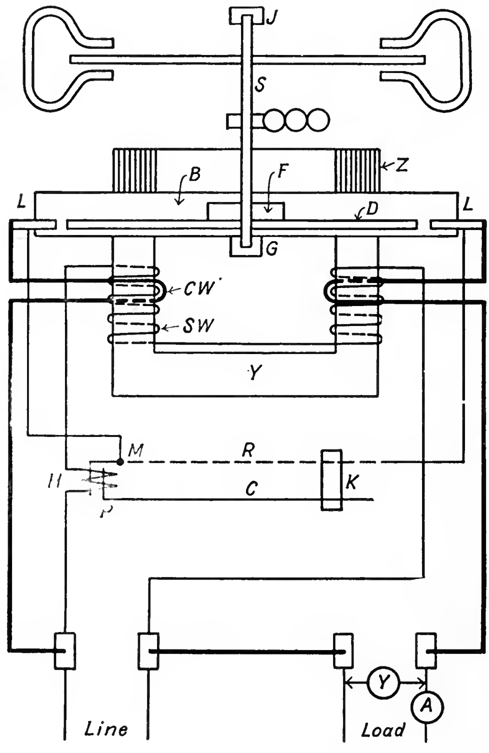


FIG. 50

At the top of Fig. 50 is shown the damping device which is the same as described before. By attaching a small float *F* of hard wood on top of the armature disc *B*, the entire moving system is given just a little excess buoyancy so as to exert a slight upward pressure against a jewel bearing *J* at the top, the spindle being kept in alignment by a guide bearing *G* at the bottom. Bearing friction is thus very much reduced.

The circuits of the meter are easy to follow. The potential circuit, taken from the line terminals, in most mercury watt-hour meters passes through a small heating unit of a thermo-couple and then around the field magnets. The current circuit is given one turn *CW* around each leg of the field magnets, in order to overcome the fluid friction of the mercury which increases with the speed of the armature disc. A compounding action with load thus results.

The light load adjustment in most mercury flotation watt-hour meters is obtained by the use of a thermo-couple *H* whose heating element is in series with the potential circuit. The two dissimilar metals of the thermo-couple generate a voltage across the points *M* and *P*, which is constant so long as the temperature of the heating element and therefore the line voltage is constant. Two rods *R* and *C*, joined electrically by a slider *K*, are used to make the necessary adjustment. Rod *R* is of resistance material and rod *C* is of copper. The current generated by the thermo-couple divides at *M*, part flowing through rod *R* to *K*, returning over rod *C* to *P*. The other portion of the current flows through the armature disc in the same direction as the load current, providing the necessary torque to overcome friction. By moving slider *K* to the right more of the resistance rod is put into circuit and more current flows through the armature disc, giving greater starting torque.

Another method of making the light load adjustment that is sometimes used, is to shunt some of the potential circuit current through the armature disc, the final adjustment being made by the use of two rods in a manner similar to that used in the thermo-couple method.

In most mercury watt-hour meters the position of the permanent magnets is fixed and in order to adjust the action of the retarding disc, magnetic shunts in proximity to the magnets are provided. By moving these closer to or farther from the magnets, more or less of the flux from the magnets is shunted away from the retarding disc.

The full-load drop through the armature disc of mercury watt-hour meters is so low that it is customary to build one standard meter for 10 amperes and to use external shunts for larger sizes. As a result the energy lost through the armature disc is comparatively low. The resistance and energy losses of the potential circuits is about the same as in commutator types. For meters below 130 volts the entire resistance of the potential circuit is in the field winding, extra resistance in series being added for higher voltages.

Connect the meter to be tested as shown in the text, using some suitable load. After applying potential, load circuit being open, see whether the meter has any creep. If it has, determine its rate. Then leaving the meter as found, determine its accuracy at 10, 50 and 100 per cent load, taking the time of a convenient number of revolutions for a period of about one minute. Take enough sets of readings for each load so that the per cent registration of three sets check within one per cent. Then reduce the load to 10 per cent and adjust the meter to within 2 per cent accuracy and do the same for 100 per cent load. After noting that the adjustment at light load is still within 2 per cent, determine the accuracy of the meter for loads of 10, 25, 50, 75, 100, 125 and 150 per cent loads. Record all readings as in Table XII.

TABLE XII

Make and type of meter.................. amperes.................... volts
Maker's meter number ....
Rated full load on meter during tests.................................. watts L.
Rate of creep........... revolutions in........... minutes......... seconds.
Disc constant K............... Testing constant $K_t = K \times 3600$..............

Volts.		Amperes.		True Watts	% Rated Load	Meter under Test.			
Observed.	True. A	Observed.	True. B	$A \times B = C$	$= 100\frac{C}{L}$.	Revs.	Secs.	Watts $W = \frac{K_t \times R}{S}$	%Registration $= 100\frac{W}{C}$

Curves. Plot a curve between per cent registration (ordinate) and per cent load from the results obtained after the meter was adjusted at light and full loads.

Conclusions. What characteristics should a watt-hour meter possess? Why are the light load and full load adjustments necessary? Which is the more important? Why? What would be the probable effect of dust, fumes, and vermin getting into a meter and what sort of a cover should a watt-hour meter therefore have? What appear to you to be the advantages and disadvantages of the two types of watt-hour meters described in the text? As the meters are connected in Figs. 49 and 50 and disregarding the accuracy of the meters, who is charged with the losses in the potential and current circuits of the meters? If the meter had any creep at the start of the test, calculate what it would cost the customer per day at ten cents per kilowatt-hour.

EXPERIMENT XV

The Lead Storage Battery.—Storage batteries are classified according to their electrolytes, as "acid" or "alkaline." The former include all of the so-called lead cells and the latter is represented by one commercial type, the "iron-nickel" or Edison cell. This experiment is intended to give the student some knowledge of the handling of a lead cell and understanding of what occurs within a cell as it is put through a cycle of discharge and charge.

A storage battery when charged comprises lead grid positive plates carrying active material of lead peroxide (dark brown in color) and lead grid negative plates with active material of sponge lead (dark slate in color) and an electrolyte of sulphuric acid varying in density from 1.23 to 1.3 depending upon its purpose.

Neither sponge lead nor lead peroxide possesses strength, rigidity or high conductivity. Mechanical considerations require the first two and the latter is necessary to conduct the current away efficiently. Therefore the finely divided and porous lead and lead peroxide are held in suitable grids which are a rigid framework or plate of lead or an alloy of lead and antimony.

When the electrodes are in condition to furnish current, the battery is said to be charged. The process of giving out current is called discharge, during which some of the active material of both plates changes to lead sulphate, the plates becoming lighter in color. The electro-motive force of the battery also gradually falls and the density of the electrolyte decreases. After the battery has furnished such an amount of energy as to bring its E.M.F. down to a predetermined value, the battery is said to be discharged. Charging is the process whereby current is sent through the cell from an outside source in a direction opposite to the flow on discharge, thereby changing the exhausted active material back to its original useful condition.

The chemical changes taking place during discharge may be represented by the following equations. When read from left to right they represent discharge and from right to left, the reactions of charging are shown. The reactions at the positive plate are,

$$PbO_2 + H_2SO_4 = PbSO_4 + H_2O + O, \quad . \quad . \quad . \quad (21)$$

and at the negative plate,

$$Pb + H_2SO_4 = PbSO_4 + H_2. \quad . \quad . \quad . \quad (22)$$

Combining we may write for the whole cell,

$$PbO_2 + Pb + 2H_2SO_4 = 2PbSO_4 + H_2O. \quad . \quad . \quad (23)$$

The capacity of a storage battery is stated either in ampere-hours or watt-hours. The latter is naturally more important as it takes into account not only the current capacity but also the cell voltage. The ampere-hour capacity of a cell can usually be approximated by assuming that from 20 to 25 square inches of positive plate surface (both sides), with plates $\frac{1}{8}$ inch thick will give 1 ampere for eight hours or eight ampere-hours at an eight-hour rate of discharge. For other thicknesses, the capacity varies as the square root of the plate thickness. Although the theoretical weights of lead peroxide and of sponge lead are respectively 0.156 and 0.137 ounce per ampere-hour capacity, in practice it is usual to allow from 2.5 to 3 times these weights. This is done to allow for the lack of porosity and gradual scaling and shedding of the active materials. Since the negative plates do not retain their capacity as well as the positives, there is generally one more negative than positive plates in a battery.

From the equations given it is evident that on discharge the density of the electrolyte will fall and lead sulphate be formed. Pure lead sulphate, when isolated, is white in color, has such high resistance as to be practically an insulator and has greater volume than that of the lead or lead peroxide from which it is formed.

If an excessive quantity of lead sulphate is allowed to form by discharging a cell beyond some safe limit, the plates may be injured. The excessive volume of sulphate will tend to cause warping and cracking of the plates and loosening of the active material. Lead sulphate which forms on the plates during discharge is readily reducible by current, so that, if soon after a cell is discharged it is put on charge, no trouble results. But if a discharged cell is allowed to stand idle for any time, the sulphate apparently changes its nature, becoming dense and inactive, so that recharging will not readily reduce it. The formation of this insoluble sulphate is called sulphation and if it has not gone too far, the plates may be cleared by overcharging the battery for a long time. When a battery is fully charged further passage of current will cause electrolysis of the water and the cell is said to be gassing. The liberation of oxygen and hydrogen thus formed tends to tear off the insoluble sulphate.

The open circuit E.M.F. of a cell falls somewhat with decrease of density of the electrolyte and temperature and is also dependent upon the character of the active material. When fully charged the open-circuit voltage of a cell is about 2.20 volts. While being discharged the voltage falls more or less rapidly during the first fifteen minutes, then much more slowly until the cell is nearly discharged, when it again falls rapidly. The decrease in voltage is largely caused by the formation of lead sulphate and increase in resistance. At first the chemical action takes place largely on the surface of the plates, the resulting formation of sulphate tending to close up the pores in the active material. As discharge continues the electrolyte occluded in the pores gives up its constituents, becoming water, and as new electrolyte cannot diffuse into the pores the cell becomes discharged. However, on standing, as electrolyte slowly works its way into the pores, the battery recovers somewhat and will have some residual charge.

From what has been said it is evident that the ampere-hour capacity of a cell will decrease as the rate of discharge is increased.

Approximate values of capacity for different rates of discharge are given in the following table:

Hours Rate of Discharge.	Ampere-hour Capacity in Per Cent of Eight Hour Rate Capacity.
1	55
2	70
3	80
4	88
5	93
8	100
12	110

From the foregoing table it is necessary to adopt some standard rate to fix the capacity of a cell and this is usually taken as the eight-hour rate. Thus an 80 ampere-hour battery is one which will furnish 10 amperes continuously for eight hours. However, practice demands in many cases rates of discharge different from the eight-hour rate and the capacity of batteries is often stated at other rates.

The limiting terminal voltage to which a cell may safely be allowed to fall on discharge also varies with the rate, being lower at high rates than on low ones. In the absence of data from the manufacturer the limiting terminal voltage (corresponding to the T hour rate of discharge) may be taken from the expression,

$$E=1.56+0.0175T, \qquad (24)$$

where T = hours rate of discharge as in the above table.

Every cell has internal resistance which is also a variable, causing an internal IR drop within the cell upon the passage of current. On discharge this subtracts from the E.M.F. of the cell, causing a lower terminal or closed circuit voltage and the reverse on charge. The resistance of a cell is increased by polarization on charge and with the formation of lead sulphate on discharge.

The density of the electrolyte in a fully charged battery should be from 1.23 to 1.3 and when the cell is fully discharged should have fallen about 0.1 in specific gravity.

Whereas a battery may be discharged at high rates, it is not advisable to charge it too rapidly. Good practice starts charging at a five- or eight-hour rate which is tapered off as the cell approaches full charge and starts to gas. As the time allowed for laboratory work is generally much less than this, the battery may be charged at higher rates. It must, however, be remembered that this is not the best practice. During charging the E.M.F. of a cell rises rapidly at first, then remains nearly constant for a period and again rises rapidly where the battery approaches full charge. The curve is thus the opposite of that on discharge.

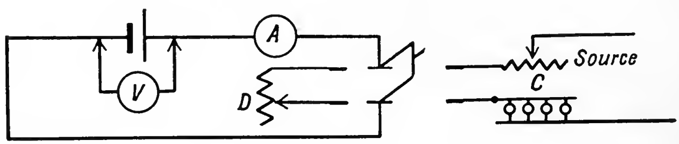


FIG. 51

The cell connections for battery tests are as given in Fig. 51. With the switch thrown to the left the cell can be discharged through the adjustable resistance *D*. To charge the cell the switch is thrown to the right and the rate of charge controlled by means of the lamp board and the adjustable resistance *C*.

Two batteries are to be tested in this experiment, one under charge and another under discharge. The battery to be charged is connected as in Fig. 51, using a carbon rheostat and a lamp board in series with the 110-volt line. Charge the battery at about a two and one-half hour rate, maintaining this rate constant by means of the adjustable rheostat *C*. Readings of open- and closed-circuit voltage, specific gravity by hydrometer and temperature are to be taken every three minutes for the first fifteen minutes or until conditions steady down. After that, readings may be taken at longer intervals until near the end of the run when, conditions again changing rapidly, three-minute readings must be taken. Continue charging until the terminal voltage and specific gravity remain constant for several readings.

After the battery to be charged has been charging for ten or fifteen minutes, start the second cell on discharge at the two-hour rate, maintaining this rate by means of a carbon rheostat. The same readings are to be taken at similar intervals as above. Continue discharge until the open-circuit voltage falls to a value as calculated from Eq. (24).

Curves. Plot curves for each cell on separate sheets, plotting elapsed time values as abscissas against open- and closed-circuit volts, specific gravity, temperature and resistance. The latter is determined by dividing the difference between open- and closed-circuit voltages by the current.

Conclusions. Explain why the curves come out as they do. Why does the terminal voltage of a cell fall on discharge? Why should a lead battery not be completely discharged? What factors influence the life of a battery? A battery is to be made up of cells such as you tested to furnish 100 amperes at 125 volts. How many cells would be necessary and how would you arrange them?

EXPERIMENT XVI

Illumination Laws and Measurements.—The unit of intensity of a light source is the candle-power, and represents a measure of the light flux or luminous energy radiated by the source. Formerly, this unit was defined as the horizontal intensity of light emitted from a specified candle (British standard candle) but due to the greater permanence and reproduceability of the incandescent lamp, the standard is now maintained in tested incandescent lamps at the Bureau of Standards, Washington, as well as at other laboratories. The international candle (the standard in Great Britain, France, and the United States) is in general use to-day, and is 1.6 per cent less than the British candle referred to above.

The unit of illumination is the foot-candle, and is defined as the illumination on a plane 1 foot distant from a source of

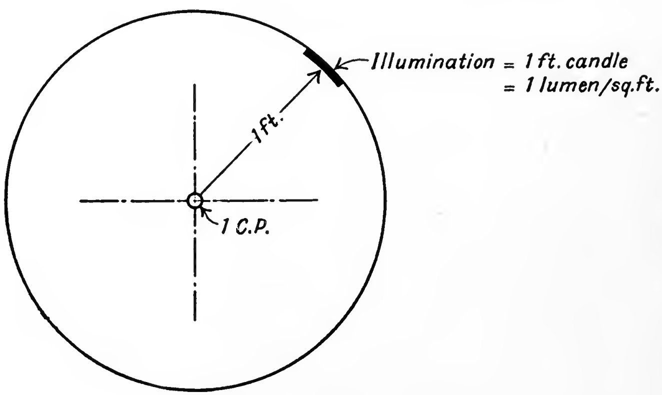


Fig. 52

light having an intensity equal to 1 candle-power, the plane being normal to the direction of the incident light flux at all points. Thus, considering a sphere of 1 foot radius (Fig. 52) with a light source placed at its center having an intensity of 1 candle-power in all directions, the illumination at all points on the surrounding sphere will be 1 foot-candle.

In discussing illumination, it is helpful and convenient to consider the luminous energy radiation as a flux emanating from the light source. The amount of such flux is expressed in lumens, an illumination of 1 foot-candle being produced by 1 lumen per square foot, or

1 foot-candle = 1 lumen per square foot.

Referring to Fig. 52, it is evident that, since the area of the surrounding sphere is $4\pi r^2$ or 4π square feet, and the illumination produced is 1 foot-candle or 1 lumen per square foot, the total flux emitted is 4π lumens. It follows that

$$\text{Light flux (in lumens)} = 4\pi CP \quad . \quad . \quad . \quad . \quad (25)$$

where CP represents the mean spherical candle power of the source.

Similarly, on a sphere of radius $2r$ or 2 feet, the illumination would equal

$$\frac{4\pi CP}{4\pi(2)^2} \quad \text{or} \quad \frac{CP}{4} \quad \text{(in ft.-candles or lumens per square foot).}$$

From the above, it may be seen that

$$\text{Illumination (on plane normal to incident light flux)} = \frac{CP}{d^2} \quad (26)$$

(where d is in feet).

This is known as the "inverse square" law, and holds for all cases where the maximum dimension of the light sources does not exceed $0.1d$, the distance between the source and the illuminated plane.

In case the illuminated plane is not normal to the incident light (Fig. 53), it may be readily shown that:

$$\text{Illumination on horizontal plane} = \frac{CP}{H^2}\cos^3\alpha. \quad . \quad . \quad (27)$$

This relation is known as the "cosine" law, or Lambert's law, and it is of great use in calculating floor illumination, etc.

The light radiated by incandescent lamps is far from being uniform in all directions, as shown by the distribution curves of a standard type of lamp (Fig. 54).

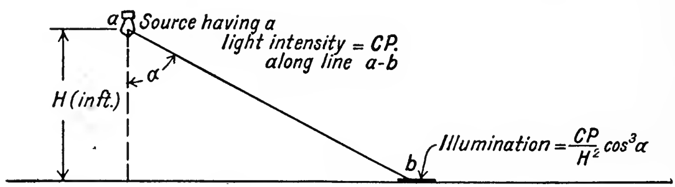
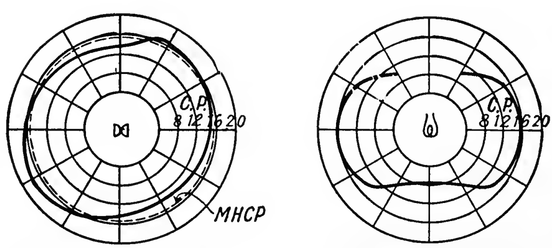


Fig. 53

The candle-power of an incandescent lamp has, therefore, no meaning unless it is clearly defined, thus: mean horizontal candle-power (M.H.C.P.) represents the average intensity in the horizontal plane (Fig. 54*a*); mean spherical candle-power



(a) Horizontal Distribution. (b) Vertical Distribution

Fig. 54

(M.S.C.P.) represents the average intensity in all directions, and is the value which must be used in Eq. (25). Mean upper hemispherical candle-power (M.U.H.C.P.) and mean lower hemispherical candle-power (M.L.H.C.P.) are also used. Where the mean hemispherical candle-power is discussed, without specifying which hemisphere is referred to, the lower is usually the one considered.

The M.H.C.P. is readily determined, whereas the determination of M.S.C.P. requires a rather lengthy investigation unless an integrating sphere is used. The two values are related by the "reduction factor," thus

$$\text{Reduction Factor} = \frac{\text{M.S.C.P.}}{\text{M.H.C.P.}} \quad . \quad . \quad . \quad . \quad . \qquad (28)$$

Therefore, with the reduction factor known for a certain type of lamp, the measurement of M.H.C.P. also permits the determination of M.S.C.P.

The integrating sphere is a convenient device which may be used to determine the M.S.C.P. If a light source is placed at the center of a hollow sphere, the illumination, due to reflected light, on the interior surface is directly proportional to the total light flux emitted by the source. By measuring the illumination on this surface, a measure of the total flux (and thus M.S.C.P.) is obtained. A screen is interposed between the light source and the point of measurement to eliminate the effect of direct illumination. The sphere must first be calibrated, using a light source whose M.S.C.P. is known.

The determination of illumination requires an instrument of light, rugged construction which may be readily carried by the observer to the different locations where measurements are required. The Macbeth Illuminometer, the General Electric Foot-candle meter, and the Sharp-Millar photometer, fulfill this requirement, and are representative of this type of instrument. Only the first two mentioned will be considered in this study.

(*a*) *Macbeth Illuminometer.*—The instrument is comprised of three elements, as shown in Fig. 55, namely, the illuminometer, controller, and primary standard.

The operation of the instrument is briefly as follows: the working standard in the illuminometer is first calibrated against the primary standard by placing the latter on the test plate (a white diffusing surface) and sighting with the illuminometer into the aperture *D*. The current through the primary standard is then adjusted to the value specified in the certificate furnished with the instrument to give 3 foot-candles; also the rachet illuminometer bar is set to a scale reading of 3 foot-candles.

The current through the working standard is next adjusted until equality of illumination is secured, and this value is used in all subsequent determinations. The arrangement of the controller permits the reading of current through either the primary standard or working standard.

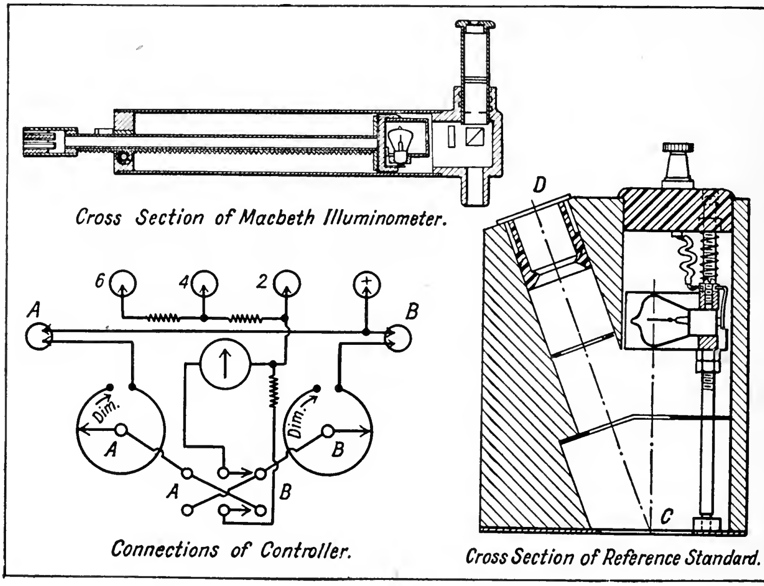
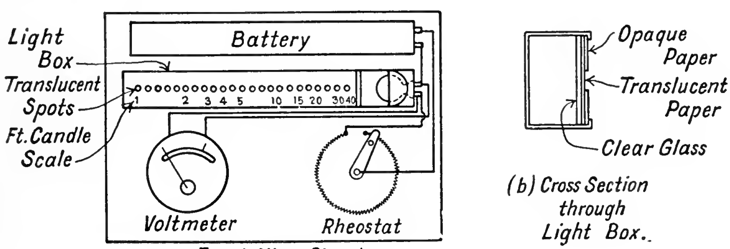


FIG. 55

After calibration, the primary standard should be disconnected from the controller, and replaced in the instrument case. The test plate is then placed at any point where the illumination is desired and, after adjusting the lamp current to the calibration value, the illuminometer is sighted on the test plate, taking care that no shadows are thrown on the test plates. The illuminometer should be held about 5 feet from the test plate in such a position that the angle between the axis of the telescope and sighting aperture and the normal to the test plate does not exceed about 40°. The position of the rachet bar (and thus the position of the standard lamp) is varied until the two illuminations of the screen equalize. The reading on the rachet bar scale then indicates directly the illumination in foot candles. The action of the illuminometer itself is similar to that of the ordinary photometer bench, with structural modifications required by the service for which it is intended.

