THE ELECTRIC POWER ENGINEERS' HANDBOOK

A MANUAL DEVOTED TO THE OPERATION AND MAINTENANCE OF MOTORS, GENERATORS, CONVERTERS, AND RECTIFIERS IN THEORY AND PRACTICE

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PREFACE

This book has been specially written to provide the knowledge requisite for the efficient control and care of all kinds of electrical machinery. It is a book for the practical man, as distinguished from the usual textbook written for the student. Whenever possible, however, not only have the practical methods of operation been clearly explained, but the principles underlying such operations are fully considered.

The aim of the author is to make the operator a thinker at his work and not a mere machine like the electrical and mechanical units he controls. Systematic treatment is fully observed and urged throughout the book in contradistinction to the "cut-and-dry" methods so commonly employed by those who have only a bare working knowledge of the operations involved. Simple descriptions, aided as far as possible by diagrams, are an essential feature of the work, and this especially applies to the sections on plant operation and the testing for faults and breakdowns. For the mechanical and marine engineer whose duties in the majority of cases now include supervision of some kind of electrical plant, the book provides the practical features so absolutely necessary as a just adjunct to perhaps a desire for a much wider knowledge of the subject.

Owing to the recent development in a.c. supply, much more attention has been paid to this branch of the subject, hence *Rectifiers* have been treated somewhat fully. Although this type of machine is taking the place of the Rotary Converter, owing to the continued operation of much Converting plant, little opportunity has presented itself in the present volume to cut down the space allotted to the latter.

Contrary to the usual conception, there are still more than one million consumers supplied with direct current in this country, so that information under the heading of d.c. Motors and Generators has been made as complete and detailed as was considered necessary. The work might have included a chapter on Electric Installation Testing, but lack of space compels the author to refer his readers to his book "Electric Wiring" for detailed information on this part of the subject.

The author wishes to express his sincere thanks to those firms who have helped him so kindly and courteously in the preparation of this book—especially would he mention The General Electric Co. Ltd., Metropolitan Vickers Electric Co. Ltd., British Thomson-Houston, Ltd., and the English Electric Co. Ltd.

CONTENTS

ELECTRIC POWER ENGINEERS' HANDBOOK

CHAPTER I

GENERAL PRINCIPLES OF ELECTRICAL ENGINEERING

THE principles stated as briefly as possible in the present chapter should be thoroughly mastered before the later chapters of this work are considered.

Such a thorough understanding will make easy much that appears difficult, and many things understood that are too often taken for granted.

Practical Units used in Electrical Engineering.—The units with which an electrician has to deal are those relating to current, pressure or voltage, resistance, power, and energy.

Current is that which flows along the conductors forming the electric circuit. It cannot be destroyed or used up, and it may show its presence in three ways—

(*a*) By its thermal or heating effect, as in lamps, heaters, etc.

(*b*) By its chemical or electrolytic effect, as in electro-plating, accumulators, etc.

(*c*) By its magnetic effect, as in motors, generators, etc.

Unit of Current.—Current is measured in amperes.

Solenoid.—If a wire be wound in the form of a coil or solenoid, and a current be passed through it, the coil becomes a magnet, having poles of opposite polarity at its two ends. This coil, if allowed to swing freely in a horizontal plane, would set in a N. and S. direction, like any compass needle.

Electro-magnet.—When a core of iron or steel is placed inside a solenoid, the iron or steel becomes magnetised, and the whole arrangement is called an electro-magnet.

Rule for finding the Polarity of an Electro-magnet.—The above principle is utilised in the field coils of motors and generators, and it is of great importance to electrical engineers to be able to tell which end of an electro-magnet is a N. pole and which a S. pole, from a knowledge of the direction of the windings and the current.

Hand Rule for Finding Direction of Current and Polarity of Solenoid.