(*b*) *G. E. Foot-candle Meter.*—This instrument, illustrated in Fig. 56, is somewhat more simple and compact in its construction than the Macbeth type previously described. It is based on the fact that if a screen of opaque paper, with a translucent grease spot at its center, be equally illumined on both sides, the grease spot will disappear and so indicate equalization. If the light on one side is increased or decreased, the grease spot



(a) Front View Showing Internal Arrangement.

(b) Cross Section through Light Box.

FIG. 56

will appear darker or lighter, respectively, than the surrounding paper.

The row of greased paper spots (Fig. 56) are illumined from within by the working standard, while the illumination on the front surface is unknown, and the value is to be determined. The working standard lamp, being placed at one end of the row, gives unequal illumination to the different spots, those nearest the lamp receiving the greatest illumination.

Underneath the row of spots is a foot-candle scale. Thus, the reading underneath the spot which disappears gives at once the illumination on the front surface of the opaque sheet. A rheostat and voltmeter are used to adjust the current through the lamp to its calibration value.

If the illumination (in lumens per square foot) be determined for a number of squares marked off in a room, the summation of the products of each area multiplied by its illumination gives the total illumination effective at the reference plane, or

$$\text{Lumens effective} = \Sigma \text{ Illumination of Square} \times \text{Area of square.}$$

Knowing the total lumens emitted by the lighting installation the "utilization constant" may be at once determined, where

$$\text{Utilization Constant} = \frac{\text{Total lumens effective at reference plane}}{\text{Total lumens emitted}}.$$

The utilization factor is a measure of the overall efficiency of the installation and varies from 65 per cent to 10 per cent, depending on the type of reflectors used (if any) and the color of the ceiling and walls.

The tests to be carried out are as follows:

(*a*) Determine the M.H.C.P. and efficiency $\left(\frac{\text{M.H.C.P.}}{\text{watts}}\right)$ of a carbon, Mazda *B* (vacuum), and Mazda *C* (gas-filled) incandescent lamp, using the photometer bench and connections indicated in Fig. 57. A calibrated standard lamp will be available for these tests.

(*b*) Using the Macbeth Illuminometer and General Electric Foot-candle meter, determine the utilization constant of a typical lighting installation.

(*c*) Check the calibration of the working standard of the Macbeth Illuminometer against the standard lamp used in (*a*). This determination should check, within 3 per cent, the value of 3 foot-candles previously obtained against the primary standard.

(*d*) Using the Macbeth Illuminometer and the integrating sphere, determine the M.S.C.P. of the four lamps tested in (*a*). Calculate the reduction factor for each lamp.

Conclusions. 1. In a photometer, arranged as in Fig. 57 the standard lamp is 134 cms. from the screen and the test lamp is 158 cms. from the screen, when balanced. If the standard lamp is 20 cp., and the reduction factor of the

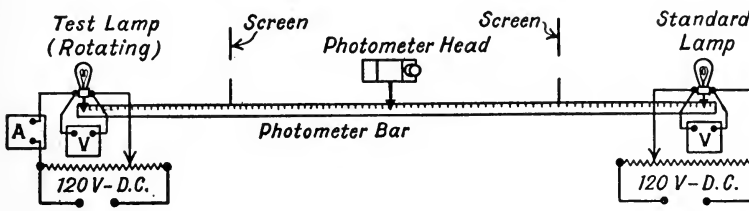


FIG. 57

test lamp is 78 per cent, what is the M.S.C.P. of the test lamp?

2. In a 20×30-ft. room, there are four 20 c.-p. (M.S.C.P.) incandescent lamps symmetrically arranged as indicated in Fig. 58. What is the illumination at centers of squares marked *a* and *b*? What is the utilization constant of the installation? Lamps are each 8 ft. above the floor. Assume no reflection from side walls or ceiling.

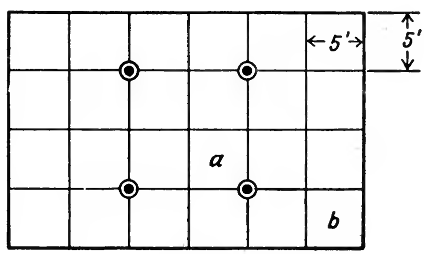


FIG. 58

3. Compare the illuminometer and the foot-candle meter with reference to

1. Cost of construction.
2. Accuracy.
3. Simplicity and ease of operation.
4. Liability to trouble.
5. Calibration.

LIST OF A. C. EXPERIMENTS

1. Wave Shape, Power and Power Factor, Effective Values.
2. Properties of the Alternating Current Circuit.
3. The Alternator; its Characteristics on Non-inductive and Inductive Load; Prediction of External Characteristic.
4. The Transformer; Operation and Characteristic Curves; Measurement of Losses and Prediction of Efficiency.
5. The Induction Motor; Its Operating Characteristics with and Without Added Rotor Resistances.
6. The Synchronous Motor; Synchronizing and Phase Characteristics.
7. The Synchronous Converter; Effect of Speed and Voltage upon Ratio; Operating Characteristics.
8. Parallel Operation of Alternators; Distribution of Load; Circulating Current, etc.
9. Three-phase Circuits; Current and Voltage Relations; Measurement of Power.
10. Single-phase Motors; Induction, Repulsion-induction, and Series.
11. The Alternating-current Watt-hour Meter.

TESTING OF ELECTRICAL MACHINERY

ALTERNATING CURRENT TESTS

EXPERIMENT I

Wave Shape, Effective Values, Power and Power Factor. An alternating current is one which periodically changes its direction of flow. The frequency (number of cycles or periods per second) depends upon the class of service for which the alternating current power is to be used. In alternating current railway motors a frequency of 15 or 25 is employed; for illumination, arc and incandescent lamps, a frequency of 60 is standard; telephone currents are made up of many superimposed frequencies, ranging from perhaps 100 to 1500; for wireless telegraphy and telephony the frequency may be between 20,000 and several hundred thousand; two small metallic spheres charged with electricity of opposite kinds will, if brought close enough together, exchange and neutralize charges; the discharge current is oscillatory in character and may be of a frequency of several billions of cycles per second.

Generally an alternating current is sinusoidal in form.

If i = instantaneous value of current;
I_{max} = maximum value of current;
$p = 2\pi \times$ frequency of current;
we have

$$i = I_{max} \cos pt.$$

An alternating current generator is generally designed so that its wave form may be expressed by the formula

$$e = E_{max} \cos pt.$$

Whether or not a generator gives such a wave form depends upon the shape of the air gap between armature and pole face and also upon the distribution of armature winding.

Whenever a sine wave of E.M.F. is applied to a circuit, the current which is caused to flow is also a sine wave (neglecting distorting effects of hysteresis, variation in permeability, dielectric loss in condensers, etc.). If the circuit is non-inductive the E.M.F. and current waves are in phase, i.e., the maximum and minimum values of the two waves occur simultaneously. If, however, the circuit offers inductance or capacity reaction, or both, the current may either lag or lead the E.M.F. in phase, depending upon which reaction predominates. These reactions are more fully analyzed in the discussion of Ex. 2.

The question arises how much power is used in a circuit in which an alternating current is flowing? The reactions which are offered to the flow of the current are of two general types, conservative or non-dissipative, and non-conservative or dissipative.

The product of the current into the dissipative reaction gives the rate at which power is being used in the circuit; the conservative reaction causes no energy loss.

If a weight suspended from a spiral spring is forced to vibrate at its natural frequency, with constant amplitude, the only force required will be that necessary to overcome the frictional resistance of the moving system. The other reactions in the system as shown to exist by the stretching of the spring (to a much greater degree than the impressed force could directly bring about) are the conservative reactions of the system; they are the forces represented by the stretching of the spring and the change in momentum of the moving weight. The power which is expended in maintaining constant amplitude of oscillation of the weight is equal to the product of the velocity of the weight into the frictional resistance of the system.

The rate at which energy is dissipated from an electrical circuit is equal, in the same way, to the product of the current into the total dissipative reaction in the system.

If i = instantaneous value of current,
R = effective resistance (see Ex. 2) of circuit, then the dissipative reaction at any instant $= iR$, and the rate at which energy is being used is equal to $i \times iR = i^2R$.

As this rate varies throughout the cycle it is necessary to get the average rate at which the power is used.

$$\text{Average power} = \frac{1}{\pi}\int_0^\pi i^2R\, dt.$$

Now if $i = I_{max} \cos pt$,

$$\text{average power} = \frac{I^2_{max}R}{\pi}\int_0^\pi \cos^2 pt\, d(pt) = \frac{I^2_{max}}{2}R.$$

Now if a direct current is passed through the same resistance the rate at which energy is dissipated is given by the formula:

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

If the alternating current is varied in amplitude until it is supplying the same amount of power as is the direct current, we have

$$I^2R = \frac{I^2_{max}}{2}R,$$

or

$$I = \frac{I_{max}}{\sqrt{2}},$$

and this is called the *effective* value of the alternating current. It equals 0.707 of the maximum value. By the same line of reasoning the *effective* value of voltage of a sinusoidal alternating E.M.F. is equal to 0.707 the maximum value. A.C. ammeters and voltmeters are always calibrated to read *effective values*.

It is to be noticed that if the wave of current or E.M.F. is not sinusoidal, the previous integration is not so simple, but involves a number of terms of a Fourier series. The effective value of such wave is not equal to 0.707 the maximum value, but varies with the wave shape. For this reason all standard tests on alternating current apparatus must be carried out with sinusoidal wave forms; otherwise inaccuracies are likely to occur.

It has been mentioned that if conservative reactions occur in a circuit the current and voltage will not generally be in the same phase. The dissipative reaction is equal to that component of the impressed force which is in phase with the current.

If ϕ = angular difference in phase of current and impressed E.M.F.;

$E_{max} \cos \phi$ = maximum value of dissipative reaction;

$\frac{E_{max} \cos \phi}{\sqrt{2}}$ = effective value of dissipative reaction.

If I = effective value of current;

$$\text{Power supplied} = \frac{IE_{max} \cos \phi}{\sqrt{2}};$$

$$= IE \cos \phi;$$

where $E = \frac{E_{max}}{\sqrt{2}}$ = effective value of impressed E.M.F.

It is therefore evident that the product of E and I as obtained from A.C. meters does not generally represent the power used in a circuit. It is necessary to know $\cos \phi$ to obtain true watts. The product EI is sometimes called "apparent watts" in distinction to $EI \cos \phi$, the true power of the circuit in watts.

This quantity, $\cos \phi$, is extremely important in all alternating-current work. It is called the *power factor* of the circuit and is that quantity by which the volt-amperes of the circuit must be multiplied to give the power, in watts, in the circuit.

If we have some method of actually plotting the waves of current and E.M.F. in a circuit, in proper magnitude and phase, the power $EI \cos \phi$, could be immediately obtained. E and I are calculated by multiplying the maximum values of the respective waves by 0.707; ϕ is measured as the angular distance between two corresponding points, say the zero points, of the two waves, remembering that a complete cycle represents 360°.

Generally it would be inconvenient and slow to use such a method, so a wattmeter is used. This instrument has two coils, one of low resistance and comparatively large cross-section and the other of very fine wire, of high resistance; it is connected to the circuit, in which the power is to be measured, as though an ammeter and voltmeter were in the same case; the two coils are so placed in relation to one another and the scale is so calibrated that the reading of the instrument is actually equal to $EI \cos \phi$. The current coil of the instrument is placed in series with the circuit the power of which it is desired to measure, and the potential coil is connected in parallel with the circuit. Unlike the A.C. ammeter and voltmeter, which cannot be so connected to an A.C. circuit that the needle is deflected backward, the wattmeter may deflect backward with a wrong connection. The connection of either the current or potential coil must be reversed in such case.

It is the object of this experiment to plot curves of E.M.F. and current in an inductive circuit, in their proper phase and magnitude, and to measure with A.C. meters the E.M.F., current, and power of the circuit in order to verify the previously stated facts regarding effective values, power, cos ϕ, etc.

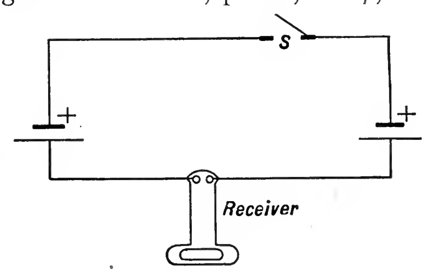


FIG. 1

The method to be employed is commonly called that of "instantaneous contact." It may be easily explained by reference to a direct current circuit. In Fig. 1 are shown two cells and a telephone receiver (any other sensitive current indicator would work as well as a telephone receiver). When switch S is closed no current will flow provided that the two E.M.F.'s in the circuit are opposite and just equal. If, however, the two E.M.F.'s are not equal and opposed, current will flow every time the switch is closed. If the switch is closed and opened at regular, short, intervals of time a more or less musical note will be heard in the telephone receiver. Suppose now this principle is applied to an alternator as shown in Fig. 2. On the same shaft with the alternator armature C, is mounted a disc of some insulating material. A metal strip H, inserted in the disc, reaches to the periphery and is connected at its inner end to a small conducting drum and so to brush F. A brush E rests on the periphery of the disc and is insulated from the alternator frame. It will be noticed that this combination of brushes, metal strip, and insulating disc is nothing but a rotating switch, the two brushes F and E being connected together once for each revolution of the armature; moreover, whenever this contact is made, the armature occupies the same position in the field. Now the E.M.F. wave generated by the revolving armature has the same value every time the armature occupies the same posi-

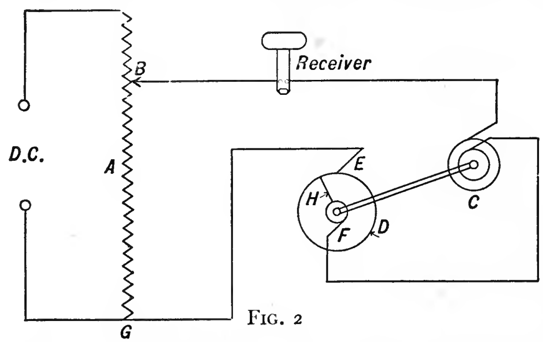


FIG. 2

tion in its field; in other words, every time the brushes F and E are connected together the instantaneous value of the E.M.F. is the same.

A variable resistance A, connected to a supply of constant voltage, serves as a source of variable potential difference; by the sliding contact B, the P.D. between G and B may be made anything desired. The local circuit, $BAGEFC$, is exactly similar in its make up to that of Fig. 1, except that the two E.M.F.'s are varying. The rotating switch closes the local circuit at the same point on successive E.M.F. waves of the alternator, shown at a, a', a'', in Fig. 3. If the slide B is moved on the potentiometer A, until the P.D. between G and B is just equal to the voltage *a*, then when the rotating switch closes, no current will flow through the telephone receiver and hence no sound will be heard. A D.C. voltmeter, connected to *B* and *G*, will then give the value of the D.C. voltage necessary to balance the instantaneous value

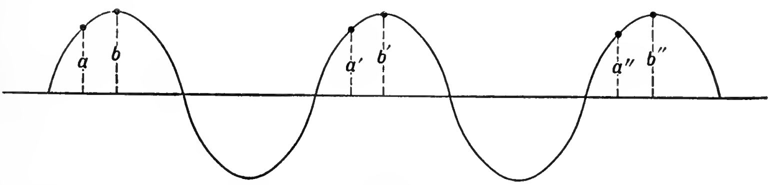


FIG. 3

of the A.C. voltage; i.e., it will give the instantaneous value of the A.C. voltage. If now the brush *E* is moved around on the periphery the local circuit will be closed when the A.C. voltage is perhaps *bb' b''* (Fig. 3). The sliding contact *B* (Fig. 2) must

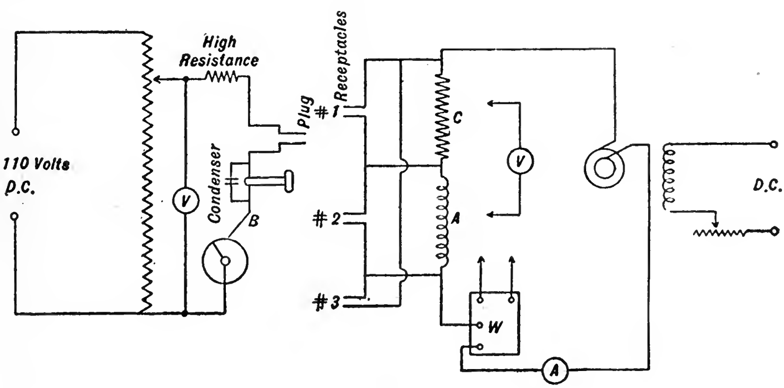


FIG. 4

then be moved to reduce the telephone sound again to zero, when the D.C. voltmeter will give the value of this voltage *b* (Fig. 3). So by moving *E* (Fig. 2) through 360 electrical degrees, taking readings at every few degrees (say 15°) the entire wave of E.M.F. may be plotted, point by point. The actual connections to be made for this test are shown in Fig. 4. The plug switch makes it possible to connect the telephone circuit to any one of the three E.M.F. waves to be measured.

An inductive coil *A* and resistance *C* are connected in series and through the current coil of wattmeter *W*, through ammeter *A* to the A.C. generator. Taps are taken off the circuit and connected to receptacles so that the jack can connect the telephone circuit either to the terminals of *A*, *C*, or the entire circuit. For each setting of the brush *B*, a balance is to be obtained with the plug inserted in each of the receptacles in turn; the brush is to be moved in steps of about 15° (electrical) until the three waves are obtained for a complete cycle.

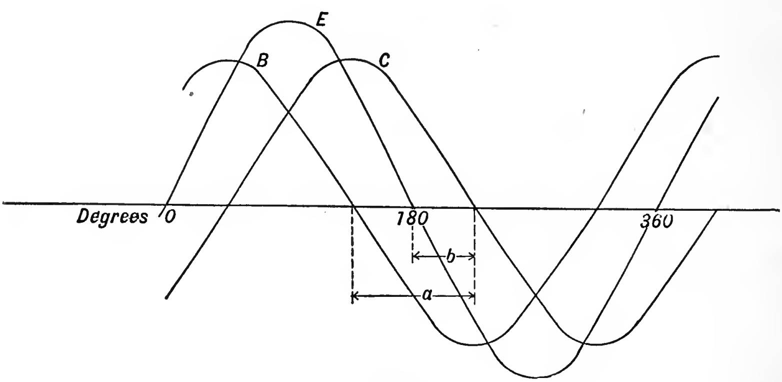


FIG. 5

The wave obtained from receptacle No. 1 gives the phase of the current, as the current and E.M.F. are in phase on a non-inductive circuit. The wave from receptacle No. 3 gives the impressed voltage, and so is the same as the terminal voltage of the alternator and shows how nearly the alternator generates a sine E.M.F.

The inductance used should have an air core, otherwise the current will be distorted and the value of ϕ obtained from the curve sheet will be difficult to interpret. After the circuit has been properly adjusted to give readable deflections on the meters used, take a reading of volts, amperes and watts for each part of the circuit, and for the whole circuit. To read watts used in any part of the circuit, connect the potential leads of the wattmeter across that part of the circuit.

Maintain the impressed voltage and frequency constant and determine the three curves of voltage.

The impressed voltage must not be greater than about 65 per cent of the D.C. voltage used on the potentiometer resistance.

The curves obtained should look about as those given in Fig. 5. *C* is the drop across the resistance, hence gives the phase and form of the current; *B* is the drop across the inductance, and *E* is the impressed E.M.F. The angle of lag for the entire circuit is equal to *b*, measured in degrees; the phase displacement of current and E.M.F. in the inductance coil is given by *a*.

A vector diagram showing the same relations as those given by the curves of Fig. 5 is shown in Fig. 6; the direction of

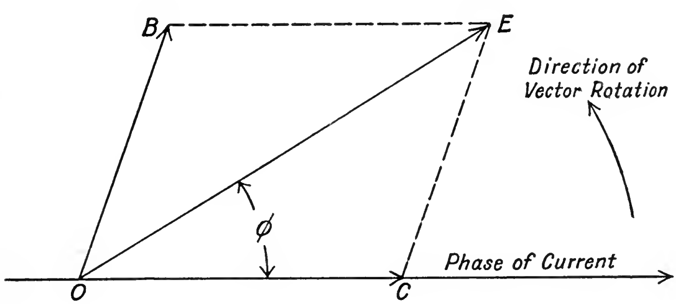


FIG. 6.

positive vector rotation is taken counter-clockwise as is the practice in all alternating-current diagrams.

The phase of the current is taken as reference vector, and in phase with this current is the voltage *OC* which is the component of the impressed voltage required to overcome the reaction of the resistance *C* of Fig. 4. At *OB* is shown the component of impressed voltage required to overcome the reactions in the inductance shown at *A* in Fig. 4; this voltage will be nearly 90° out of phase with the current if the resistance of the inductance coil is small compared to its reactance. The impressed voltage *OE* must be of such magnitude and phase as to supply the two required drops *OB* and *OC*.

The angle ϕ of Fig. 6 is equal to the angle indicated at *b* in Fig. 5; it may have nearly any value between zero and 90° depending upon the relative values of reactance and resistance in the circuit.

Check the values of cos ϕ, obtained from the plotted curves, with the values computed from readings of wattmeter, ammeter and voltmeter. With the same base and maximum value as curve *E*, construct a sine curve to see how closely the generated E.M.F. approximates this shape. Compare the voltmeter readings of the three parts of the circuit with the effective values as computed from the curve sheet (0.707 $\times$ maximum value).

Questions

What difficulty would be encountered in this test if the voltage across the circuit as read on the alternating current voltmeter was 85, while the voltage across the potentiometer was 105?

If the readings on a certain circuit were 60 volts, 2.5 amperes, 85 watts, what should be the distance *b* of Fig. 5?

What relation exists between the *instantaneous* values of voltage across each part of the circuit and across the whole circuit?

Why should the strap *H* and the brush *E* (of Fig. 2) be as narrow as possible?

EXPERIMENT II

Properties of the Alternating Current Circuit. The object of this test is to investigate the relations existing between the phase and magnitude of the current and impressed E.M.F. of a circuit containing inductance, capacity and resistance in series. Also the effect of frequency is to be noted and the difference between ohmic and " effective " resistance is to be measured.

When an E.M.F., either A.C. or D.C., is impressed upon any circuit, a current is caused to flow, the value of which depends upon the reactions which the circuit offers. When the characteristics of the circuit are known, the value of the current may always be found by setting up the differential equation of reactions existing in the circuit, and putting their sum equal to the impressed E.M.F. In general the reactions are proportional to the current or some function of the current, so that the differential equation involves the current, constants of the circuit, and impressed force; its solution expresses the current in terms of the impressed force and the constants of the circuit.

In the direct current circuit the solution is extremely simple, because the current itself is generally a constant quantity, but in the case of alternating currents the reactions are more complex and so the solution is more difficult. The solution will not be attempted here, but the results of the solution will be used and discussed.

The three reactions which occur in the circuit to be tested are resistance reaction, inductance reaction and capacity reaction; they will each be discussed separately.

In the ordinary D.C. circuit, as e.g., an incandescent lamp connected to a supply line, Ohm's law expresses the relation existing between current and E.M.F.,

$$E=IR$$

where

E=potential difference at terminals of lamp;
I=current flowing through lamp;
R=resistance of lamp.

In case an A.C. E.M.F. is applied to this lamp, exactly the same law holds; E and I will be the effective values of the voltage and current while R will have exactly the same value as it had

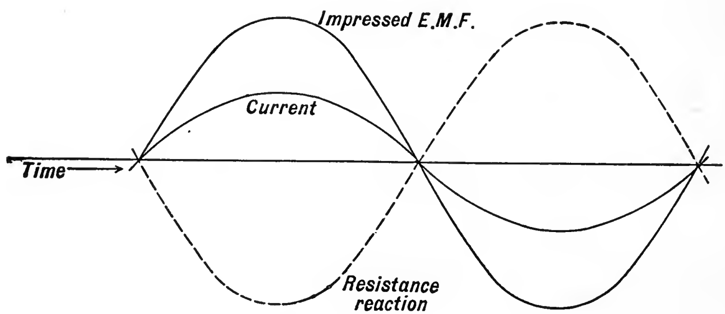


FIG. 7

for the direct current. This is the case of an A.C. circuit having only resistance reaction; moreover, the effective resistance is the same as the ohmic resistance. (This will always be true, for ordinary frequencies, unless the circuit embraces a magnetic path made up of iron. The difference will be discussed later.)

The above law gives the magnitude of the alternating current through the lamp, and its phase will be the same as that of the E.M.F. As R is a constant the current will *at every instant be directly proportional* to the E.M.F. If the voltage is a sine curve, the current will also be a sine curve (in general of different amplitude) in exactly the same phase as the voltage. The curve representation of the two variables is given in Fig. 7.

The next reaction to be considered is that offered by a coil of wire having a considerable number of turns. (A coil of few turns shows the same effect as one having many turns, but not to an extent sufficient to measure with ordinary laboratory instruments.) A current flowing through such a coil produces a magnetic field the strength of which is at any instant directly proportional to the value of the current. It is a property of such a magnetic field that whenever its strength is changed an electromotive force is set up in the electric circuit which embraces the magnetic field. The direction of this E.M.F. of self induction

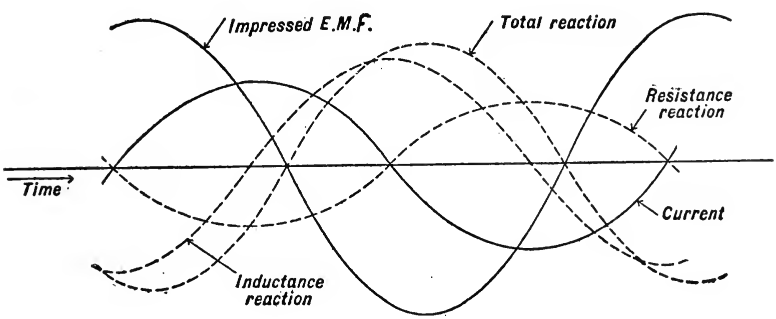


FIG. 8

depends upon whether the field is increasing or decreasing, and its magnitude depends upon the rate of change of the field and number of turns in the coil. As the field is always proportional to the current, it is evident that this inductance reaction is proportional to the rate of change of the current.

It is evident, therefore, that if an alternating current is sent through such a coil, there will be two reacting forces set up in the circuit, the resistance reaction (the coil will of course have resistance) and the inductance reaction. If the current is a sine function of the time the rate of change of the current, to which the inductance reaction is proportional, will be of similar form but displaced 90° from it. By further analysis it may be shown that this inductance reaction is 90° behind the phase of the current. The two reactions may be presented in the form of curves as shown in Fig. 8. The current is assumed in magnitude and phase, the resistance and inductance reactions can then be plotted, and the impressed force is then found as equal to the sum of the two reactions and, of course, opposite in phase. Represented vectorially it will be seen that the different forces of Fig. 8 are properly given in Fig. 9. The phase of the current is assumed as OI. The resistance reaction is shown as OR and the inductance reaction as OX. The combined reactions are then given by the vector OZ; the impressed force must be equal and opposite

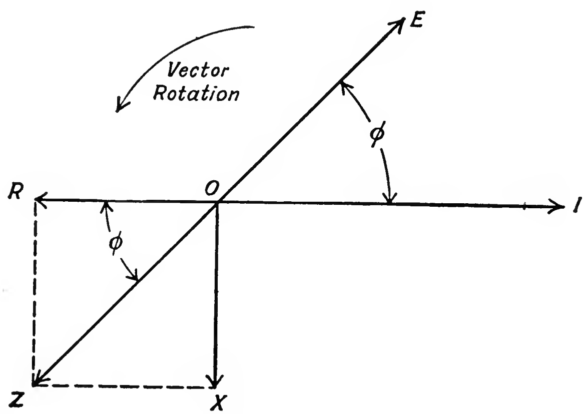


FIG. 9

to this, so is properly shown as OE. The length of the vector OR is equal (in scale of volts) to the current (in amperes) multiplied by resistance (in ohms). Maximum values of E.M.F. and current would naturally be used in constructing the vector diagram, but the diagram holds good if effective values (maximum value $/\sqrt{2}$) are used, as it simply amounts to a change in scale.

The length of the vector OX is proportional to L, the coefficient of self induction of the circuit expressed in henrys, and to the rate of change of the current. But if the current is expressed by $i=I_{\max} \sin 2\pi ft$ it is at once evident that the maximum value of the inductance reaction is $2\pi fLI_{\max}$. But if the other reactions are expressed in effective values, the inductance reaction is given by $OX=2\pi fLI$, where I is the effective value of the current.

The phase difference of the impressed force is generally designated by ϕ and from the diagram it is seen that

$$\tan\phi=\frac{2\pi fL}{R} \quad \text{or} \quad \cos\phi=\frac{R}{\sqrt{R^2+(2\pi fL)^2}}.$$

The power used up in the circuit is equal to the current $\times$ resistance reaction. But resistance reaction = impressed E.M.F. $\times\cos\phi$. So that power used up (expressed in watts) $=I\times IR=IE\cos\phi$.

It was proved in Ex. 1 that the wattmeter reading does give $EI\cos\phi$.

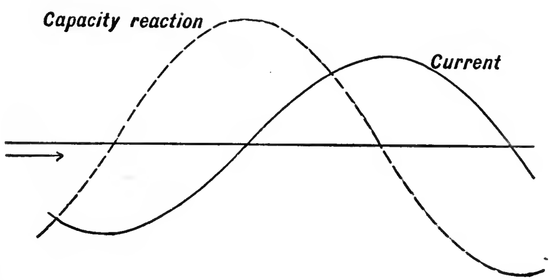


FIG. 10

If now a condenser is put in the circuit a capacity reaction will result. The counter E.M.F. of a condenser is equal to Q/C

where Q = quantity of electricity in condenser;

C = capacity of condenser.

If Q is expressed in coulombs, and C in farads, the counter E.M.F. will be given by the formula in volts.

The quantity of electricity in a condenser, of positive polarity, e.g., will be a maximum at the end of a positive alternation of the current. When the current reverses, some of the electricity begins to flow out of the condenser, so that the truth of the above statement is evident. The condenser reaction will therefore have a maximum positive value at the end of a positive loop of current and the reaction is of the same form, with respect to time, as the current wave (if the current is a simple sine wave). The phase relations between current and condenser reaction is shown in Fig. 10 and vectorially in Fig. 11. In this latter figure OI represents the current and OC gives the condenser reaction. The magnitude of this reaction is

$$E_c = I\left(\frac{1}{2\pi fC}\right),$$

where E_c = capacity reaction in volts; I = current in amperes; f = frequency; C = capacity in farads.

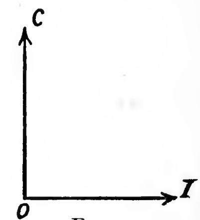


FIG. 11

The three reactions which have been discussed may now be grouped for convenience:

Resistance reaction $= IR$, 180° out of phase with current;
Inductance reaction $= 2\pi fLI$, 90° behind current,
Capacity reaction $= \frac{I}{2\pi fC}$, 90° ahead of current.

The quantity $2\pi fL$ is called the reactance of an inductive circuit; for a condensive circuit the quantity $\frac{1}{2\pi fC}$ is called the reactance. In case both condenser and inductance are present, and connected in series the reactance is equal to $\left(2\pi fL - \frac{1}{2\pi fC}\right)$.

The reactance is generally designated by the letter X, so for a condenser

$$X = \frac{1}{2\pi fC};$$

and for an inductance, $X = 2\pi fL$;

and if both are connected in series,

$$X = 2\pi fL - \frac{1}{2\pi fC}.$$

When an inductance, resistance and condenser are connected in series the relation between voltage impressed and current is

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2}}$$

$$= \frac{E}{\sqrt{R^2 + X^2}} = \frac{E}{Z}.$$

This quantity Z is called the impedance of a circuit and is expressed in ohms, just the same as resistance or reactance.

Generally vector diagrams do not give the reactions themselves, but the components of the impressed E.M.F. used in overcoming these reactions. These components are sometimes called the reactions; it must be remembered, however, that really the reactions are 180° out of phase with these components of the E.M.F. In so far as no ambiguity will arise from such nomenclature and as text-books on the subject of alternating currents generally use the terms inductance drop, etc., signifying "the component of the impressed E.M.F. to balance the inductance reaction" such use of the terms will be made here. We have, therefore,

Current lags 90° behind inductance drop;
Current leads 90° ahead of capacity drop;
Current in phase with resistance drop.

The difference between ohmic and effective resistance is now to be noted. If current is sent through one coil of a transformer (a coil having a magnetic circuit in which iron is used) and the power used in the coil is measured by a wattmeter, it will be found that the wattmeter indication is much greater than I^2r where

I = the current,
r = resistance of coil, calculated from size and length of wire, or measured by direct current test.

The continually reversing magnetic field in the iron uses up energy as hysteresis and eddy current loss. This loss must be furnished by the line supplying the current, and the wattmeter measures this loss and so gives the same reading as though the ohmic resistance of the coil was much greater than it actually is.

If I = current;
r = ohmic resistance;
W = watts consumed, shown by wattmeter;
R = effective resistance;

Then $W = I^2R$;

Since copper loss $= I^2r$. we may write

$$W = I^2(r + x)$$

where x represents the apparent increase in resistance of the circuit produced by hysteresis and eddy currents in the iron. The value of x depends upon the quantity and quality of the iron in the magnetic circuit, the flux density in the iron and the frequency of the current.

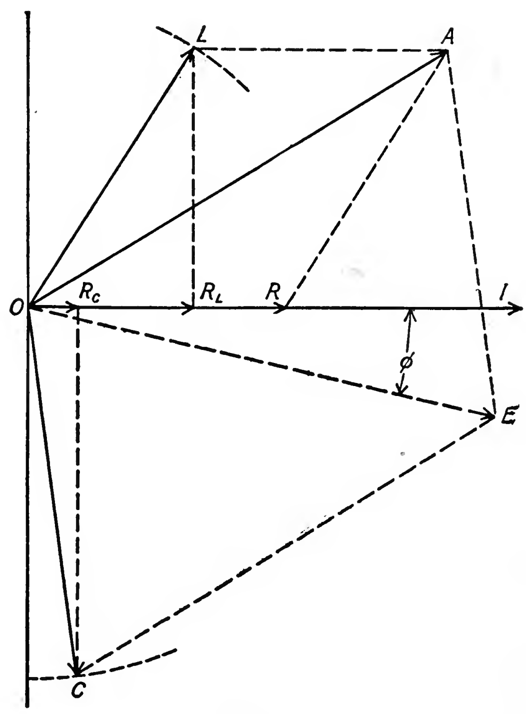


FIG. 12

If a condenser, inductance and non-inductive resistance are connected in series, all of the previously discussed reactions will occur in the circuit. The different reacting forces may be measured and their relative phases determined. Added vectorially these component E.M.F.'s should give the impressed E.M.F. both in phase and magnitude. As was shown in Ex. 1, the wattmeter reading of any part of the circuit gives the product of the resistance (effective) reaction and the current. By dividing the watts by current in the circuit the resistance reaction is therefore found. The proper phase for the voltage drop in the circuit, (or part of circuit) referred to the current, is thus obtained. In Fig. 12, is shown the vector diagram for the circuit as given

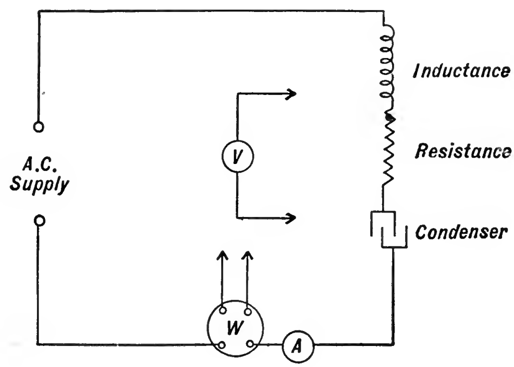


FIG. 13

in Fig. 13. The phase of the current is assumed as *OI*. The non-inductive resistance drop, *OR*, is plotted in phase with *OI* and equal in magnitude to the voltage across the non-inductive resistance as indicated by the voltmeter. The resistance reaction of the inductance coil is obtained by dividing the watts used in the inductance coil by the current. This voltage is plotted in Fig. 12 as OR_L. With a radius equal to the voltage drop across the inductance coil (measured by voltmeter) an arc is drawn about *O* as center and the inductance drop is then plotted in such a phase as will give the requisite component OR_L in phase with the current. It is shown as *OL*, and the resultant of *OR* and

OL is shown as OA. The capacity drop is plotted as OC. (It is supposed that some power is used in the condenser, giving a voltage component in phase with the current. This component is obtained in the same manner as OR_L was obtained.) The resultant of the three voltages OR, OL and OC, is shown as OE. This vector, OE, should agree both in magnitude and phase with the impressed voltage as measured and calculated from readings of voltmeter, wattmeter and ammeter.

It is to be noticed that the angle ϕ may not check very closely with the value as obtained by the formula,

$$\cos\phi = \frac{\text{watts in total circuit}}{\text{current} \times \text{impressed voltage}}.$$

This will be especially true if ϕ is small. The value determined experimentally is $\cos\phi$ and not ϕ itself. When ϕ is small a large change in ϕ is accompanied by only a small change in $\cos\phi$.

With connections made as in Fig. 13, using an inductance coil with iron core and a frequency as low as obtainable with the generator used, adjust the different parts of the circuit until the drop in the condenser is about 50 per cent greater than the resistance drop and the drop across the coil is about 50 per cent smaller than the resistance drop. Read current, volts and watts for each part and for the whole circuit keeping the impressed voltage constant while getting the set of readings. Then increase the frequency to as high a value as is obtainable (say twice as much as that used in the first test), leaving the circuit exactly as it was for the low frequency. Now vary the impressed voltage until the current flowing in the circuit is just the same as for the low-frequency run. Read current, volts impressed, and drop across each part, and watts used in whole circuit and in each part.

Take two more sets of readings after having adjusted L, R, and C to different values. Keep the current for these two runs the same, not necessarily the same as for the two former runs.

By direct current "drop of potential" method measure the ohmic resistance of the inductance coil, of the condenser, and of the non-inductive resistance. If possible make these measurements of resistance with about the same value of current as used in the A.C. test to avoid errors due to heating.

It will of course be found that the condenser will not take as much current on the D.C. test as on the A.C. test; generally the current in the D.C. test will be so small that an ordinary ammeter gives no discernible deflection.

The resistance of the condenser is most conveniently measured by use of a voltmeter of known resistance; if none is available it may be remembered that the ordinary portable direct current voltmeter, such as used for laboratory work, has about 80 ohms resistance per volt of scale (thus a 150 voltmeter has about 12,000 ohms resistance). Take the voltmeter reading when connected directly across any convenient power source (say the 110-volt laboratory supply) and again when connected to the same line *with the condenser in series.* Calling V_1 and V_2 these voltmeter readings and R_v the resistance of the voltmeter we can easily derive the relation

$$R_c = R_v \frac{V_1 - V_2}{V_2}.$$

The value of R_c so obtained by direct current measurement is the leakage resistance of the condenser, an entirely different quantity from the resistance obtained in the A.C. test by dividing the watts used in the condenser by the square of the current. The leakage resistance (or insulation resistance) will generally be many megohms for one microfared of capacity whereas the equivalent series resistance, obtained in A.C. test, will be but a few ohms. Both these resistances vary inversely with the number of condensers connected in parallel.

Calculate cos ϕ, for whole circuit, for the four different runs. Construct vector diagrams of the voltages across the different parts of the circuit and from these construct the resultant voltage; this should, of course, equal the impressed voltage, in magnitude and phase. Carry this construction out for the values obtained in each of the four sets of readings. On each diagram plot the measured value of impressed voltage for comparison with the vectorially obtained resultant.

Questions

Compare the resistances as obtained in D.C. test with those obtained in A.C. test. Explain.

What would be the power factor of the circuit if the inductance and capacity reactances were equal?

Why does the arithmetical sum of the watts used in the different parts of the circuit equal the total watts?

Why does not the arithmetical sum of the different voltages equal the impressed E.M.F.?

The voltage across one part of the series circuit may be larger than the impressed voltage. Explain.

If an inductance of 0.1 henry and a capacity of 100 microfarads are connected in series with a resistance of 5 ohms to a 110-volt circuit, the voltage of which is held constant while the frequency is varied, at what value of frequency will the current be a maximum, and how much will it be? What will be the drop in voltage across the resistance, condenser, and inductance at this value of frequency?

What will be the power factor and current in the above circuit when the impressed voltage has a frequency of 60 cycles?

What is the reactance and what is the impedance of the circuit at this frequency?

EXPERIMENT III

The Alternator; its Characteristics, Measured and Predicted.* The alternating current generator consists essentially of a coil of wire rotating in a magnetic field, the ends of the coil being connected to slip rings from which power is taken by means of brushes. Such a generator gives an E.M.F. which is continually reversing in direction. The air gap is so shaped and the coils so placed on the armature that the wave of generated E.M.F. is, as nearly as possible, a sine wave with respect to time.

The magnetic field of the machine is obtained from electromagnets which must be excited from some source of direct current power. This is one feature which distinguishes the A.C. from the D.C. generator, the latter being self exciting. In an alternating current generating station several comparatively small direct current machines, called exciters, are run merely to supply the field current for the alternators.

The E.M.F. induced in an armature coil reverses every time the coil passes a field pole and so makes a complete cycle for every pair of poles passed. To figure the frequency (number of cycles per second) an A.C. generator is supplying, it is only necessary to multiply the revolutions per second by the number of *pairs of poles*.

For a given strength of magnetic field and fixed speed the generated voltage of an A.C. generator must remain constant, i.e., independent of load. As load is put on the machine with above conditions fixed the terminal voltage will, however, decrease, the decrease being nearly proportional to the load current. At loads greater than rated value the decrease in voltage is considerably greater for a given increase of load. When the load

* Although the following tests are analyzed from the viewpoint of single-phase apparatus, we have found it more satisfactory to carry out Ex. 9 after Ex. 2, and then perform all of the machine tests with polyphase connections and loads.

is zero the terminal and generated voltages are equal. But when current is flowing through the armature windings, there occur in the armature coils, reactions which must be overcome by the generated E.M.F. As these reactions are proportional to the current it is evident that the terminal voltage will fall with increasing load, the generated E.M.F. remaining constant. The decrease of terminal voltage with load depends not only upon the amount of load, but also upon the kind of load, the decrease being much greater for inductive than for non-inductive loads. The reason for this will appear later.

The voltage of a line to which incandescent lamps are connected should remain as nearly constant as possible. If the voltage decreases the amount of light given off decreases very rapidly, while if the lamps are operated at a higher than rated voltage, the life is materially shortened. A decrease of 5 per cent from rated voltage cuts down the amount of light from a carbon incandescent lamp nearly 30 per cent; an increase of voltage of 5 per cent above rating cuts down the life to 35 per cent of its rated value. Similar effects occur with tungsten incandescent lamps but not to such a marked degree, as the resistance of tungsten increases with an increase in temperature, while the opposite is true of carbon.

The feasibility of maintaining constant voltage on the line when the load is varied is an important point to investigate. That alternator giving the most constant terminal voltage with varying load, will most satisfactorily carry a lighting load and will require the least field adjustment with change of load. If rated load is put on an alternator and the field current adjusted until rated terminal voltage is obtained, then maintaining field current constant, the load is taken off, the terminal voltage will rise and the amount of this rise is a measure of the regulation of the machine. By definition,

$$\text{Regulation (in \%)} = \frac{\text{voltage at no load} - \text{voltage at full load}}{\text{voltage at full load}}.$$

The regulation of an alternator on non-inductive load will be somewhere from 5 to 15 per cent, depending upon the constants of the armature (resistance, inductance, etc.).