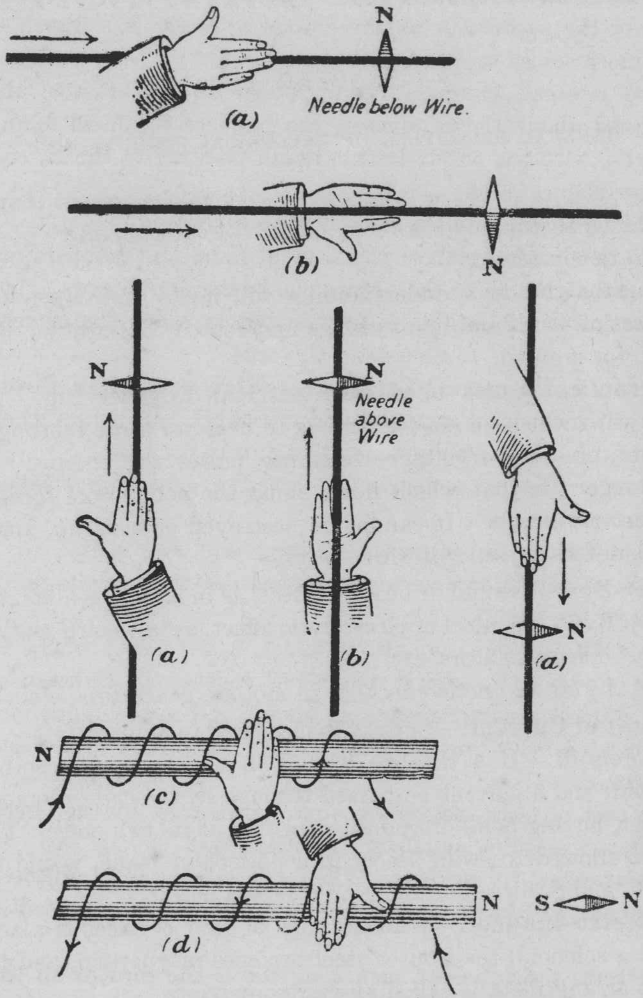

Fig. 1.—The figures illustrate the method of finding the direction of current in a conductor from its effect on a small compass needle, and also the method of finding the polarity of an electro-magnet, the direction of current being known.

Place the **right** hand on the coil, the fingers pointing in the direction the current is flowing, the outstretched thumb indicates the N. end of the core of the electro-magnet. Fig. 1 (*c* and *d*) illustrates this rule.

Rule for finding the Direction of Current in a Conductor.—It is of equal importance to be able to tell the direction of current or the positive or negative main or mains in a bunch of two or more cables supplied with d.c.

Place a small compass needle under the conductor, the **right** hand above the conductor, the palm of the hand facing the needle, with the outstretched thumb pointing to the N. end of the needle.

The fingers will indicate the direction of current.

Note that if the relative positions of hand and compass are reversed, that the N. of the needle points the opposite way, but the direction of the fingers is always that in which the current flows. Fig. 1 (*a* and *b*) illustrates this rule.

Pressure, Potential, Voltage, or Electro-motive Force is that which causes a current to flow between two points when they are joined by a conductor. The unit is the volt.

The total pressure generated by a cell or generator is called its electro-motive force (e.m.f.).

The difference in pressure between any two points in a circuit is simply known as the potential difference, voltage, or pressure of the circuit.

Resistance.—The opposition which a substance offers to the flow of current through it is called its resistance. Substances having a small resistance, such as metals and most liquids, are called *conductors*, those offering a high resistance are called insulators.

The unit of resistance is the ohm, represented by the Greek letter Ω. A megohm equals one million ohms.

Resistances in Series.—When resistances are connected in succession to form a circuit, they are said to be connected in series.

The total resistance of such a circuit is the sum of all the resistances.

Resistances in Parallel.—Resistances connected to the same terminals are said to be in parallel.

The equation used to calculate the equivalent resistance of such a group is expressed :—

$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}+\frac{1}{r_3}+\frac{1}{r_4}+\text{etc.}$$

where R = resultant resistance. r_1, r_2, r_3, r_4 represent the values of the separate resistances connected in parallel.

Laws of Resistance.—The resistance of a body depends directly upon its length, upon its specific resistance, and inversely upon its area of cross-section.

Expressed algebraically—

$$R=\frac{l\times\rho}{a}$$

where
- R = resistance in ohms.
- l = length in inches.
- a = area of cross-section in square inches.
- ρ = specific resistance (copper = 0·00000066).