The first part of this experiment consists in actually loading the generator, and, by taking readings of terminal voltage and load current, getting enough points to actually construct the curve, showing the relation between load current and terminal voltage, which is called the external characteristic. For non-inductive load a water barrel or lamp board may be used; for inductive load a variable inductance coil is to be connected in parallel with the non-inductive load. The connections will be as in Fig. 14, in which *A* represents the lamp board and *B* the variable inductance. For getting the external characteristic with non-inductive load switch *C* is left open, and *A*, the non-inductive load, is so varied that the armature current is adjusted for the desired values.

After the alternator is running at rated speed, adjust the load current and field current so that *rated terminal voltage is obtained with rated current.* Read the field current and maintain it at

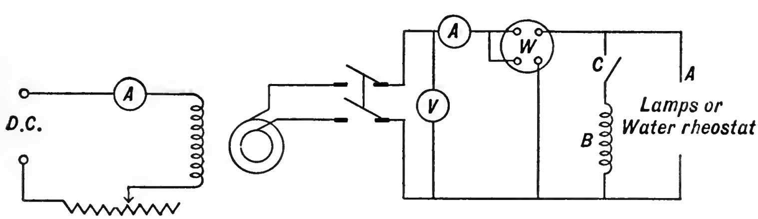


FIG. 14

this value throughout the run. Keeping speed constant, take readings of armature current and terminal voltage, with values of current equal approximately to $1\frac{1}{2}$, $1\frac{1}{4}$, rated, $\frac{3}{4}$, $\frac{1}{2}$, $\frac{1}{4}$ and zero load.

To get the external characteristic with inductive load (corresponding to a commercial load of transformers, induction motors, etc.), the variable inductance must be used. The method of manipulating the inductance coil is as follows. Suppose the machine is rated at 50 amperes at 110 volts and the power factor desired is 0.8.

With maximum inductance in the coil, close switch C, having the voltage about normal. The watts necessary for full load current at .8 power factor are $110 \times 50 \times .8 = 4400$. Adjust the lamp bank until the wattmeter reads approximately 4.4 K.W. Then decrease the inductance of coil B until the ammeter A reads about 50 amperes. Then adjust the field current to bring the terminal voltage to rated value and bring the reading of the ammeter A to exactly 50 amperes, and recalculate the power factor. A slight readjustment of loads A and B will probably be necessary to bring this to the desired value. Time should be taken to adjust conditions accurately for the full load setting; after the adjustment has been carried out as carefully as is feasible, read field current, armature current, terminal voltage and speed (which must, of course, be at rated value). Keep field current and speed at these values and proceed in similar fashion to get points on the external characteristic at about the same values as in the previous run.

Suppose for example the half load point on the curve is to be obtained. By inspection of the external characteristic for non-inductive load it is found the terminal voltage was (let us suppose) 114 volts. As we know, the external characteristic for inductive loads rises more rapidly with decreasing load than does that for load of $\cos \phi = 1$; we assume that the terminal voltage when the machine is delivering 25 amperes at $\cos \phi = 0.8$ will be, say, 118. Then the volt-amperes at half load $= 118 \times 25 = 2950$. If the power factor is to be 0.8, the output must be $2950 \times 0.8 = 2.36$ K.W. So the load A (Fig. 13) is decreased until the wattmeter reads approximately 2.36 K.W. and then the inductance B is increased until the current, as indicated in the ammeter, is about 25 amperes.

The terminal voltage is now read and power factor is checked. It is probable that the slight readjustment of the two load circuits, A and B, will be required. It requires a deal of time to set for a certain power factor exactly; in this test it is satisfactory if the power factor is obtained within about 2 per cent, that is, if $\cos \phi$ is between 0.78 and 0.82.

The curves should look about like those given in Fig. 15 and should be plotted in similar fashion, the inductive character-

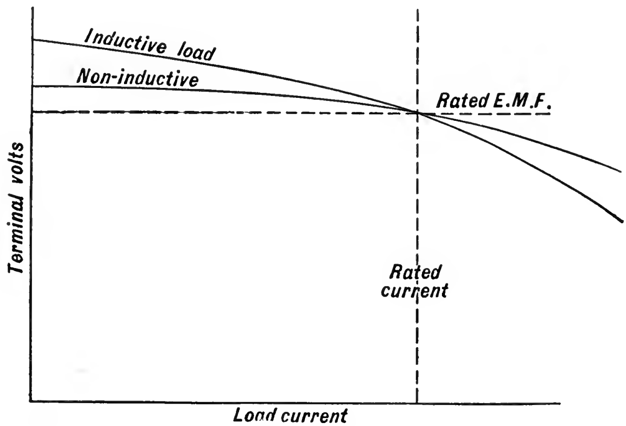


Fig. 15

istic being plotted in some manner to distinguish its points from the other curve.

To determine experimentally the external characteristic of an alternator is always more or less expensive (because of the power used) and frequently it is difficult to find proper inductances and resistances for loading. The latter consideration is very important when the alternators are of high capacity and voltage. Therefore various methods for predetermining the characteristic have been devised. One of the simplest methods will be described here.

When current is flowing through the armature it offers resistance and inductance reactions to the passage of the current. For a given generated E.M.F. we can determine the terminal voltage by subtracting from the generated E.M.F. the two reactions in their proper magnitude and phase. The only measurements which it is necessary to make, for this scheme of predetermining the characteristic, are the resistance and inductance reactions at some known value of current (rated current preferably). These two reactions, combined vectorially with the rated terminal voltage, give the generated voltage (as explained in Ex. 2). If from this generated voltage the reactions for any other value of current are vectorially subtracted the vector remainder will be the terminal voltage for that current.

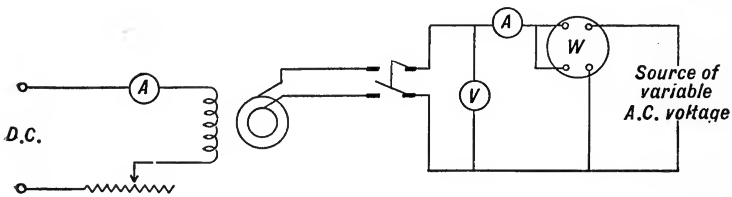


FIG. 16

With the armature stationary and connections as in Fig. 16, impress enough A.C. voltage (of frequency same as that the alternator is rated to give) to force full load current through the armature with normal exciting current in the field coils. Read amperes, volts and watts. The voltage necessary will generally be about 20 per cent of the rated E.M.F. of the machine. Take four sets of readings with the armature in different angular positions with respect to the field poles. Take the positions about 45° (electrical) apart.

Calculate the resistance reaction by dividing the average watts by current. Obtain the average impedance drop and so calculate the average inductance reaction by the formula,

$$\text{Inductance reaction} = \sqrt{\text{impedance reaction}^2 - \text{resistance reaction}^2}$$

Referring to Fig. 17, the method for predetermining the external characteristic for non-inductive load is given. The rated terminal voltage OE_t is laid off in phase with the current OI. The resistance and inductance reactions are shown at OR and OX. The generated voltage is found as OE_g, and the locus of the E.M.F. as the load varies is the circular arc through E_g described with O as center. At half load the reactions will be one-half as large (of course in same phase with respect to current as before) and the generated voltage is the same. The terminal voltage is therefore found at OE_t'. At no load the terminal voltage OE_t'' is equal to the generated voltage OE_g.

For inductive load the construction is very similar. If the power factor at which the characteristic is desired is cos ϕ, the

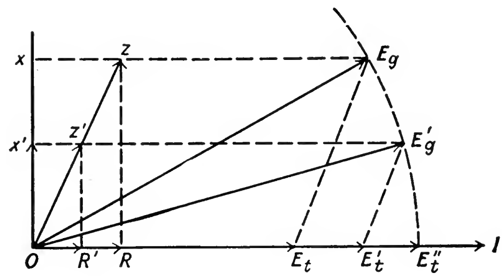


FIG. 17

rated terminal voltage is laid off along the line OA, making the angle ϕ with the assumed phase of the current OI. In Fig. 18

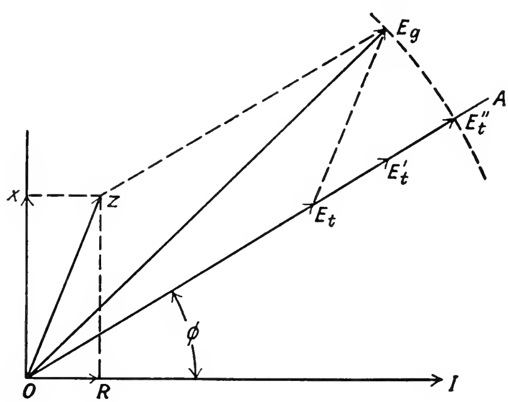


FIG. 18

the construction is plainly indicated, so that further explanation is unnecessary.

Construct the vector diagrams for prediction of the characteristics for loads of same power factors as were used in first part of test. Indicate on the curve sheet the points as obtained from vector construction for loads of approximately those used in test.

There exists in alternating current generators another effect which has not yet been mentioned; the armature current has an influence on the field strength of the alternator, and even if the field current be maintained constant, the generated E.M.F. OE_g does not stay constant as the load is varied. For this reason the above simple scheme for predetermining the alternator characteristic is not very accurate, especially for loads of low power factors. In this short course on testing, however, it is not feasible to employ one of the more complicated methods which do take account of the armature magnetizing or demagnetizing effect.

Questions

In this test it is convenient to use for the inductive part of the load, an iron core inductance with a variable air gap. How would you expect the current through the inductance to vary with the length of the air gap and why?

Assuming that the inductive circuit of the load has a negligible resistance, how much current is going through each branch of the load circuit (Fig. 14) when the meters read as follows: 112 volts, 62 amperes, 5000 watts?

If the resistance of an armature is 0.1 ohm and the reactance is 0.3 ohm, and the terminal voltage is 125 when a non-inductive load of 40 amperes is being supplied, what will be the no-load terminal voltage?

With its armature stationary a certain machine had its armature connected to a 60-cycle line and the readings taken were: 18 volts, 50 amperes, and 325 watts. What was the impedance of the armature? Reactance? Self-induction? Resistance?

EXPERIMENT IV

The Transformer; its Operating Characteristics; Analysis of Losses and Predetermination of Efficiency. The transformer is a stationary piece of apparatus by means of which A.C. power may be transformed from one voltage to another, either higher or lower. It finds its application where A.C. power is to be carried any considerable distance. For a given size of transmission line the power loss in the line varies as the square of the current, so that from the standpoint of efficiency the power should be at as high a voltage as the transmission line will safely carry. The voltage being high, the current will be correspondingly low and therefore the loss in the line low. At present it is not feasible to operate transmission lines at higher than 140,000 volts; if a higher pressure than this is used the losses by leakage over insulators and actual leakage currents into the surrounding atmosphere become so great, that the efficiency of transmission begins to decrease because of these losses.

A.C. generators are not economically built for E.M.F.'s exceeding perhaps 15,000 volts. At the point where power is used for motors, lights, etc., the required voltage is generally less than 440 volts. A possible problem then is to generate at perhaps 10,000 volts, transmit at 100,000 volts and utilize at 200 volts. To accomplish these changes in voltage is the function of the stationary transformer. At the beginning of the line a "step up" transformer with ratio 1 to 10 would be used; at the end of the line a "step down" transformer of ratio 500 to 1 would be used. The latter transformation might possibly be carried out in two steps: the transmission line might be connected to the distributing feeders with 50:1 transformers, and the supply for lights, etc., be taken off the distributing feeders by step down transformers of ratio 10:1. The difference between a "step up" and a "step down" transformer is merely one of service; a 10 K.V.A. 1100–110 volt transformer is one which will transform 10 kilo-volt amperes from 1100 to 110 volts if used as a "step down" transformer or will transform the same amount of power from 110 volts to about 1100 volts, when used as a "step up" transformer.

A transformer consists essentially of a closed iron magnetic circuit upon which are wound two insulated coils of wire. The two coils are generally wound in sections, the different sections being so interspersed that the magnetic leakage between the two coils is a minimum. On open circuit (i.e., the transformer supplying no load) the ratio of voltages is equal to the ratio of the numbers of turns of the two coils; as load is put on the transformer the terminal voltage of the secondary will decrease slightly from this value. The name "secondary" is applied to that coil from which power is taken; the coil connected to the power supply line is termed the "primary."

The operation of a transformer is essentially as follows: When the primary coil is connected to a source of A.C. power, a current will flow in the coil, and if there were no variation of permeability in the iron core this current would be of the same form as the E.M.F. wave of the source of supply. When variation of the permeability occurs to any appreciable extent in the iron core this exciting current is distorted in form, but alternates with the same frequency as the impressed E.M.F. The alternating current produces in the iron core an alternating magnetic field. Now any other coil threading the alternating magnetic field has induced in it an alternating E.M.F., the magnitude of which E.M.F. depends upon the number of turns in the second coil. The secondary E.M.F. has the same shape as the E.M.F. impressed on the primary.

The exciting current (primary current with secondary open circuited) is only a few per cent of the full load rated current of the transformer. When the secondary is loaded with a certain current a corresponding current flows into the primary because of the reactions occurring between the two coils, the reactions being brought about by the magnetic field which is common to the two coils.

If a constant E.M.F. is impressed on the primary the secondary terminal volts decrease somewhat with increase of load; the decrease is caused by the resistance and inductance reactions which occur in the transformer itself.

Three characteristics to be investigated in this test, are efficiency, primary power factor, and secondary terminal volts, the load to be non-inductive and the primary impressed E.M.F. to be maintained constant at rated value.

The efficiency will be found to rise very rapidly with the load and will be practically constant between $\frac{1}{4}$ full load and $1\frac{1}{4}$ full load. There are no moving parts to the transformer and hence no mechanical losses to be supplied. This feature makes the transformer the most efficient of all pieces of A.C. apparatus. The full load efficiency of a transformer may be between 92 and 98 per cent, depending upon the capacity, being greater for the larger sizes.

At no load the power factor is very low, perhaps 0.3 or 0.4. As load is put on, this rapidly increases and from $\frac{1}{4}$ load up will be between .98 and 1.0, these figures being for non-inductive load on the secondary. At no load the secondary voltage is equal to the impressed E.M.F. multiplied by the ratio of the numbers of turns on the primary and secondary. As load is applied the secondary terminal E.M.F. gradually decreases, the amount of decrease depending upon the amount of load and whether or not it is inductive. For non-inductive load the decrease from no load to full load may be about 5 per cent or less.

In obtaining these three characteristics by loading, make connections as in Fig. 19. By the arrangement of two double throw and two single throw switches as shown, only one set of meters is required. The most important reason for using this switching arrangement, however, is to get rid of calibration errors in the instruments. The efficiency and power factor being so high, the different meters have to be very accurate, if absurd results are not to be obtained (efficiency greater than 100 per cent, etc.). The voltmeter V_1 is used merely to maintain the impressed voltage of the transformer constant. The input in volts, amperes and watts is obtained by having S_1 and S_2 thrown to the left, S_4 open and S_3 closed. To get output, S_4 is first closed, S_1 and S_2 thrown to the right, then S_3 opened. The load is fixed at the desired value, then while V_1 is maintained at the rated value of the transformer, both input and output are read.

As the load is non-inductive, the wattmeter reading of output should equal volt-amperes output. If it is not so, a wattmeter

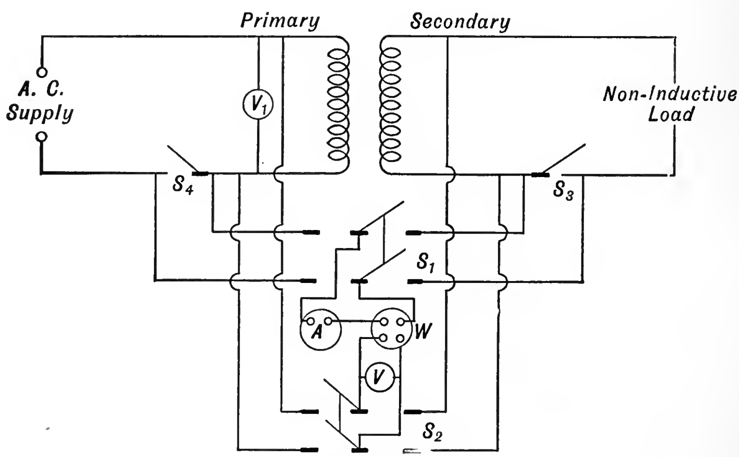


FIG. 19

calibration curve is to be constructed, using wattmeter reading (of secondary load) as one ordinate and volts × amperes as the other. Calling the voltmeter and ammeter correct in their calibration, the correct wattmeter reading is thus given in terms of their readings. From this calibration curve, correct the readings of input watts. The efficiency is then obtained as the quotient of watts output to watts input, corrected readings being used. The power factor of the primary is obtained as quotient of watts (corrected) by volt-amperes of primary. The external characteristic is obtained directly from the readings of secondary E.M.F. and current.

There are two different losses which occur in the transformer: hysteresis and eddy currents in the iron core, due to the continually reversing magnetic field, and the ohmic or copper loss, due to the currents flowing through the windings of the transformer. The iron loss is practically independent of load as the strength of the magnetic field in the core changes but slightly from no load to full load. It is to be regarded as constant in this test.

When there is no load on the transformer there is flowing in the primary coil merely the exciting current, the magnitude of which varies with different makes of transformers between 2 and 8 per cent of full load current. In the secondary coil there is no current at all; when it is remembered that the copper loss varies with the $(\text{current})^2$ it is readily appreciated that the copper loss of the transformer with open secondary circuit is entirely negligible. The iron loss is, however, normal. The no-load input is therefore taken as being all iron loss; the loss is measured by using a suitable wattmeter in the primary and impressing normal E.M.F. at rated frequency; *the secondary is to be open.*

The wattmeter to be used for obtaining this reading must have a potential capacity equal to the rated E.M.F. of the transformer and a current coil of capacity equal to about 5 per cent of the current rating of the transformer. *This wattmeter is to be used only for the iron loss test;* be sure and remove it from the circuit before making the copper loss test which is described below.

Because of the retentiveness of the iron magnetic circuit of the transformer, the current which is taken when the transformer is first switched to a line of rated voltage may be excessive and generally will cause damage to the wattmeter. To get rid of this possibility, before connecting the transformer to the line *reduce the voltage of the line supplying the power to as low a value as possible,* switch the transformer to the line and then gradually bring up the voltage to normal. Only one reading of the iron loss is necessary.

The copper loss may be put equal to $(I_p^2R_p+I_s^2R_s)$ where

I_p and I_s represent the primary and secondary currents and R_p and R_s represent the two resistances. If a is the transformation ratio of the transformer we must have $I_p = aI_s$. The secondary coil will then have a times as many turns as the primary and the cross section of the secondary wire will be $1/a$ times as large as that of the primary for the most efficient use of the copper wire. We therefore have $R_s = a^2R_p$.

$$\begin{aligned} \text{Therefore copper loss} &= I_p^2R_p + I_s^2R_s \\ &= I_s^2R_s + I_s^2R_s \\ &= I_s^2(R_s + R_s) \\ &= I_s^2R; \end{aligned}$$

where R is what we may call the equivalent resistance of the transformer. If the copper loss is measured for any value of I_s, R can be computed. If connections are made as in Fig. 20 the copper loss may be measured. With the secondary short circuited only a very small impressed E.M.F. is necessary to cause full load current to flow in the secondary circuit. If then

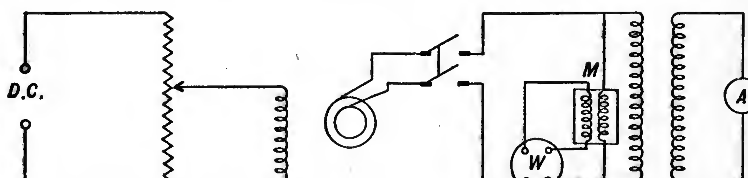


FIG. 20

the wattmeter reading is taken, it represents the copper loss in both coils for full load secondary current. It is well to excite the alternator field by a potentiometer connection to the D.C. line; the voltage may be reduced as low as desirable with this scheme of connections.

The wattmeter used in this test must have a current capacity *equal to full load current of the primary.* It will likely be necessary to use a small potential transformer M to get sufficient E.M.F. on the wattmeter to give a readable deflection. The wattmeter reading must then be divided by the ratio of M.

A small iron loss is incurred in this test, but it is so small as to be negligible. The iron loss varies nearly with the impressed

E.M.F. to the 1.6 power and so is very small when the impressed E.M.F. is small.

After R is computed from the copper loss test, the curve of I^2R may be plotted by taking suitable values of I. The two loss curves have the form given in Fig. 21, and they may be used to predict quite accurately the efficiency of the transformer for different loads. The total loss curve is plotted as the sum of the iron and copper losses. Suppose the curves represent the losses in a transformer whose secondary voltage is 100 (assumed constant for this calculation with practically no error involved.) At 40 amperes output, non-inductive load, the watts output=

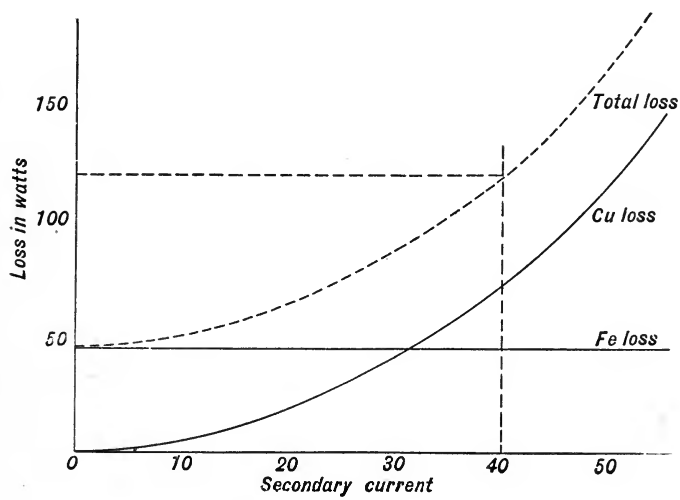


FIG. 21

100×40=4000. From the loss curve it is seen that with 40 amperes output the loss is 115 watts. The input must therefore be =4000+115=4115 watts. The efficiency=output/ input$=\frac{4000}{4115}$. The efficiency for any other output may be similarly computed.

Make the load test called for and plot the three characteristics on one curve sheet with current output as abscissa.

Measure the two losses as described; plot the results on a second sheet and calculate the efficiency for several outputs. Plot the efficiency points so obtained on curve sheet No. 1, to see how nearly the predicted values of efficiency agree with the measured values. If discrepancies occur it is likely that the predicted values are the correct ones, as this prediction method is more accurate than the actual measurement.

The other characteristics may also be predetermined, as was the efficiency, but it is not thought well to further complicate the test.

Questions

A 10 : 1 transformer has a primary resistance of 13.1 ohms and a secondary resistance of 0.125 ohm. What is the equivalent resistance of the transformer in terms of primary current?

A certain transformer has a primary rating of 11,000 volts and 100 amperes. The exciting current is 7 per cent of full load current and the iron loss is 16.5 K.W. What is the no-load power factor?

What are the active and reactive components of the exciting current? If the copper loss of above transformer is 5.5 K.W. at half-load, what is the full load efficiency? What is the equivalent resistance in terms of primary current?

A certain transformer has a rating of 110 volts, 70 amperes. Its full load efficiency is 96.5 per cent. The input at no load (rated frequency and voltage impressed on primary) is 122 watts. What is the copper loss at quarter load?

A transformer is used for supplying power to induction motors, the average power factor of which is 0.70. What must be the rating (in kilovolt-amperes) of a transformer suitable for supplying 65 K.W. of power to this load?

A 10-kilovolt-ampere transformer supplies its full rated output to a lamp load for 2 hours a day and half load for 1½ hours a day. Its full-load copper loss is 2 per cent of its rating and iron loss is 1½ per cent of its rating. What is its all-day efficiency?

EXPERIMENT V

The Induction Motor; its Operating Characteristics with and without Added Rotor Resistance. For such purposes as require a driver of practically constant speed, when alternating current power is available, the induction motor is nearly always used. Its speed is not quite constant, but decreases as the load is increased; the decrease in speed, or "slip," as it is called, may

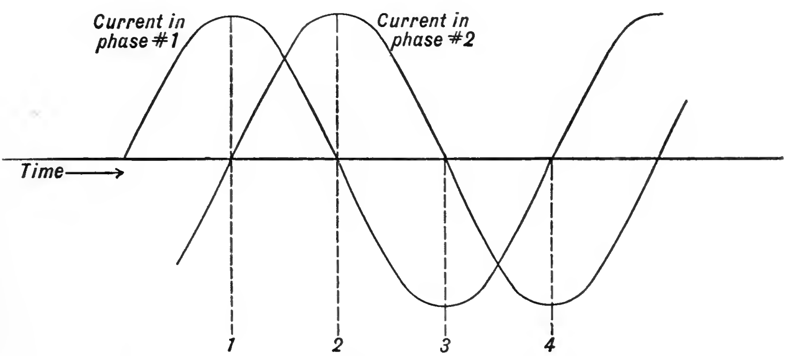


FIG. 22

be between 5 and 8 per cent at full load, the slip being expressed in percentage of synchronous speed. A motor which runs at 1198 R.P.M. at no load for example, might run at 1126 R.P.M. at full load; it would have a slip of 6 per cent.

Nearly all induction motors are polyphase, i.e., they are fed from a network of conductors, from which currents of different phases may be taken. Of all polyphase systems the three phase is most important, but as the two phase motor serves as well for analysis as the three phase and is somewhat simpler to represent, it will be described here.

A two phase generator is one having usually two entirely separate coils. The coils are identical in every respect except their position on the armature, one coil being placed 90° (electrical) behind the other. The two coils are connected each to two slip rings and the two phase power is distributed on four wires. (Three rings and three wires may sometimes be used.) If two similar loads are connected to the two phases, the currents in these load circuits will have the form and phase relations given in Fig. 22.

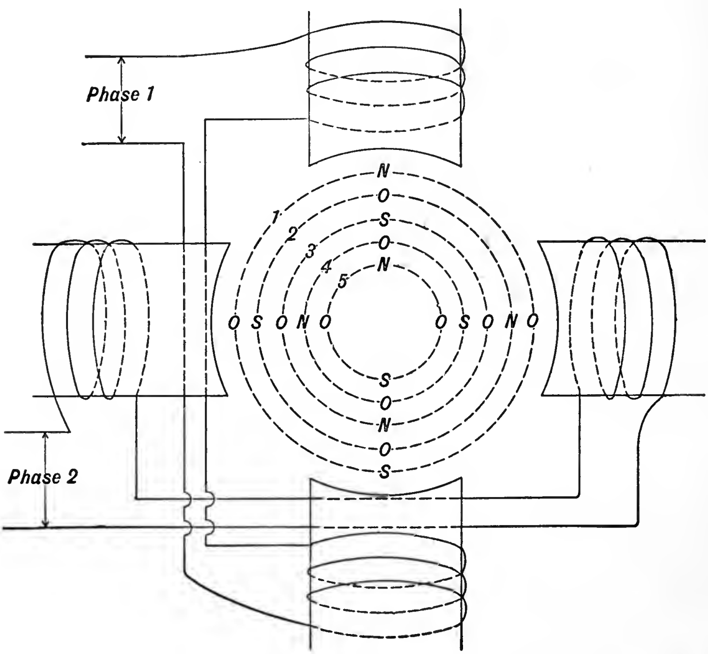


FIG. 23

Suppose now that we have a two phase induction motor with the stator (stationary part) wound with two sets of coils on poles as shown and that the two coils are connected to a two phase system as shown. By reference to Fig. 23, the polarity of the magnetic field of the motor may be determined at any time, and in Fig. 23 this polarity is represented for the different times shown in Fig. 22, by the letters *N*, *S*, *O*, on the different circles. Circle numbered 1 shows the polarity of the field at time 1. It may thus be easily seen that a magnetic field produced by two windings 90° apart and supplied with currents 90° apart is essentially a rotating one, the *N* pole traveling in a clockwise direction in Fig. 23. Three windings spaced 120° apart and supplied with three phase currents 120° apart likewise produce a rotating magnetic field. The stator of an actual induction motor is not built exactly as shown; there are no separate projecting pole pieces; the different windings are imbedded in slots, like the winding of a D.C. armature.

The rotor, or moving part, consists of a laminated iron core accurately fitted to turn between the poles of the stator. In the periphery of the rotor are imbedded conductors which may be interconnected in different ways. In the squirrel cage winding the conductors are all short circuited on one another by being connected to conducting end rings. Or the rotor may be equipped with wound coils and the ends of the coils be connected to slip rings. Brushes bearing on these rings make it feasible to short circuit the coils if desired or else the brushes may be connected together through resistances, thereby increasing the resistance of the rotor circuit. This scheme of having a wound rotor and inserting external resistance when desired is used in most large size motors; the squirrel cage rotor is generally not used in motors over 15 H.P. in capacity. Motors built for special service, however, may have squirrel cage rotors in sizes as high as 75 H.P. or larger.

Consider the squirrel cage rotor in the rotating magnetic field. If the rotor is standing still and the magnetic field is revolving it is evident that an E.M.F. will be developed in the rotor winding and as the winding is short circuited, a current will flow in the rotor conductors. But it is a fundamental principle that a conductor carrying current placed in a magnetic field will be acted upon by a force. By consideration of the motion of the field, direction of induced E.M.F., etc., it may be shown that the force acting in the rotor conductors will be in such a direction that the rotor is urged to revolve in the same direction as the magnetic field. Just so long as there is relative motion between the rotor and magnetic field, a torque will be produced which tends to accelerate the rotor. If there were no losses of any kind in the revolving rotor it would continue to accelerate until the relative motion of rotor and field was zero, i.e., the rotor would turn at the same angular speed as the field, called synchronous speed; the slip is then zero. There always exists some brush friction and windage to overcome, so that it is always necessary for the rotor to exert some torque, therefore the rotor never quite reaches synchronous speed; at no load the slip may be between .2% and 1.0%.

Now as the rotor is called upon to exert more torque, more current must flow in the rotor conductors; this can only occur if a greater E.M.F. is induced in them, which in turn requires an increase in the slip. The slip must therefore increase with load; *for small loads the slip and load are nearly proportional.*

The effect of increasing the rotor resistance is to increase the slip necessary to exert a certain torque. The reason for this is almost self evident. To exert a certain torque requires a certain current in the rotor; but if the resistance of the rotor circuit is increased, the E.M.F. must be correspondingly increased to produce the required current. The E.M.F. can only increase by an increase in slip. The increase in slip for a certain torque, by increase of the rotor circuit resistance, is only obtained by a decrease in efficiency. Whatever heat is generated in the external resistance added to the rotor circuit, is just so much loss, as it is useless in producing turning effort in the motor.

The maximum torque which an induction motor can exert is independent of the variations of the rotor resistance. But the speed at which this maximum torque occurs decreases with increase of resistance. Therefore the "pull out" point, or maximum output of the motor, decreases with addition of external resistance to the rotor circuit.

The power factor of the induction motor is very low at light loads, increases with load up to about rated load, and then decreases again with overload. It may be about 30 per cent at no load and rise to between 80 and 93 per cent for maximum value, the higher figure being for large size motors.

At standstill the induction motor is essentially a short-circuited transformer, the rotor corresponding to the secondary of a transformer. But if a short-circuited transformer is connected to a line of normal voltage the current taken is excessive, being perhaps 20 or 30 times full load value. Because of magnetic leakage between rotor and stator the conditions in the induction motor at starting (rotor at standstill) are not quite so bad as

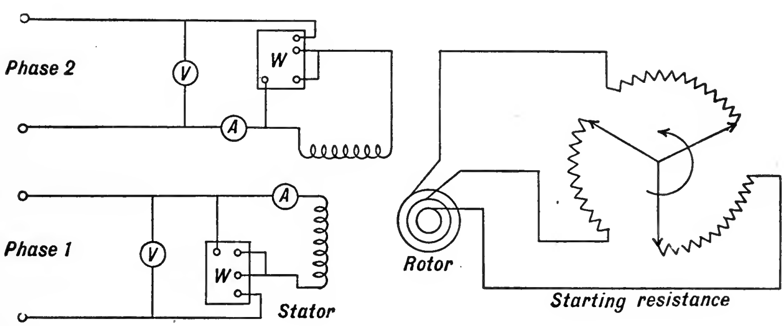


FIG. 24

with an ordinary transformer. However, the starting current when an induction motor is connected to a line of normal voltage is excessive and it is the principal object of the added external rotor resistances to limit this starting current.

Another effect of introducing resistance in the rotor circuit at starting is to increase the starting torque. An induction motor exert its maximum torque when *the rotor reactance is just equal to the rotor resistance.* The rotor reactance varies directly with the slip and at standstill is much greater than the resistance in the ordinary rotor winding. By inserting extra resistance at starting, the resistance is brought equal to the reactance and maximum torque is exerted at starting, a very favorable condition when the motor has to start line shafting, etc. As the motor speeds up the extra resistance is cut out in steps and if properly done, the equality of resistance and reactance is nearly maintained as the motor speeds up; thus the rotor may be made to exert approximately its maximum torque all the time during which it is accelerating.

With a polyphase induction motor three runs are to be made, one with the rotor short circuited and two with additional resistance in the rotor circuit. If a two phase motor is used make connections as in Fig. 24, and if three phase, as in Fig. 25. Note the effect on the direction of starting of reversing the connections of one phase; of reversing two phases.

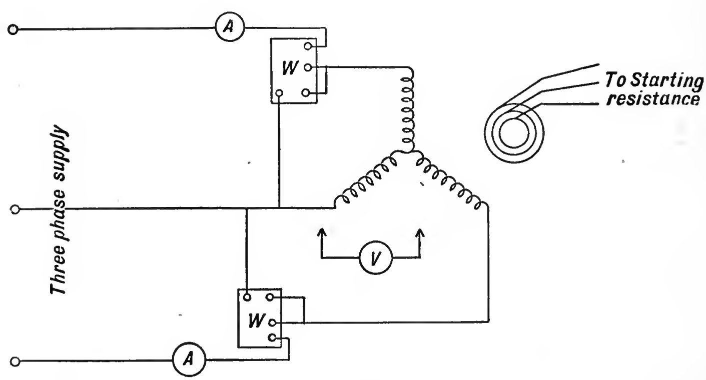


Fig. 25

Instead of using two sets of instruments as shown in above figures, a single set of instruments may be used with the combination of switches given in Ex. 4.

In measuring three-phase power with two wattmeters as above, one wattmeter will read negative if the power factor of the motor is less than .5. Begin the run at full load and connect the wattmeters so that positive readings are obtained on both phases; at full load the power factor will surely be greater than .5. As the load decreases one wattmeter reading will decrease faster than the other, will reach zero at perhaps one-quarter load and at lighter load will deflect backward. Under this condition the potential coil is to be reversed, reading taken and *called negative*, i.e., the motor input is the difference of the two wattmeter readings. No such difficulty will be encountered with the two-phase four-wire systems given in Fig. 24, but may arise if a three-wire two-phase system is used for power.

Calculate the full load torque of the motor (assuming no slip) and take readings of input, torque and speed for about eight values of torque between zero and 50 per cent overload. Keep impressed voltage and frequency at rated values of the motor.

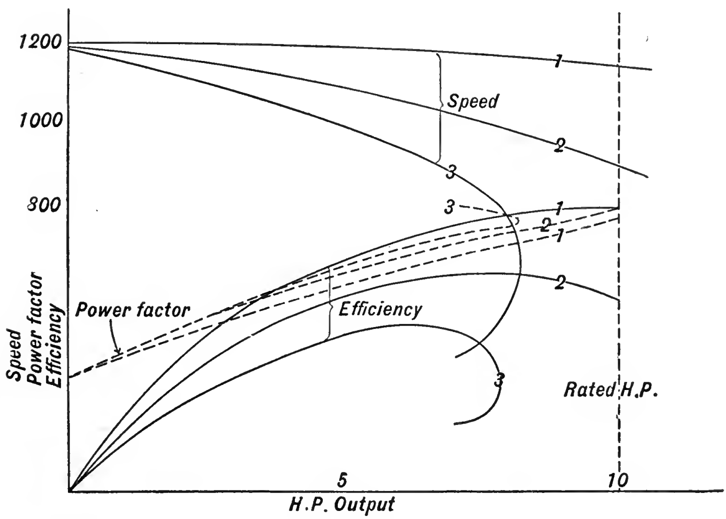


FIG. 26

Make this run with the rotor short circuited and make similar runs with two different values of added resistance in the rotor circuit. The greater value of resistance should be about sufficient to give the rated full load torque at half synchronous speed; the other resistance to be about one-half this value.

The curves obtained from test should look similar to those of Fig. 26, which were obtained from a 10 H.P., 60 cycle, 220 volt, 2 phase motor.

The next characteristic of the motor to be investigated is the relation of starting torque and current to the resistance of the rotor circuit. Apply one-half rated voltage (at rated frequency) to the motor, having the rotor locked. Take readings of torque and current for the different points of the starting resistance.

Find out how much starting torque a single-phase induction motor has; this may be tried by opening one of the lines supplying the power to the stator. The stator will then be supplied with single-phase power only, and it will be found that under such

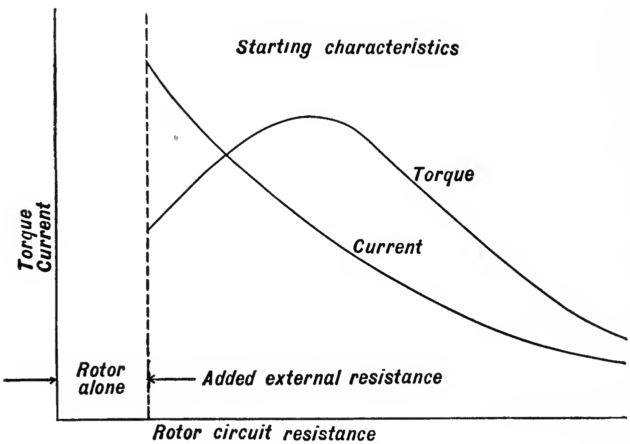


FIG. 27

conditions the motor exerts no starting torque whatsoever. If, however, the motor is allowed to reach normal running speed while supplied with polyphase power and then one line is opened, it will be found that the motor will run all right and will carry nearly full load before the " pull out " point is reached.

Measure resistance of rotor and of the various steps of the starting resistance, if they are not given. Plot curves of starting torque and current against rotor circuit resistance. The results should be somewhat of the form of those given in Fig. 27, which are for the same motor as the curves of Fig. 26.

Questions

What will be the no-load speed of a 6-pole 60-cycle induction motor? Of a 4-pole, 25-cycle motor? What would be the approximate full-load speeds of these two motors, assuming no resistance is added to the rotor circuit?

Could an induction motor be obtained from a manufacturing company, which would give a no-load speed of 1000 R.P.M. when operated on a 60-cycle line? How many poles would it have?

If a 60-cycle, 8-pole motor is made to give a full-load speed of 450 R.P.M. by added rotor resistance, about what efficiency might be expected?

If a three-phase induction motor has a fuse blown in one line, how much starting torque will the motor exert?

If the brushes on the slip rings of a wound rotor induction motor are lifted, how much torque will the motor exert? Why?

A 60-cycle motor has a slip at full load of 8 per cent The self-induction of a rotor coil is 0.001 of a henry. The resistance of the rotor coil is 0.05 ohm. What is the impedance of the coil at full load? At standstill?

EXPERIMENT VI

The Synchronous Motor; Phase Characteristics and Phase Shifting with Load. If two alternating current generators are operating in parallel, supplying power to the same line, and the driving power is taken away from one of them, it will ordinarily continue to run at exactly the same speed it had before (provided the other alternator does not slow down) and it draws from the other alternator the power necessary to run itself. An alternator so running is termed a synchronous motor, as it runs *exactly in synchronism* with the alternator supplying its power. This point is to be emphasized; a 6-pole synchronous motor running from a 60-cycle power line runs at 1200 r.p.m. no load and 1200 r.p.m. full load, and continues to run at 1200 r.p.m. as the load is further increased, until the "pull out" point of the motor is reached at perhaps 50 per cent overload; when this load is reached the motor pulls out of synchronism with the line and stops. As soon as it pulls out of step it draws an excessive current and the protective apparatus either at the motor or in the generating station must open if disastrous results are not to be incurred.

A synchronous motor is generally not self-starting; some auxiliary driving power must bring it up to synchronous speed and when the proper conditions are reached the switch connecting the motor to the supply line is closed. A polyphase synchronous motor is sometimes started *as an induction motor*, in which case, of course, no auxiliary starter is necessary. In this method of starting the field is left unexcited, the armature is connected to some low voltage taps (generally 50 per cent normal or less) on the supply transformers. The armature draws a rather heavy current, perhaps 100 per cent in excess of full load, and this armature current induces eddy currents in the pole faces. The interaction of the armature current and these eddy currents tend to make the armature rotate. It will continue to accelerate until it reaches synchronous speed; the armature is then connected to the normal voltage taps of the supply transformers and the field gradually excited until normal field current is reached. In revolving field synchronous motors where this method of starting is used, each pole face of the machine is pierced by a number of brass or copper rods placed parallel to the shaft; the ends of these rods are connected to brass short circuiting rings. The machine thus starts as a squirrel cage induction motor.

The connection of the armature to one-half voltage taps and then to normal voltage taps is accomplished by a double throw switch; the transition is made as quickly as possible so that the motor has no time to slow down during the process.

The disadvantage of this method of starting is *the large starting current taken from the line at very low power factor;* the resultant fluctuations in the line voltage may seriously interfere with the operation of other synchronous apparatus connected to the line; in fact, if the fluctuations in line voltage are large, other synchronous apparatus may actually fall out of step. In spite of these disavantages the method is a very common one for starting revolving field synchronous motors.

Another method for starting a synchronous motor is to use a small induction motor, the rotor of which is mounted on the extended shaft of the synchronous motor. The induction motor may be 10 per cent the size of the synchronous motor; it must have at least one pair of poles less than the synchronous motor; and it is so designed that when its load is equal to the no load losses of the synchronous motor (core loss and friction) it is turning the synchronous motor at synchronous speed. After the synchronous motor is connected to the line, power is cut off from the induction motor and the rotor runs idle.

The switch connecting the armature of the synchronous motor to the supply line is called the *synchronizing switch.* Before this may be closed four conditions must be fulfilled, unless the induction motor principle, as described above, is used for starting the motor. These conditions are:

1. Motor voltage equal to line voltage.

2. Motor frequency equal to line frequency.

3. Phase of motor voltage exactly opposite to that of line.

4. Wave form of motor E.M.F. must be nearly similar in form to wave of line E.M.F.

The first three conditions may be adjusted by the operator, the fourth is satisfied or not when the machine is built. As was mentioned in the discussion of the alternator, the wave form of an A.C. machine is determined by the shape of air gap and pole piece and the distribution of the armature windings.

By analyzing the four conditions named, it is seen that they demand that the motor voltage shall at every instant be equal and opposite to the line voltage. If that were not the case a

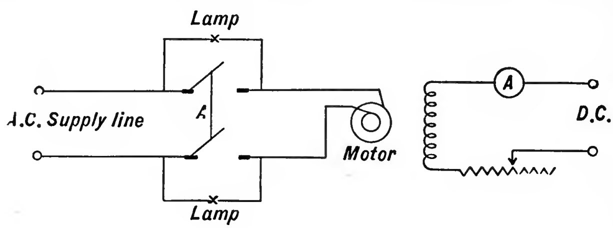


FIG. 28

heavy current would flow through the armature due to the unbalanced voltage; the current will be large even for a small unbalancing of voltage, because of the low impedance of the armature.

The first two conditions can be satisfied by the use of a voltmeter and speed counter when frequency of line supply is known. To determine the third condition, synchronizing lamps or a synchronoscope must be used. The synchronoscope is an indicating instrument having two internal circuits, one of which is connected to the line and one to the motor. The position of the pointer indicates the relative phases of the two E.M.F.'s.

Lamps are to be used in this test, so their action will be more fully described. One lamp is connected across each blade of the synchronizing switch A, as in Fig. 28. The lamps will flicker as the motor phase changes with respect to the line phase. They complete a circuit consisting of the motor armature, the line and armature of the generator supplying the line. In this circuit *there are acting two E.M.Fs.*, that of the motor and that of the generator. At any instant the effective voltage causing current to flow through the lamps is the resultant of the two; as their relative phase changes, the resultant changes and has for its locus a circle as shown in Fig. 29. The resultant voltage for any position of E_m is seen to be OR, the chord to the circle from the point O. The current through the lamps, and therefore their brilliancy, will increase as the motor voltage E_m catches up (in phase) with E_g and will decrease as the two E.M.Fs. separate in phase. There will be no current through the lamps when E_m

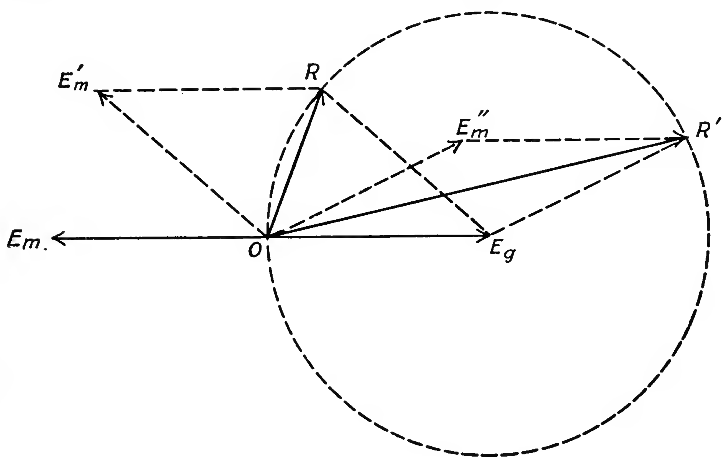


FIG. 29

is just opposite in phase to E_g; condition No. 3 is therefore satisfied when the lamps are dark and this is called the "*dark*" connection for synchronizing. With the lamps connected diagonally across the switch, the proper time for closing the switch is at the middle of a *bright* period.