Example.—What would be the resistance of a pair of mains each 250 yds. long, 0·35 sq. in. cross-sectional area (sp. res. = 0·00000066) ?

$$R=\frac{l\times\rho}{a}$$

$$R=\frac{(250\times2\times3\times12)\times(0{\cdot}00000066)}{0{\cdot}35}$$

$$R=0{\cdot}0339\ \text{ohm}$$

Effect of Heat on Resistances.—The resistance of a body also depends upon its temperature.

Metals and alloys generally increase in resistance with increased temperature.

Liquids, insulators, and most grades of carbon decrease in resistance with increased temperature.

Ohm's Law.—In a circuit in which a steady direct current is flowing there is a direct relation between the current, voltage, and resistance, temperature remaining constant, and this is expressed by what is known as Ohm's law.

The law is represented by the following equations :—

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

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

$$E=I\times R$$

where
- I = current in amperes.
- R = resistance in ohms.
- E = pressure in volts.

Examples of the use of Ohm's Law.—

(*a*) The voltage of supply is 250, and the total resistance of a group of lamps connected across the mains is 20 ohms. What is the value of the current supplied ?

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

$$\therefore\ I = \tfrac{250}{20} = \underline{12{\cdot}5 \text{ amperes}}$$

If the group of lamps consisted of 12 lamps of equal resistance the current through each lamp would equal—

$$\frac{12{\cdot}5}{12} = \underline{1{\cdot}04 \text{ amperes}}$$

(*b*) A shunt field coil has a current passing through it of 1·5 amperes, and the voltage at its terminals is 240. What is the resistance of the coil ?

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

$$\therefore\ R = \frac{240}{1{\cdot}5} = \underline{160 \text{ ohms}}$$

(*c*) A cable has a resistance of 0·055 ohm, and a current of 150 amperes flows down it. What is the drop in the cable ?

$$\text{Since } E = I \times R$$

$$\therefore\ E = 150 \times 0{\cdot}055 = \underline{8{\cdot}25 \text{ volts}}$$

Measurement of Electrical Power.—The power in a circuit is found from the product of the amperes flowing in it and the pressure at its terminals.

The unit of power is the *watt*. It is the power in a circuit when a current of one ampere flows under a pressure of one volt.

The total watts in a d.c. circuit may be obtained by applying the following equations :—

$$W = I \times E$$
$$W = I^2 \times R$$
$$W = \frac{E^2}{R}$$

where $\begin{cases} W = \text{power in watts.} \\ I = \text{current in amperes.} \\ E = \text{pressure in volts.} \\ R = \text{resistance in ohms.} \end{cases}$

Since the watt is a very small unit, a larger unit called a kilowatt (kW.) is used. It is equal to 1000 watts.

One horse-power equals 746 watts.

Examples.—

(*a*) The pressure at the terminals of a circuit is 250 volts, and a current of 220 amperes flows down it. What is the power in the circuit ?

Since $W = I \times E$

$$W = 220 \times 250 = \underline{55{,}000 \text{ watts}} = \underline{55 \text{ kW.}}$$

(*b*) A current of 125 amperes flows down a cable whose resistance is 0·5 ohm per mile. What power is lost per half-mile of the cable ?

Since $W = I^2 \times R$

$$\therefore W = 125^2 \times 0{\cdot}25 \qquad \left(\text{Res. of half-mile} = \frac{0{\cdot}5}{2} = 0{\cdot}25 \text{ ohm}\right)$$

$$W = 15625 \times 0{\cdot}25$$

$$W = \underline{3906 \text{ watts}} = \underline{3{\cdot}91 \text{ kW.}}$$

(*c*) A 10 H.P. motor is connected across 550-volt mains. What current will it take at full load if its efficiency is 80 per cent. ?

$$10 \text{ H.P.} = 10 \times 746 \text{ watts}$$

$$= 7460 \text{ W.}$$

Since $W = I \times E$

$$\therefore I = \frac{W}{E}$$

$$\therefore I = \frac{7460}{550} \times \frac{100}{80} \text{ (since efficiency} = 80 \text{ per cent.)}$$

$$= \underline{16{\cdot}9 \text{ amperes}}$$

Allowing 50 per cent. overload, a fuse of about 25 amperes would be suitable for such a motor.

Electrical Energy.—The practical unit of electrical energy is the kilowatt-hour (kW.h.).

It is the energy transformed in a circuit when the power is one kilowatt and the time taken is one hour.

In general practice this value is simply spoken of as a *unit*, and is the basis of charges for electrical energy.

$$\text{kW.h.} = \frac{\text{watts} \times \text{hours}}{1000}$$

$$= \frac{I \times E \times \text{hours}}{1000}$$

$$\text{or} = \frac{I^2 \times R \times \text{hours}}{1000}$$

$$\text{or} = \frac{E^2 \times \text{hours}}{R \times 1000}$$

In order to find the units absorbed in a circuit, it is necessary to find the power of the circuit in kW. and multiply the result by the time in hours, for which this power is utilised.

To find the cost, the kW.h. thus found are multiplied by the charge per unit.

CHAPTER II

OHM'S LAW APPLIED TO ALTERNATING CURRENT CIRCUITS

OHM'S law as usually expressed is only true for circuits in which the current is constant. Even in cases in which d.c. is supplied, if the current is changing in value the law does not apply.

In the case of a shunt field coil, it takes the current quite an appreciable time to rise to its full value, and during this time the relation between the current, voltage, and resistance of the circuit does not follow Ohm's law.

In an alternating current circuit, where the load is wholly composed of incandescent lamps and some forms of radiators, Ohm's law may be applied.

Such non-inductive circuits, however, are practically unknown in practice, and, generally speaking, a.c. circuits do not obey Ohm's law.

If a current is sent along a conductor, a magnetic field is at once sent out from the conductor. The lines composing this field cut the conductor as they are produced. When the current ceases to flow, the field ceases to exist and appears to close in on the conductor, its lines again cutting it. Any change in current or direction of current in the conductor will produce a change in the field produced, and every change in the number of lines means cutting of the conductor by these lines.

Whenever a conductor is cut by lines of force, or *vice versa*, an e.m.f. is set up in the conductor (this is the first principle of the generator), and naturally the effect of such induced e.m.f.'s in the conductor carrying the varying current producing them is to oppose the applied e.m.f. at the terminals of the conductor. For this reason these so-called induced e.m.f.'s, because they are induced in the conductors, are often called back e.m.f.'s, and are produced in all a.c. circuits. They are produced slightly by varying currents in straight wires, much more so in coils of wire, since the lines of force cut more conductors as they vary, and still more so if the coil has an iron core.

This inductive effect is therefore very apparent in a.c. circuits where electro-magnets are used, such as lamp circuits, motor circuits, transformer circuits, etc.

Effect of the Induced E.M.F.—Since these back e.m.f.'s oppose the applied or impressed voltage and reduce its effective value, the resulting current flowing through the circuit must be less than would otherwise be the case; but in addition to its decrease, the current is also caused to lag behind the voltage, so that in such a.c. circuits the voltage reaches its maximum value before the current reaches its maximum value. Since the power in a circuit is the product of the simultaneous values of current and voltage, the student will realise that the actual power available must therefore be reduced by the lagging effect of the induced e.m.f.'s on the current in the circuit.

Choking Coil.—A choking coil is the name given to a coil of wire having a great inductive effect, due to the number of its turns and its iron core. It is placed in an a.c. circuit to reduce the power used, just as a resistance coil is placed in a d.c. circuit, but its effect is due both to its ohmic or ordinary resistance and to its inductive effect, which may be looked upon as an additional resistance.

A constant pressure applied to its terminals would send a large current through it and probably burn out the insulation, whereas the inductive effect on an a.c. circuit chokes back the current and reduces the power absorbed to a minimum.

It is due to this action that an unloaded transformer, which acts as a very effective choking coil, may be left permanently connected across the mains of an a.c. circuit and yet absorb very little power.

The Law of the A.C. Circuit.—The reader will now be aware that the study of a simple inductive circuit is not easy compared with the simple d.c. circuit.