After having adjusted the motor voltage to equal the line voltage, the speed of the motor is so adjusted (by adjusting its driving motor) that the lamps flicker once in 4 or 5 seconds; the switch A is then closed in the middle of a dark or bright period, according to the connection of the lamps. The power supplying the starting motor may then be cut off.

If a three phase motor is used, it is necessary to use three synchronizing lamps, one connected across each pole of the three pole synchronizing switch. The lights must flicker together; if they are bright and dark in rotation instead of simultaneously, one of the phases is incorrectly connected and two of the supply lines must be reversed in their connection to the motor.

One of the important features of the synchronous motor is well shown by the set of curves called "phase characteristics."

If the load on a synchronous motor is kept constant and the

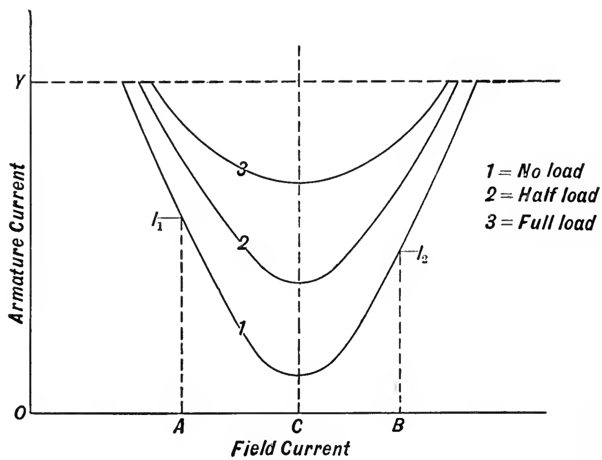


FIG. 30

field current varied, the armature current is caused to vary in about the fashion indicated in Fig. 30. It is this curve, drawn between armature current and field current as variables, which is called the phase characteristic. For any load a certain definite field current gives a minimum armature current. This value of field current gives the so called *normal* excitation. For any value of field current other than normal the armature current is greater than that taken with normal excitation.

Now as the load of the motor is supposed constant the power component of the armature current must remain practically constant. It must be, therefore, that any other than normal excitation on the motor produces in the armature a wattless or reactive current, which, being 90° out of phase with the motor voltage, represents no expenditure of power in the motor. In fact an overexcited synchronous motor draws a leading current from the supply line and an underexcited motor a lagging current, as shown in Fig. 31. *OE* is the phase of the line voltage and *OI* is the armature current for no load with excitation *OC*, Fig. 30. Excitations *OA* and *OB* result in armature currents AI_1, and BI_2, Fig. 30, which are represented vectorially in Fig. 31; as OI_1 and OI_2.

If the speed of a synchronous motor is independent of load

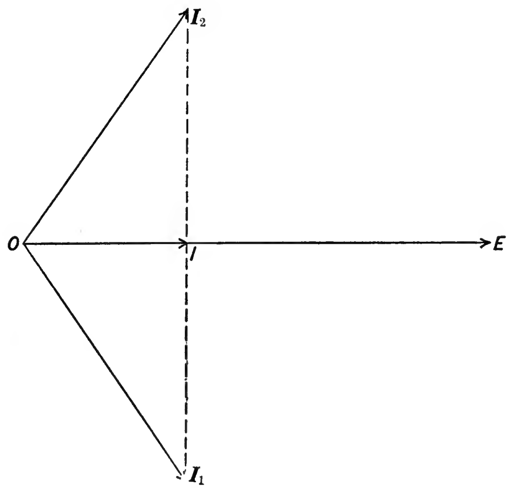


FIG. 31

the question arises, how does the motor adjust itself to take more or less load? The phase shifting of the motor armature is what accomplishes this end.

The E.M.F. causing current to flow through the armature of the motor, is the vector resultant of the motor voltage and line voltage. This resultant varies with the variation of the phase difference of the two E.M.Fs. In Fig. 32 are shown two positions of E_m, the motor voltage, with respect to a fixed line voltage E_t. The resultant, OE_r, is the E.M.F. causing current to flow in the motor and this changes widely with a small shifting of OE_m. The current OI is equal to the voltage OE_r divided by the armature impedance. It is laid off behind OE_r by the angle θ, where

$$\tan\theta = \frac{\text{armature reactance}}{\text{armature resistance}}.$$

It is variation of the angle α, giving the phase position of the armature, which permits the motor to take more or less load.

The variation in α may be easily determined. Suppose that two insulated discs with metallic strips (as used in Ex. 1) are placed one on the shaft of the generator supplying the power and one on the shaft of the motor, and that a voltmeter is wired to

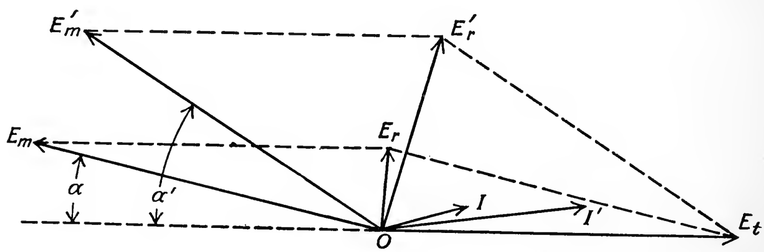


Fig. 32

a 110-volt circuit through these two discs and their brushes (Fig. 33). The voltmeter will indicate only if the two brushes are in contact with the metal strips at the *same time*. The brush on the motor moves over a graduated arc so that its position may be read and the brush on the generator remains stationary. The position to which the motor brush must be moved before the voltmeter gives maximum deflection gives the phase position of the motor armature with respect to the generator armature. If the generator is large compared to the motor, its armature position is also a measure of the phase of the E.M.F. impressed on the motor. It will be found that the value of α is almost directly proportional to the load.

With the connections as in Fig. 34, obtain the phase characteristics of the motor for no load, $\frac{1}{2}$ load and full load. On each curve get about 8 points, using for armature current not more than 150% of the rated current of the motor; i.e., in Fig. 30, OY should not be greater than 50% above the rating of the motor. The motor may be loaded by Prony brake or, what is more convenient, by a D.C. generator. The generator may be used as a starting

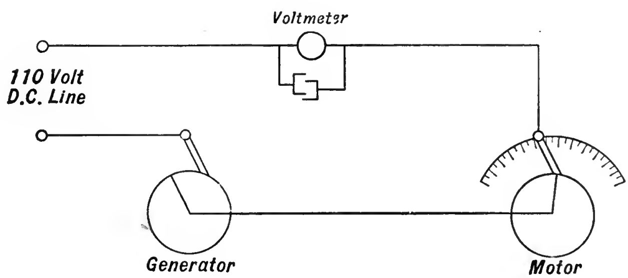


FIG. 33

motor until the A.C. motor is synchronized and then it may be used as generator to load the synchronous motor.

In getting the phase characteristics it is not necessary to know the exact load on the motor; $\frac{1}{2}$ rated current may be used as half load, etc.

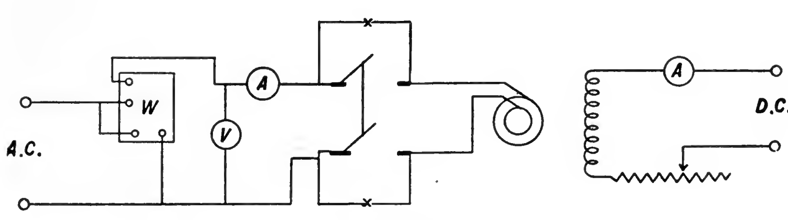


FIG. 34

The impressed voltage and frequency are to be held constant; read volts, amperes, watts input and field current.

Then adjust the field current to the value for minimum armature current at no load. Adjust the brush on the motor disc until the voltmeter shows maximum deflection, and read brush position. Read also impressed E.M.F. and field current, which are to be maintained constant, and also watts and amperes supplied to armature.

Put on load in about 8 steps from no load to 50 per cent overload, taking same readings as for no load.

Plot on one sheet, against field current as abscissa, watts input, amperes input and power factor for each of the runs.

Plot on a second curve sheet, watts input to motor (armature input only) against brush position as abscissa. Note whether the brush is moved *with or against* the direction of rotation as load is increased, and so determine whether the motor armature is *advanced or retarded* in phase as the load on the motor is increased.

Questions

If a line shaft is to be driven by a direct connected synchronous motor, what speeds are ordinarily obtainable if the power supply is 60-cycle? If 25-cycle?

A single-phase synchronous motor is drawing 125 amperes from a 2300-volt line at a power factor of 0.70, leading current. How much power is being supplied to the motor? How much is the leading component of the armature current?

A synchronous motor is to be used as a synchronous condenser to compensate for the lagging component of current taken by an induction motor load. The induction motor load is 65 amperes at a lagging power factor of 0.76; the line voltage is 6600. Assuming that it requires no power to run the synchronous condenser, what must be its rating to just neutralize the lagging current of the motor load? What must be its rating if the power factor of the line is to be increased from 0.76 to 0.95? With the latter condition what will be the current taken by the motor if it is also required to deliver mechanical energy as well, at the rate of 200 horse-power (assuming motor efficiency is 90 per cent)?

EXPERIMENT VII

The Rotary, or Synchronous, Converter; Effect of Voltage and Speed upon Ratio; Operating Characteristics. The efficient transmission of electric power over any considerable distance requires the use of alternating currents, as explained in Ex. 4. Practically all motors for driving electric trains are D.C. motors; although alternating current motors have been used in some few cases, the field of electric traction in America is so exclusively controlled by the direct current motor that from the general standpoint the A.C. motor need not be considered. The characteristics of a small A.C. series motor are given in Fig. 35. Also in dotted lines are given the characteristics of the same motor run with direct current power; the superiority of its behavior as a D.C. motor is so evident that nothing further need be said regarding the comparative merits of A.C. and D.C. railway motors.

The electric railway generating station is always located where water and coaling facilities are good, and A.C. power is generated. This power is transmitted at a high voltage to a substation where the voltage is stepped down. It is the function of the rotary converter to change this low voltage A.C. power into D.C. power for use in the car motors.

An elementary explanation of the performance of a rotary converter may be given by supposing that the winding of a D.C. shunt motor is tapped (on the end opposite to the commutator) at two points 180° (electrical) apart. These two taps are to be connected to two slip rings. Now any winding revolving in a magnetic field generates an alternating E.M.F. If the winding is connected to slip rings an alternating current is delivered to the outside circuit; if the winding is connected to a commutator the delivered current will be direct. From this it follows that the shunt wound motor would have on its slip rings an alternating E.M.F.; if the rings are connected to an external circuit an alternating current will flow from the A.C. brushes and a corresponding increase in the D.C. input will occur. Such a machine converts D.C. power into A.C. power; it is ordinarily termed an

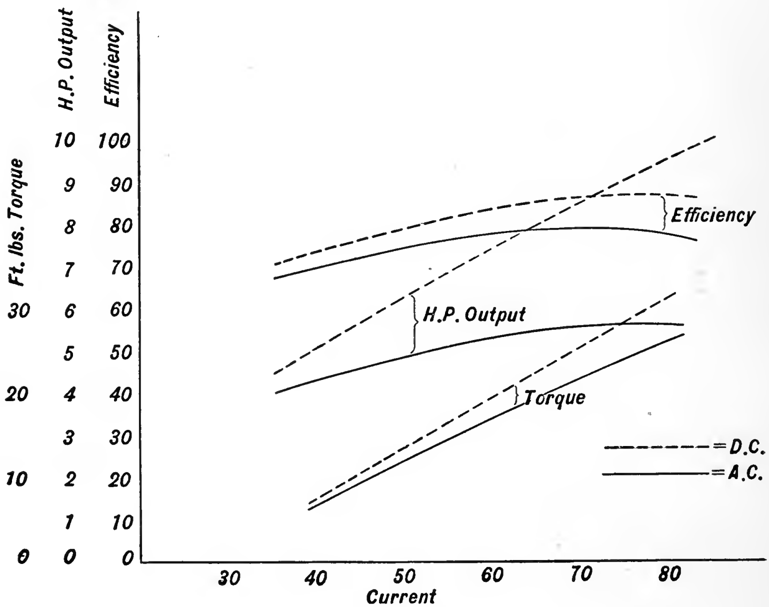


FIG. 35

"inverted" rotary. If now the function of the machine is reversed, i.e., A. C. power is supplied to the slip rings, the machine running as a synchronous motor, and D.C. power is taken from the commutator end, it will be operating as a rotary converter normally does. The amount of A.C. power input depends upon the amount of D.C. power output.

The efficiency of a rotary varies, of course, with the size, being perhaps 95 per cent in the larger machines and 85 – 90 per cent in the smaller ones.

The distinctive feature of a rotary of the ordinary type is the ratio of A.C. to D.C. volts. For a single phase machine it is .707, for a three-phase machine .612; it is a constant which depends only on the number of A.C. taps. For a given impressed A.C. voltage the D.C. voltage is nearly independent of load; it decreases somewhat with increase of load because of the impedance drop in the armature windings.

The power factor of the A.C. input will depend upon the value of the field current; in this respect the rotary is exactly similar to the synchronous motor. Under ordinary conditions

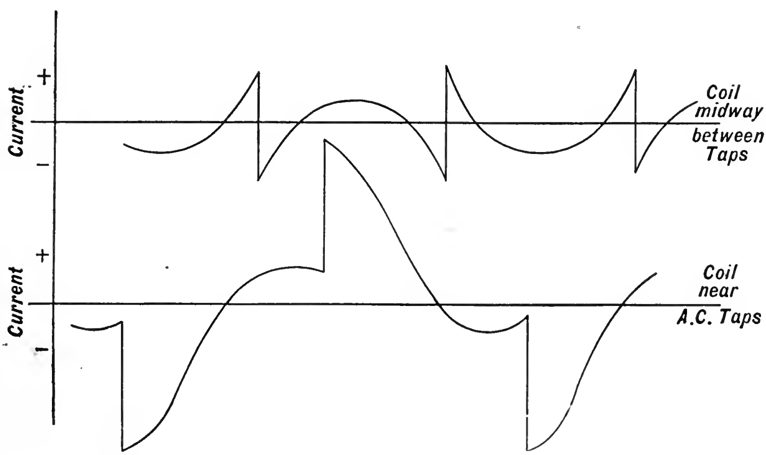


FIG. 36

the field current should be adjusted to that value which gives a minimum armature current for the load being carried; this value of field current does not change much with the load; if adjusted for one load it will be nearly correct for any other.

The coils of the armature carry the instantaneous difference of the A.C. and D.C. currents, the form of the current flowing in any one coil being displaced sections of a sine curve. The form of the current wave in the coils, one close to the tap and one half way between taps is shown in Fig. 36. The peculiar shape of these current waves results in unequal heating in the different coils of a rotary, those nearest the taps getting hottest.

Because of the fact that the D.C. and A.C. currents in the different coils tend to neutralize one another the capacity of a given machine is considerably greater run as a rotary than as an alternating or direct current generator. A certain size machine used as generator or rotary has capacities as follows:

D.C. generator capacity	= 100 K.W.
Single phase A.C. generator capacity	= 70.7 K.W.
Single phase rotary capacity	= 84.8 K.W.;
Three phase rotary capacity	= 133.8 K.W.;
Six phase rotary capacity	= 193.7 K.W.

The above values are for power factor of one. For other power factors the values are somewhat different.

Because of the fact that the ratio of D.C. to A.C. voltage is fixed for any given rotary, it might seem that a rotary could not be compounded, i.e., give a D.C. voltage increasing with load. In one way this is true; for a given impressed A.C. voltage the D.C. voltage cannot be increased, but in practice the impressed A.C. voltage is made to increase with load, thereby making the D.C. voltage rise also.

Recently a special type of rotary using field poles in two sections has been developed; in this rotary the ratio of E.M.F.'s is not fixed. In a small laboratory machine of this type, by proper adjustment of the currents in the two sections of the pole, the D.C. voltage may be made to vary from 90 to 135, while the impressed A.C. voltage is kept constant at 88. This is a very special type of machine and not much used as yet.

The ratio of an ordinary rotary having the A.C. taps separated by the angle α, measured in electrical degrees, is given by the formula,

$$\text{A.C. volts} = \frac{\text{D.C. volts}}{\sqrt{2}} \times \sin\frac{\alpha}{2}.$$

There are several methods for starting a rotary and bringing it into synchronism with the A.C. line. Either of the two methods described for a synchronous motor may be used and there is in the rotary the additional possibility of starting from the D.C. end as a D.C. shunt motor. This is a convenient method for use in the laboratory as D.C. power is always available. In substations D.C. power may not be available, under which condition one of the methods employing A.C. power must be used.

For starting from the D.C. end it is necessary to have a D.C. line of at least the rated voltage of the machine. For a single phase machine rated at 110 volts A.C. the necessary D.C. voltage is 110/.707 = 157 volts; for a three-phase 110 volt A.C. rotary, the necessary D.C. voltage is 110/.612 = 181 volts. A D.C.

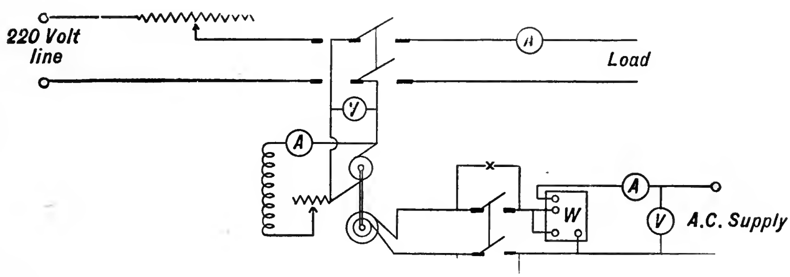


Fig. 37

starting rheostat is used as with a D.C. motor. The rheostat resistance is decreased until the impressed D.C. voltage is just that necessary to give the required A.C. voltage. Then the rotary is bought into synchronism with the line by changing the field current; a synchroscope or synchronizing lamps, as with the synchronous motor, may be used to indicate the proper time for closing the synchronizing switch.

Two runs are to be made with the rotary, one running from the D.C. end to determine the ratio of the converter and its possible variation and the second to get the operating characteristics of the machine when running from the A.C. end, as it is normally designed to do.

For making these two runs it is convenient to make connections as given in Fig. 37. The rotary represented is a single-phase machine designed for 110 volts on the A.C. end.

In testing the voltage ratio make one run, keeping the impressed D.C. voltage constant, and vary the speed through as wide a range as possible by changing the field strength; read A.C. volts, D.C. volts and speed. Then take another run with various D.C. voltages impressed, keeping the speed constant by variation of field strength; read same as before.

In taking the load run the machine is first to be synchronized with the A.C. line. After the starting rheostat, *R* has been so adjusted that the rotary A.C. voltage is equal to that of the A.C. line, change the speed (by field variations) until the synchronizing lamps indicate synchronism, and then close the synchronizing switch in the middle of a dark period, with lamps connected as in Fig. 37. Of course "bright" connections of lamps may be used if desired. When synchronized the D.C. supply line is to be opened and the switch thrown over to load side.

Adjust the value of field strength so that at no load the A.C. armature current is a minimum. Leave the field circuit resistance constant at this value and put load on the D.C. end of the rotary in about 8 steps between zero and 50 per cent overload. Keep impressed A.C. voltage constant. Read A.C. volts, amperes, and watts, field current, D.C. load current and D.C. volts.

On one curve sheet plot the ratio values obtained in first run, using ratio as ordinates. On second curve sheet, plot curves of D.C. volts, efficiency and power factor, using D.C. load current as abscissæ for all curves.

Questions

What voltage must be impressed on the A.C. end of a three-phase converter if the voltage on the D.C. end is to be 600?

If this converter is to be compounded 50 volts on the D.C. end, how much must the voltage impressed on the A.C. end increase from no load to full load (neglecting armature drop)?

Through what range can the voltage ratio of an ordinary converter be varied?

A converter, running inverted on a D.C. line of 110 volts, gives what voltage on its slip rings, three-phase machine assumed?

A railway converter rated at 1000 K.W., six hundred volts, would draw what current from the A.C. line, if it were run single phase and had an efficiency of 93 per cent?

Explain why the voltage on the D.C. end of a converter, running normally, does not increase as the field strength is increased.

EXPERIMENT VIII

Parallel Operation of Alternators; Circulating Current; Division of Load Dependent upon Phase Shifting. At present the largest sizes in which it is feasible to build A.C. generators is about 20,000 K.V.A. To equip a station for a capacity of 100,000 K.V.A. it is therefore necessary to install several generators, and as there is generally only one set of bus bars and one

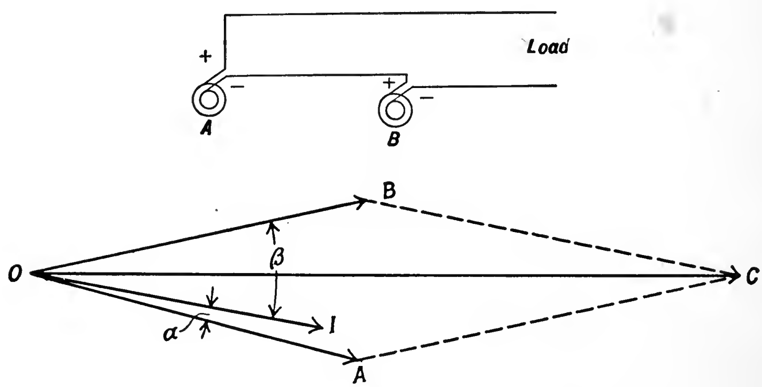


Fig. 38

distribution system, it is necessary to so connect these generators electrically, that they all supply power to the same line. The only stable connection is to have them working in parallel, and many stations have as many as ten or more large alternators all connected in parallel to the same switchboard. It is therefore important to investigate the operating characteristics of such a set of machines.

It will first be shown that two alternators operating in series are not in stable equilibrium. Two single phase machines, connected in series, supplying a load drawing a current, lagging somewhat behind the line E.M.F., are shown in Fig. 38. Each machine is generating the same voltage and it is supposed that for some reason that machine B has pulled slightly ahead of machine A in phase. The vector diagram of E.M.Fs. and current is given in Fig. 38. The vectors OA and OB represent the machine voltages, OC the resultant or line voltage, and OI the line current. The load on machine B is equal to $OB \times OI \times \cos \beta$ and that on machine A is equal to $OA \times OI \times \cos \alpha$. As α is less than β it is evident that machine B, which for some reason has pulled ahead of A in phase, has thereby relieved itself of part of its share of the load. This effect will make machine

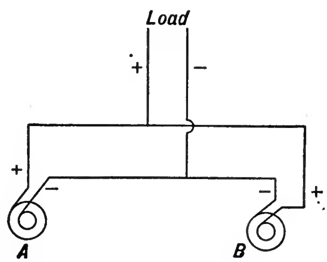


Fig. 39

B speed up still more because any ordinary prime mover will increase its speed if load is taken from it. B will continue to get ahead of A in phase until the two vectors OA and OB are practically in opposition, under which condition there is no line voltage and therefore no load.

The polarities marked in Fig. 38, of course, are true only at a certain instant, but the two machines will both reverse at the same time, leaving the phase of E.M.Fs. *relative to one another*, the same. If, however, when the two machines have pulled into opposition, with respect to each other, the load circuit is short circuited and the load attached as in Fig. 39, the conditions of operation and load distribution are stable. The vector diagram given in Fig. 40 will make this point clear. When the two machines are exactly in opposition, with respect to each other, the E.M.F. vectors are shown at OA and OB. There is no resultant E.M.F. in the circuit consisting of the two armatures and connecting bus bars and therefore there is no current flowing around this local circuit. The two machines will, under these conditions, divide the load equally, provided that the two armatures have equal impedances.

In Fig. 39 it is seen that although the two E.M.Fs. oppose one another around the local armature circuit, they act together, in parallel, in so far as the load circuit is concerned.

Suppose now that machine B speeds up for an instant with respect to A, so that the relative phases of the two E.M.F. vectors are as shown as OA and OB', in Fig. 40. In the local circuit

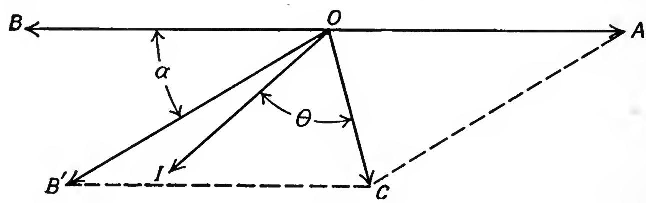


FIG. 40

there now exists a resultant voltage OC which will force current to flow through the two armatures, *in addition to whatever load current* the two machines may be carrying. As the inductance of the armature is much greater than the resistance, this local current will lag nearly 90° behind the E.M.F. causing it; OI represents this current in phase, behind the voltage OC, by the angle θ where

$$\tan \theta = \frac{\text{armature reactance}}{\text{armature resistance}}.$$

Now this current is nearly in phase with the voltage OB', and hence is a load on machine B, while it is a motor current for machine A, as it is nearly 180° out of phase with OA. The real effect of this current is therefore to take some of the load from machine A and put it on machine B; this will tend to slow down B and is therefore an effect which tends to prevent the machines leaving their phase position of 180° with respect to one another.

The previous analysis has been on the assumption that the two machines were generating the same voltage. Suppose now that the load on the two machines is equally divided (E.M.Fs., 180° apart) and the excitation of machine A is increased. Will this change the distribution of load? By reference to Fig. 41, it is seen that the resultant voltage OC, now lies in phase with OA. The resultant local current OI is shown lagging by the angle θ behind OC; this current OI is practically a wattless current, as it is in 90° position, nearly, with respect to both E.M.Fs. As it is not in phase with the generator E.M.Fs., it cannot, with non-inductive load, represent load current. As a matter of fact, this increase in voltage of machine A will scarcely affect the load distribution at all, but will produce a current which flows

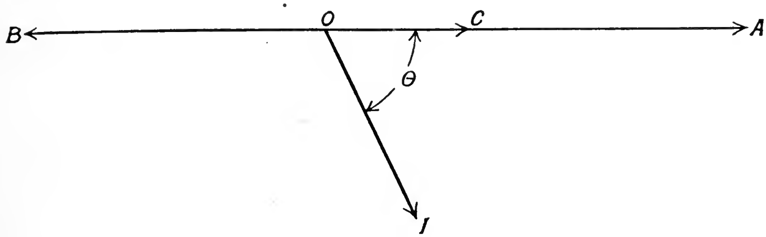


FIG. 41

in the local circuit only; it is practically 90° out of phase with the E.M.Fs. and its only effect is to tend to equalize the two voltages OA and OB. It will tend to magnetize the machine B and demagnetize machine A. This effect of armature reaction by the circulating current will change the voltage of the line somewhat as excitation of machine A is varied.

Referring to Fig. 40 it is evident that the division of load depends upon the angle α. Now the only way of changing this angle is to vary the driving torque of the prime mover, and it is in this fashion that load is distributed between the different machines in a station. The steam supply of the driving engine or turbine is generally under the control of the switchboard operator.

Summing up the conclusions reached we have: the division of load between two alternators operating in parallel depends only upon their relative phase position; the load division cannot be affected by varying the field strength, but such variation of field results in a nearly wattless current circulating in the local circuit, which merely heats the machines, represents no power output and is therefore detrimental to the operation of the machines.

The first run to be made in this test is to show the variation of load on machine *B* by variation of the driving torque, and hence the phase angle α, with constant excitation of *B*; the second is run to keep the driving torque of *B* fixed, and to vary the excitation of *B* both above and below normal to show variation of circulating current and independence of load division.

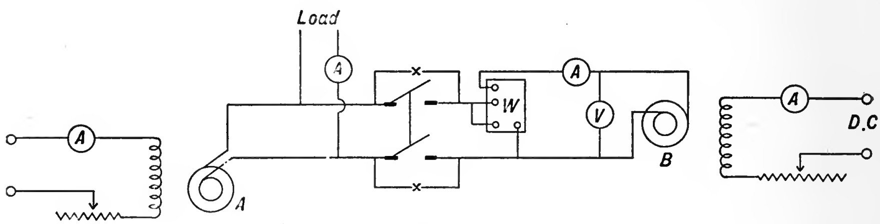


FIG. 42

Make connections as in Fig. 42, bring machine *A* to rated voltage and read its field current. Keep it constant at this value throughout the test. Put upon machine *A*, a load of about one-half its rated capacity. Synchronize machine *B* with machine *A* and read field current, watts, output, armature current and line voltage. Leave the field current fixed at this value and increase the torque of *B*'s prime mover in such steps as will produce changes in the armature current of *B* of about one-quarter rating. Take readings up to 50 per cent overload, reading for each step watts and armature amperes of *B* and line voltage. Get the values of α for each setting of load by the scheme of two insulated discs used in experiment No. 6.

Then reduce the torque of *B*'s prime mover until the wattmeter reads zero. Now vary the field current of *B* in such steps as produce increments in the armature current of about one-quarter rating, reading for each setting, field current, armature current and watts, line voltage and phase position of *B*'s armature.

On one curve sheet plot the variations of watts load of *B* and phase position of its armature. Calculate also the value of the circulating or wattless current flowing in *B*'s armature for each reading. Plot load and circulating current against phase position as abscissæ. On a second sheet plot variations of load in watts, circulating current and phase position, against field current of *B* as abscissæ.

NOTE.—The remarks regarding effect on load distribution of variation of *B*'s field current were made on the assumption that the angle θ was nearly 90°. In so far as this is not true the conclusions reached are more or less inaccurate, but a more detailed discussion makes the question too complex.

QUESTIONS

A 12-pole alternator is to be synchronized with a 60-cycle line. At what speed must it be run?

Referring to Fig. 42, suppose the readings of the instruments on machine *B* are volts 110, amperes 55, watts 4850, the load circuit being non-inductive. How much is the circulating current between the two machines? If machine *A* is furnishing to the load 10 K.W. of power, how much current is there flowing in its armature?

If machine *A* is generating 60 cycles and, before synchronizing, the lamps flicker twice per second, how fast is machine *B* running if it has 8 poles? There are two possible answers to this question.

Why should the field currents of the various alternators in a station, operating in parallel, be so adjusted that the circulating current is a minimum?

Suppose that the maximum safe armature current of machine *B*, Fig. 42, is 150 amperes, and also that the fields of *A* and *B* are so adjusted that there is a circulating (wattless) current of 45 amperes flowing between them. If the bus bar voltage is 125, what is the maximum load (in K.W.) that machine *B* can furnish to the load circuit?

EXPERIMENT IX

Current and Voltage Relations in a Three Phase Circuit; Measurement of Power on Non-Inductive and Inductive Loads. Practically all A.C. power is generated, transmitted and utilized by polyphase circuits and machines. Of all polyphase circuits the three phase is by far the most important.

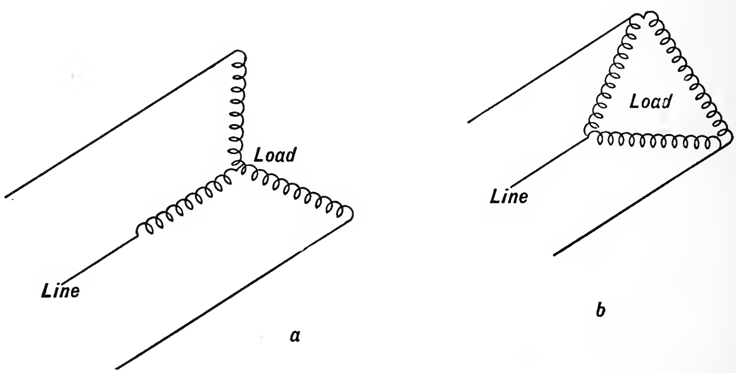


Fig. 43

The easiest way to study the current and E.M.F. relations in such a circuit is by first considering it as three single phase circuits. The problem will be investigated only for balanced loads, i.e., a polyphase system which may be considered as made up of a group of equally loaded single phase circuits.

A three phase load may be connected in two ways: the star or Y connection shown at a, Fig. 43, and the mesh or Δ shown at b. With either connection only three wires are used. It is apparent that only three wires are needed for the Δ connection, and it may be shown that in the Y connection a wire connecting to the center or neutral point of the load is unnecessary. In Fig. 44 the three phases are supposed separate, each phase is carrying the same magnitude current and of course the three currents, represented as vectors, are 120° apart. This feature of the three phase system is a result of the method of placing the coils on the armature of the three phase generator; the coils are placed 120° (electrical) apart, hence generate three sine E.M.Fs. 120° apart, and so the currents from such a generator are 120° apart.

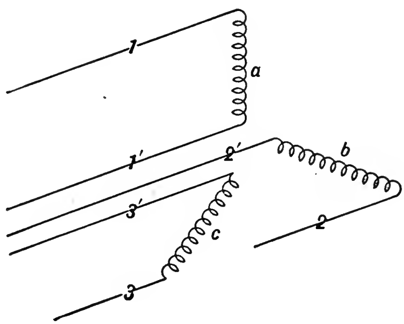


FIG. 44

In Fig. 44 the three single phases are shown at *a*, *b*, and *c*. The three lines, 1′, 2′ and 3′ are evidently carrying three equal currents, 120° apart in time. If then these three lines are joined throughout their entire length, the resultant single line will carry the resultant of three equal sine currents spaced 120° apart. But such resultant is zero, and therefore the combination line or neutral, as it is called, is useless and so not used. The three single circuits, joined together at 1′,2,′3′ then constitute a *Y* load, supplied with three phase power through the lines 1, 2, 3. In discussing voltage and current relations we have,

i=current in each phase of load;
e=voltage across one phase;
I=current in any line;
E=voltage between lines.

In the Y connection of load it is evident that $I=i$. To get the line voltage it is necessary to take the vector difference of two voltages, each of magnitude $=e$, spaced 120° apart. The voltage between lines by this construction gives $E=e\sqrt{3}$.*

In the delta connection $E=e$. To get I it is necessary to take the vector difference of two currents each of magnitude i, and 120° apart in phase, and this gives $I=i\sqrt{3}$.

Now no matter how the load is connected, it is evident that the power used in the three phases is equal to $3ei$, if $\cos\phi=1$. Substituting values of line current and line voltage gives power of a three-phase load $=EI\sqrt{3}$, and this holds good for either con-

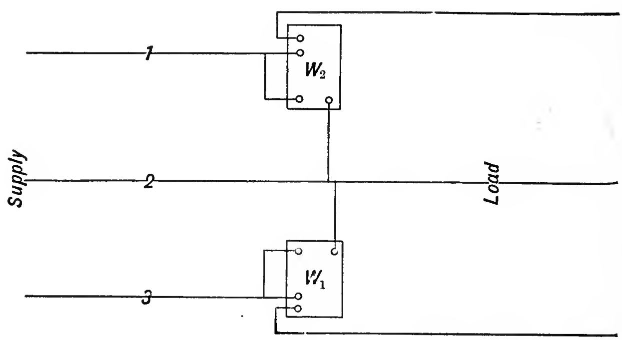


FIG. 45

nection of load. If the power in each phase is equal to $ei\cos\phi$, then in terms of line quantities we have, watts used in three-phase load $=EI\sqrt{3}\cos\phi$.

To measure the power used in a three phase line it is not necessary to actually measure the watts in each phase and multiply by three. If it is known that the load is non-inductive, then the power used is easily determined by measuring the line current

* The derivations of the formulæ for voltage and current relations, as well as power relations, in three-phase circuits are not introduced here, as it is a somewhat more involved discussion than it is thought well to incorporate in this text. The student is referred to Morecroft's Laboratory Manual of Alternating Currents, Experiment XXV.

and voltage and multiplying by $\sqrt{3}$. When the power factor is unknown, as is generally the case, another method must be used

If two wattmeters are used as shown in Fig. 45 the sum of the two readings will always be the power used in the three phase circuit, no matter what the power factor may be or whether the load is balanced or not balanced. If the power factor is less than .5, one wattmeter will indicate negatively and then the algebraic sum must be used, not the arithmetical sum. For balanced loads it may be shown that the current in line 1 is 30° out of phase with the voltage between 1–2, and the current in line 3 is 30° out of phase with the voltage between lines 3–2. If ϕ is the phase angle of the load,*

$$W_1 = EI \cos (\phi + 30°);$$
$$W_2 = EI \cos (\phi - 30°);$$

from which

$$W_1 + W_2 = EI\sqrt{3} \cos \phi.$$

But we had already shown that this is the power used in the three phase load.

A convenient switching arrangement for making measurements on three phase, delta loads is shown in Fig. 46. Three single pole, double throw switches are so inserted that the ammeters and wattmeters may be readily transferred from the line to the phase. In balancing or unbalancing the Δ load the meters are connected in the phase (switches all thrown to left in Fig. 46); then when it is desired to read line values the switches are thrown to the right.

With connections as shown in Fig. 46, with meters connected in phases, adjust the three phases so that the load is balanced (using non-inductive load, such as incandescent lamps) and read the three phase currents. With the potential coils of the wattmeter connected as shown in Fig. 46 it is evident that when the switches are thrown to the right the wattmeters will read the power in the correspondingly numbered phases; read each of the meters.

*See note bottom of page 200.

Now, leaving the load fixed at this value, transfer the meters to the line, by throwing the switches to the right; read the three ammeters. The three meters should read equal to each other and equal to phase current $\times\sqrt{3}$. Connection a of wattmeter

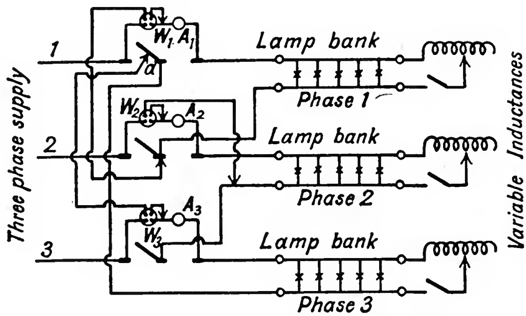


FIG. 46

W_3 should be clipped on to the blade of switch in line 1 so that this switch cannot be thrown to the right without removing the connection. As the switches are all thrown to the right, connection a must be removed from the blade of switch 1 and connected to the blade of switch 2. Wattmeters W_1 and W_3 are now connected as shown in Fig. 45 so that the sum of their readings should give the total three phase power, that is, should check with the sum of the three wattmeter readings in the previous test. In getting the power from the line meters the reading of W_2 is, of course, neglected.

It is to be noted that any two of the wattmeters connected in the lines may be used to get the three phase power. Thus, if W_1 and W_2 have respectively their potential coils connected to lines 1 and 3, and 2 and 3, the sum of their readings will also be the true three phase power. Carry out the above measurements for two values of current with balanced load and for two conditions of unbalanced load.

Next close the switches connecting the variable inductances in parallel with the lamp banks, as shown in Fig. 46. The lamps in parallel with the variable inductance make it possible to obtain a lagging load of adjustable power factor.

With switches thrown to the left (meters connected in phase) adjust the three phases for equal current and equal power factors. This is most easily done by unscrewing all the lamps in their sockets so that they are out of circuit, leaving only the three variable inductances connected to the three phase line. The

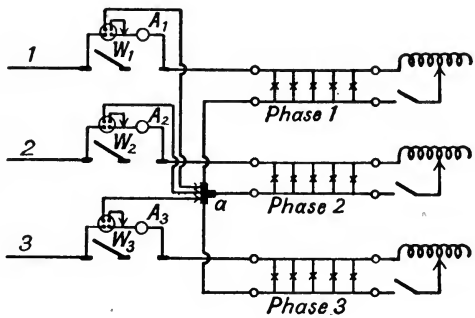


FIG. 47

inductances are then adjusted to give equal currents in the three phases. Then enough lamps are connected in circuit to bring the power factor up to the desired value, connecting the same number in each phase to keep the load balanced. The power factor is of course determined by the ratio of watts per phase to volt-amperes per phase.

With inductive load, balanced, take a set of phase readings, and line readings as for non-inductive load. Do this for one adjustment of power factor about 0.8 and one about 0.4. In the latter case it will be found that when reading watts in the line, one of the wattmeters must have its potential leads reversed to get a reading on the scale. The reading of this meter must be reckoned negative in obtaining the total three phase power from the line wattmeter readings. From the readings obtained from these two runs check the formula for power factor in a three phase circuit, $\cos\phi = \frac{W_1 + W_2}{EI\sqrt{3}}$. In this formula, W_1 and W_2 are reading of line wattmeters while E and I are average values of line voltage and current. The value of $\cos\phi$ obtained by this formula should check with the value obtained from the ratio of watts per phase to volt-amperes per phase, which values have been obtained.

Take another set of readings with load unbalanced and compare line and phase values as before. The two line wattmeters will still give the total three phase power correctly, but the formula for power factor will not hold (except approximately) for slightly unbalanced load and the ratio between line current and phase current will not be $\sqrt{3}$.

The same sets of readings are to be now taken for Y-connected load as have been obtained for Δ loads. The connection scheme of Fig. 46 is charged as indicated in Fig. 47; the three cables which formerly connected to the blades of the switches now are connected together by the three way connector *a*. The wattmeter potential coils being connected as shown each wattmeter reads the power used in its respective phase. By taking the two potential leads of W_1 and W_3, which connect to the neutral point *a* of Fig. 47, and connecting them both to line 2, W_1 and W_3 are properly connected for reading the total three phase power; the sum of their readings should check with the sum of the three wattmeter readings when all potential coils were connected at *a*. Of course it is just as well to use any two of the three wattmeters; thus if the potential leads of W_1 and W_2 (those leads connecting at *a* in Fig. 47) are connected to line 3 then their sum will also give the total three phase power.

With balanced non-inductive load (inductances disconnected) get the relation between phase quantities and line quantities. In this connection evidently the phase current and line current are equal, and it is the line voltage and phase voltage that have the $\sqrt{3}$ relations. The sum of the three phase wattmeter readings will check with the two line wattmeter readings as in the Δ-connected load. Take other readings for unbalanced non-inductive load, and then readings for inductive load, balanced and unbalanced. For balanced loads it will be found that the line voltage is equal to the phase voltage $\times \sqrt{3}$, and that the power factor formula holds good, but for unbalanced loads neither of these relations is true. However, for all conditions of load the sum of the two line wattmeter does give correctly the three phase power.

A convenient method for balancing the three phase Y-connected non-inductive load consists in opening one line (say line 3) and then adjusting phases 1 and 2 for equality by making the voltage drops across the two equal. With line 3 open phases 1 and 2 form a simple series connection on lines 1 and 2. Hence, when they are adjusted for equal voltages the impedances must be the same as the current is the same in both. When 1 and 2 have been adjusted to equality, open line 1 and close line 3. Now adjust phases 2 and 3 for equal voltage drop by varying phase 3, leaving 2 just as it was balanced with 1. When 3 is adjusted equal to 2 then line 1 may be closed and the load will be balanced. In the case of the inductive load the inductances should first be balanced, with no lamps connected, then, when the inductances are equal a suitable number of lamps may be inserted (inserting the same number in each phase) to bring the power factor to the desired value.

Questions

What are the advantages of three phase power compared to single phase power?

An alternator generates 6600 volts per phase. What will be its rated voltage if it is connected in Δ and in Y. With which connections will its possible power output be the greater?

A three phase induction motor has an efficiency of 92 per cent, and is delivering 75 horse-power to its load. Its power factor is .83 and line voltage is 440. What is the current in each of its supply lines? If its stator winding is connected in Δ, what is the current in each phase of the winding?

A 60,000-volt three phase transmission line is delivering 10,000 K.W. of power to an induction motor load of power factor .80. What is the current in each wire of the line? If three transformers are connected to the line, primaries in Y, and secondaries in Δ, what will be the voltage of the line to which the secondaries are connected, the transformer ratio being 190 to 1?

EXPERIMENT X

Single Phase Motors

The single phase induction motor—The repulsion-induction motor—The single phase series motor.—There is much need of a satisfactory single phase motor in small sizes (10 H.P. or less) because the power delivered to the small consumer is generally single phase; for such service any one of the above-mentioned types is available. The single phase series motor has been used in a few cases in comparatively large sizes, notably the installation of the N. Y., N. H. and H. Railroad.

For general use the speed of the single phase motor should be practically independent of load; for such work the single phase series motor is not at all suited and one of the other two types must be used. On the other hand, when the motor has to be used on both continuous and alternating current power the series motor is the only one which will function.

As was pointed out in Ex. 5 the single phase induction motor, as such, has no starting torque whatever, but if it is brought to nearly synchronous speed by some means or other its action is practically the same as that of a polyphase motor. The first motor to be tested is of this type; it starts as a repulsion motor, accelerates as such until operating at nearly synchronous speed when a centrifugal device throws off the repulsion motor brushes and clamps a short-circuiting ring against the commutator making the armature the equivalent of a squirrel cage rotor, the motor then operating as a straight single phase induction motor.

The action of the repulsion motor may be analyzed by referenece to Fig. 48. The two field coils shown at *A* and *B*, are in series and connected to a single phase supply; on the armature we imagine a short-circuited turn, shown in three possible positions, 1–1′, 2–2′, and 3–3′. The field coils produce an alternating flux which threads the armature so that the short-circuited turn will have currents set up in it for any position except that shown at 1–1′; in this position the plane of the coil is parallel to the direction of the magnetic field so there is no E.M.F. induced in the coil. In position 3–3′ there will be a large current in the short-circuited turn but no torque will be developed, the plane of the coil being perpendicular to the direction of the flux. At some intermediate position, such as 2–2′, current will be set up in the short-circuited turn and torque will be developed tending to make the coil pull into position 1–1′. If we use the plane of coil 3–3′ as reference the torque

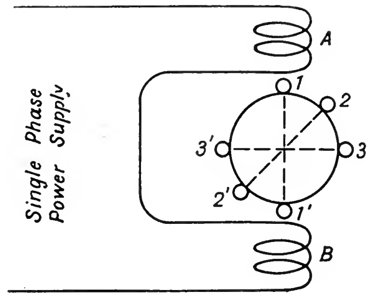


Fig. 48

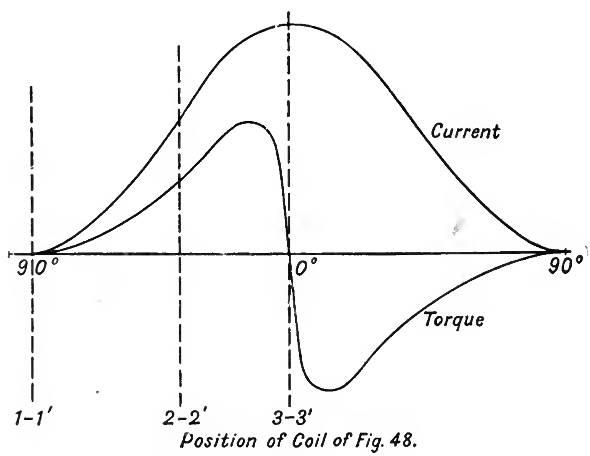


Fig. 49

and current in the short-circuited turn for various positions around the armature are about as shown in Fig. 49; the direction of the torque reverses as the coil goes through position 3–3′, where the current is a maximum.

In the actual motor the armature has a winding just like that of a continuous current motor, connected to a commutator. Brushes, 180 electrical degrees apart, make contact on the commutator and these brushes are short circuited. Such a winding (with the short-circuited brushes) is nearly equivalent to one short-circuited turn, the plane of which is fixed by the position of the brushes. By moving the brushes around the commutator the current in the armature, and the torque developed by it, vary as shown in Fig. 49. As the armature rotates under the influence of the torque developed, the equivalent short-circuited turn, to which we have supposed the actual winding equivalent, remains in the same angular position, this being fixed by the position of the brushes, which remain stationary as the armature rotates. In the actual motor the brush position is so taken that the angle between the equivalent coil and position 3–3′ (Fig. 48) is about 20 electrical degrees.

The repulsion motor has running characteristics like those of a series motor; it continually speeds up unless suitably loaded. In the case of the Wagner motor as it approaches synchronous speed, a copper ring, carried on a toggle joint, is snapped hard against the commutator, short-circuiting all the bars of the commutator and thus making the armature winding equivalent to the squirrel cage rotor winding of the ordinary small induction motor. Motors built to operate in this fashion may be made to develop starting torques in excess of the rated, full-load, torque.

The repulsion-induction motor has a commutator and armature winding similar to the ordinary continuous current motor and has two pairs of brushes (for a two-pole motor) nearly 90 electrical degrees apart. In the ordinary form of this type of motor one pair of brushes is short circuited and the other pair connects to two taps on the stator winding, as indicated in Fig. 50, giving what is called the compensated repulsion-induction motor. The electrical actions of such a motor are too complex to analyze in a brief text of this kind, so will not be attempted. The angle between the brushes *A–A* and brushes *B–B* is properly adjusted at the factory and is not adjustable thereafter. By having a proper angle between the brushes and connecting brushes *B–B* to the proper points on the stator winding the motor gives a good starting torque and has a speed-load curve like that of the ordinary induction motor, with the difference that the motor may run at speeds higher than synchronous speed. The power factor of the motor is greatly affected by the connection of brushes *B–B* to the stator winding; it may approximate unity throughout a large variation of load. In this type of motor all brushes remain permanently on the commutator.

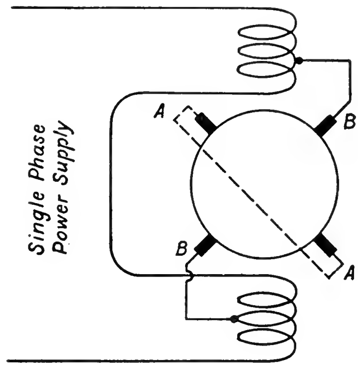


Fig. 50

The single phase series motor is electrically similar to the continuous current series motor; there are certain important changes required in the construction due to the fact that the field flux is alternating instead of constant. All of the magnetic circuit, carrying alternating flux, must be laminated, thus requiring laminated poles and yoke; due to the hysteresis and eddy current losses in the field iron the flux density in the whole field structure must be kept much lower than is the case in the continuous current motor. In order to obtain a reasonably high-power factor in this type of motor the armature ampere-turns must be neutralized as nearly as possible, this requiring a compensating winding in the pole faces. The compensating winding is connected in series with the armature and main field windings.

Due to a transformer effect from the alternating field flux producing heavy currents in those coils short circuited by the brushes (which coils are undergoing commutation) it is necessary to use so-called "resistance leads" in connecting the coil junctions to the commutator bars. Instead of connecting the coil junctions directly to the commutator as is done in the ordinary continuous current motor this connection is made through a piece of resistance wire, the resistance of which may be perhaps five times as much as the coil resistance. This feature of construction practically eliminates sparking at the commutator in so far as this sparking is caused by the effect of the alternating field flux. Even when all the above outlined precautions have been taken in constructing the alternating current motor its performance on an alternating current line is much inferior to what the same motor will give when operated on a continuous current line.

The single phase series motor is practically never used (except in very small sizes, such as required by portable vcauum cleaners) on frequencies higher than 25 cycles; due to difficulty in compensating the armature ampere-turns the output and power factor fall off very rapidly as the frequency is increased above that for which the motor was designed.

With the single phase induction motor loaded by Prony brake get all of its characteristics, operating as an induction motor (speed, current input, efficiency, power factor, etc.); note the "pull-out" torque. Impressing half voltage (to hold down to a safe limit the current taken by the motor) get the characteristics of the motor as a repulsion motor for speeds below that at which the centrifugal device throws on the short-circuiting ring. With half voltage impressed and the rotor clamped get a set of readings similar to those shown in Fig. 49, reading torque and current for about six positions on either side of the position giving zero torque. In plotting the results of the two half voltage runs change the torque to what it would have been at normal voltage by multiplying by four, and the current to what it would have been at normal voltage by multiplying by two.

With the compensated induction-repulsion motor loaded by brake get curves of speed, input, power factor, and efficiency from no load to the maximum safely obtainable from the motor.

With the series single phase motor normally connected get the ordinary characteristics operating at rated voltage and frequency; if loaded by Prony brake observe proper precautions to prevent the motor over-speeding if the brake should accidentally come off. Get the same characteristics for the motor when running from a line of frequency about twice that for which it is rated (say 60 cycles for a 25-cycle motor). Get the same characteristics with the motor operating from a continuous current line, of voltage equal to that for which the motor is rated; in this test take special precautions to prevent the motor from running away.

Questions

How does the starting torque of a repulsion motor vary with the impressed voltage, and why?

With no change in connections would a 60-cycle motor of the type starting as repulsion motor operate properly on a 25-cycle line? Why?

How about the behavior and amount of power output safely available, of a single phase 10 H.P. 220-volt 60-cycle induction motor is run from a 110-volt 25-cycle line?

For a given current and line voltage why is the output of a series motor so much greater on a continuous current line than on an alternating current line?

With full load current of 60 amperes flowing a 110-volt 25-cycle motor shows a power factor of 0.7. Approximately what current will it draw from a 110-volt 60-cycle line at standstill?

EXPERIMENT XI

The Alternating Current Watt-hour Meter. Practically all of the electric power sold in the United States is delivered to the customer as alternating current power, hence the importance of the alternating current watt-hour meter. Although the commutator type of meter as well as the mercury motor meter (explained in Ex. 14) will operate on alternating current lines the induction type of watt-hour meter, to be studied in this test, is so far superior that it practically monopolizes the field.

An elementary sketch of the essential parts of the induction meter is shown in Fig. 51, by reference to which the action of the meter will be explained. A laminated iron frame, of the form shown, is equipped with three-pole pieces, *E*, *D*, and *D′*. The faces of these three-pole pieces are parallel and separated by sufficient distance to give the aluminum disc, *A*, sufficient mechanical clearance.

The upper pole piece, *E*, is wound with two coils, *B* and *C*, the former (of many turns) being the *potential coil* and the latter of very few turns, being the *lag coil*. The two lower poles, *D* and *D′*, are wound in series with each other, with a few turns of wire of sufficient size to safely carry the current of the line in which the meter is to be installed. The two poles are wound in opposite directions so that they have opposite polarities.

The aluminum disc, *A*, is carried on the steel spindle *F*, the lower bearing of which is carried on a jewel. On the upper part of the spindle is a worm engaging the gear train which records the amount of energy which has passed the meter. The disc is caused to rotate by the interaction of the effects of the potential and current coils. The disc turns between the poles of permanent magnets, *F* and *F′*, the eddy currents produced by the magnets serving to limit properly the speed at which the meter turns for a definite load.

The coil B is made up of sufficient number of turns that its reactance is sufficient to permit the coil being connected directly across the line in which the meter is connected, this being generally 110 volts. The current in coil B will lag nearly 90 degrees behind the voltage impressed on its terminals and the flux in

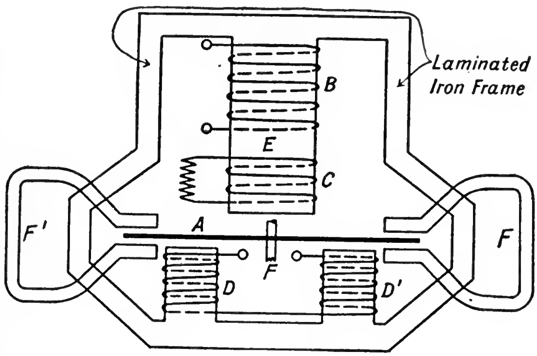


FIG. 51

the potential pole will be in phase with this current (neglecting for the moment the effect of the lag coil). Of course, it is impossible to make the current lag as much as 90 degrees behind the E.M.F. because the coil must have some resistance; it probably lags about 80 degrees in the average meter. To make the meter operate properly, however, it is necessary that the flux which passes from the potential pole into the disc, A, be exactly 90 degrees behind the phase of the E.M.F. impressed on the meter. This is the function of the lag coil, which is generally short-circuited through a suitable resistance.

To show the effect of the lag coil we refer to Fig. 52. The line voltage, impressed on coil B, is shown at OE; the ampere-turns (M.M.F.) produced by the current flowing in the coil are shown at OB, about 80 degrees behind the voltage. This M.M.F. will produce a flux in phase with itself which, by its rate of change, generates a voltage in coil C, which voltage will be 90 degrees behind the flux; it is shown at OC. This voltage will cause a current *OE* to flow in the coil *C* (as it is short-circuited) and this current will lag behind the voltage *OC* by an amount controlled by the amount of resistance in the wire used to short-circuit coil *C*. The M.M.F. due to the current in *C* is in phase with the current *OE* and is given by the vector *OF*. The M.M.F. producing flux through the pole *E* is then the vector resultant of the M.M.Fs. of the two coils; in Fig. 52 it is shown at *OD*, just 90° behind the E.M.F. impressed on coil *B*. The flux from pole *E* is therefore properly shown at *OG*.

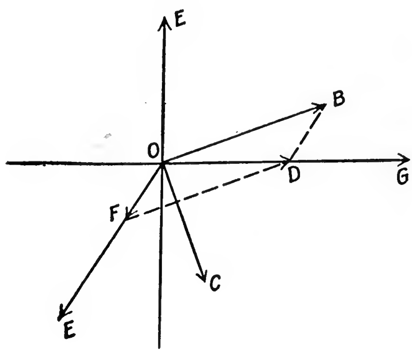


FIG. 52

A plan of the disc is given in Fig. 53, it shows the relative positions of the three poles and the retarding magnets *F*, *F'*. The alternating flux from the current poles induces in the disc eddy currents which flow in the disc about as indicated by the lines of Fig. 53; due to the opposite polarities of the two current poles the eddy currents around the poles will be in opposite directions as shown. It will be noticed, however, that both currents flow in the same direction under the potential pole. These eddy currents in the disc will be practically in phase with the E.M.F. inducing them; this E.M.F., which is caused by the rate of change of flux through the current poles will be 90° behind the current exciting the current poles, that is, 90° behind the load current. If the load connected to the meter is non-inductive the load current will be in phase with the line E.M.F.; we have previously shown that the flux into the disc from the potential pole is 90° behind the line E.M.F. so that it is now evident that the eddy currents shown in Fig. 53 will be *in phase with the flux from the potential pole.* The disc will therefore experience a torque tending to turn it, this torque being proportional to the flux from the potential pole and to the strength of the eddy currents around the current coils, which in turn, are proportional to the load current.

One-quarter of a cycle after the time assumed in the above analysis the currents around the current poles will be zero, and the flux from the current poles will be a maximum. The flux from the potential pole will be zero at this time but there will be

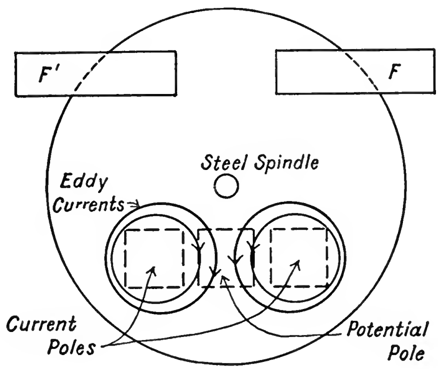


FIG. 53

eddy currents in the disc produced by the changing flux from the potential pole. The reaction between these eddy currents and the flux from the current poles will again give a torque to the disc, tending to turn it in the same direction as does the torque previously analyzed. The disc therefore experiences a torque, the average value of which depends upon the product of the line current and line E.M.F., that is, to the power flowing through the meter.

It will be seen that the average value of this torque will be a maximum (for a certain voltage and current), when the current through the meter and the voltage on the potential coil are in phase with each other; as the phase between the two increases the average torque will diminish until, with a phase difference of 90° between current and voltage, the average torque is zero.

Analysis of the action of the meter, as well as actual test, shows that the average torque is proprtional to the cosine of the angle between current and voltage, that is, to the power factor of the load.

The disc will speed up until the driving torque is just balanced by the eddy current drag on magnets F, F' which drag is directly proportional to the speed; hence the disc will rotate at a speed fixed by the power ($EI \cos \phi$) being supplied to the load.

Just as in the case of the direct-current watt-hour meter some special attachment must be used to make the meter indicate

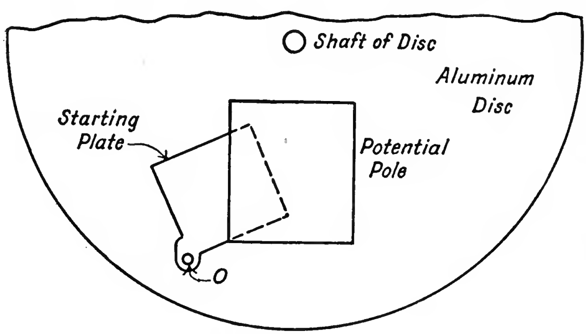


FIG. 54

accurately at light loads; the starting friction of the ordinary watt-hour meter is such that there is required a considerable percentage of the full-load current to overcome it and hence at light loads the meter would not run at all. To neutralize this starting friction there is attached to the potential pole a small adjustable copper plate, so mounted that it can be moved parallel to the face of the potential pole; it is attached so that it can be swung to cover more or less of the face of the potential pole. This arrangement is called the *starting plate*, sometimes the shading plate or shading coil. The action of this plate may be explained with the help of Fig. 54, which shows a plan of the face of the potential pole and the starting plate. This plate is pivoted at some point (o) so that it can be swung under the pole.

Flux from the potential pole will induce currents in this plate; these currents in the starting plate will induce currents in the disc A, which, reacting with the flux from the unshaded portion of the potential pole, will produce a slight turning effort. The amount of the turning effort is controlled by the position of the starting plate.

An induction watt-meter may be single phase, two or three wire, or it may be polyphase; in either of the two latter cases it consists of two single-phase meters on the same shaft. These two element meters are generally tested by connecting the two sets of current coils in series and the potential coils in parallel and then loading the meter single phase.

In adjusting the meter to make it run accurately one run is made at light loads (5–10 per cent of rating) and the starting plate varied in position until the required accuracy is obtained. At full load the meter speed is adjusted by moving the permanent magnets in or out from the center of the rotating disc, in to increase the speed, and vice versa.

The accuracy to which the meter should be adjusted depends upon the ruling of the local authorities; in the case of New York the meter must be within 1.5 per cent of correct indication at full load and at 5 per cent of full load the allowed deviation is plus or minus 3 per cent from accurate indication. The above figures are for a load of 100 per cent power factor; for 75 per cent and 50 per cent power factor the accuracy at full load must be within 2 per cent and 4 per cent respectively.

The induction meter may be tested in the same fashion as that described for the continuous current meter, in Ex. 14, but the uniform practice nowadays is to use a portable rotating induction meter as a secondary standard, this being frequently checked with some other standard rotating instrument which is not carried around. The potential circuits of both meters should be connected to the power line at the same place, between the power supply and the first of the two meters, so that neither meter is affected by the power consumed in the two potential circuits. The two current coils are connected in series and in series with the load. In case the load on the meter is measured by indicating instruments the potential coil of the watt-hour meter as well as that of the indicating watt-meter and the voltmeter should all be connected at the same place, between the power supply and the first of the meters; this is indicated in Fig. 55. Unless this precaution is taken the test may be in error by an amount depending on the power consumption in the various potential circuits. With the connection scheme shown in Fig. 55 the meters record the power used in the load plus that

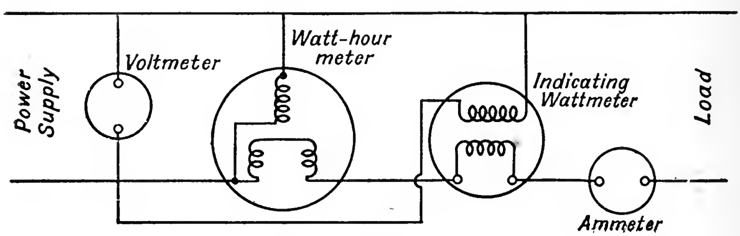


FIG. 55

used in the three-current coils; the amount used in the potential circuits is not recorded.

The meter is to be tested, as found, for loads of 5 per cent, 10 per cent, 50 per cent, 100 per cent, and 150 per cent load, at unity power factor and at 0.7 power factor, lagging current. It is then to be adjusted to the required accuracy at 5 per cent and 100 per cent load, unity power factor, the light load adjustment being made by the position of the starting plate and the full-load adjustment by the position of the magnets. When these adjustments have been made take two more runs similar to those first made to see how the calibration holds throughout the range of the meter, at the two power factors.

In case a rotating watt-hour meter is used for the calibration it is connected in series with the meter to be tested and the load is adjusted to that at which the test is to be made. The potential circuit of the rotating standard is opened or closed by a push-button switch; by closing this switch the rotating meter is made to run, the meter being "dead" until the potential circuit is closed even though there may be full-load current flowing through the current coil. The reading of the standard meter is noted. By means of a stop watch (an ordinary watch may be used if no stop watch is available) the time is taken for a suitable whole number of revolutions of the test meter, such a number of revolutions being taken that the time required is between one and two minutes. During this same interval of time the standard meter must be recording; this is most conveniently done by the tester having the potential circuit switch of the standard meter in one hand and the stop watch in the other; as the mark on the disc of the test meter passes a convenient point (such as under the edge of a pole) the stop watch and standard meter are both started; when the test meter has made the required number of revolutions they are both stopped. The calibration constant of both the standard and test meter being known the true watts and the watts indicated by the test meter are obtained and thus the accuracy of the test meter determined.

In case indicating meters are used to check the test meter the load is adjusted to the required amount and power factor by readings of voltmeter, ammeter, and wattmeter; the time for a convenient number of revolutions of the test meter is taken as before, the load being obtained by taking the average of the indicating wattmeter reading during the minute or so the test is being run.

In the above runs the meter constant must be known; this is different for the various meters on the market but can be readily obtained as outlined in Ex. 14.

For each setting of load, for which the meter is to be tested, three sets of readings should be taken, these not to be regarded as accurate if they differ from the average by more than 1 per cent. If they do, other runs should be made until three do agree with their average to within 1 per cent; the average of these three readings is to be taken as the meter reading.

Draw curves of meter calibration as found, and as left, for the two different power factors, plotting as abscissæ per cent of full load and as ordinates the ratio of meter watts to true watts.

Questions

How does the torque due to the starting plate vary with speed? How about that due to bearing friction?

Why does the magnet adjustment, carried out for full load, have negligible effect on the light load adjustment?

Considering separately the potential coil, current coils, and damping disc, what will be the effect of increasing temperature on the accuracy of the meter?

For the same diameter and weight of disc, and same braking effort, which requires stronger magnets, an aluminum disc or one of copper?

What would be the effect on the speed of the meter of putting a thin sheet of copper over the poles of the current coils, between the disc and the pole faces?

With a given disc how does the braking effort vary with the magnet strength, and why?

How about connecting a 110-volt 60-cycle induction meter to a 110-volt 25-cycle line?