The law applying to such a circuit may be expressed as follows :—

$$\text{Current} = \frac{\text{impressed volts}}{\text{ohmic resistance} + \text{inductive resistance}}$$

If we know the value of the inductance and the periodicity of the a.c. supply, we can calculate the current flowing from the law expressed in the following manner :—

$$I = \frac{E}{\sqrt{R^2 + (2\pi f L)^2}} \quad \text{where} \begin{cases} E = \text{impressed volts.} \\ I = \text{current in amperes.} \\ R = \text{ohmic resistance of the circuit.} \\ f = \text{periodicity of the a.c. supply.} \\ L = \text{inductance of the circuit in henrys.} \end{cases}$$

The term $(2\pi f L)$ is called the *reactance* of the circuit, and R the ohmic resistance. The two together are called the impedance of the circuit.

The equation may therefore be expressed—

$$\text{Current} = \frac{\text{impressed volts}}{\text{resistance} + \text{reactance}} = \frac{\text{impressed volts}}{\text{impedance}}$$

Measurement of Power in A.C. Circuits.—The power in an a.c. circuit which has no inductance, as in the case of a load composed wholly of incandescent lighting units, is found at any instant by taking the product of amperes as indicated on the ammeter, and volts as indicated on the voltmeter, exactly the same as for a d.c. circuit.

$$\text{Watts} = \text{amperes} \times \text{volts}$$

Generally, however, an a.c. circuit has some inductance produced by the electro-magnets of motors, appliances, etc., in circuit, or may have capacity, both of which cause the current to fall out of phase with the voltage supply.

The current in such a circuit would therefore lag or lead on the volts, and the maximum current value would not occur at the same time as the maximum voltage value.

We can represent such an out-of-phase current by two currents, one in phase with the e.m.f., and the other known as a wattless current out of phase with the e.m.f. by 90 degrees.

In such a circuit the product of amperes, as indicated on an ammeter in the circuit, and the volts, as indicated on a voltmeter, would not represent the true watts supplied, but a result something in excess of this, and known as the apparent watts.

It is better, therefore, to represent the output of an alternator or the input of a motor in volt amperes (V.A.) or (kV.A.) instead of watts or kilowatts, since a machine rated at 50,000 watts might at 500 volts give out far more than 100 amperes when its wattmeter was reading 50,000, and be exceeding its heating limit; whereas if rated at 50,000 V.A. we should know its output has not to exceed 100 amperes, as indicated by an ammeter in circuit.

Power Factor.—As previously stated, the product of volts and amperes as indicated on a voltmeter and ammeter respectively is known as the apparent watts.

The ratio of the true watts to the apparent watts is known as the power factor of the circuit; its value may be one or unity, but it is generally less, and represented 0·9 (point 9) or 0·86 (point 86), as the case may be.

The power factor may be expressed as follows:—

$$\text{Power factor} = \frac{\text{true watts}}{\text{apparent watts}} = \frac{W}{V \times A}$$

From which we get—

$$W = V \times A \times \text{power factor}$$

Power Measurement in A.C. Circuits.

Single-phase.

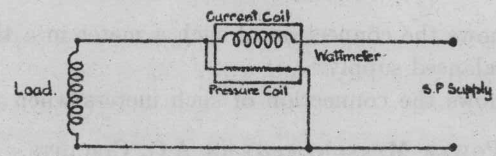

Fig. 2.—Connection of wattmeter in single-phase a.c. circuit.

If the current lags behind the impressed volts and we know the angle of lag, we can find the value of the power factor from a table of cosines, since—

$$\text{Power factor} = \cos \text{ of the angle}$$

and the equation may be expressed—

$$W = V \times A \times \cos \phi, \quad \text{where } \phi = \text{angle of lag}$$

Measurement of Power and Energy in Single-phase Circuits.—In practice the output of an alternator is measured by means of a wattmeter, which indicates the true power in the circuit, or by means of an energy meter, which measures the true energy supplied to the circuit.

The connections for this instrument in a single-phase circuit are shown in Fig. 2. The thick coil, representing the current coil, is connected in series with one line, and the fine coil or pressure coil between the two mains.

Measurement of Power and Energy in Two-phase Circuits.—If the load is balanced, a single-phase meter placed in one phase will give half the total power or energy produced, as the case might be, and the scale of the instrument may be calibrated to read the total power or energy supplied.

POWER MEASUREMENT IN A.C. CIRCUITS.
TWO-PHASE.

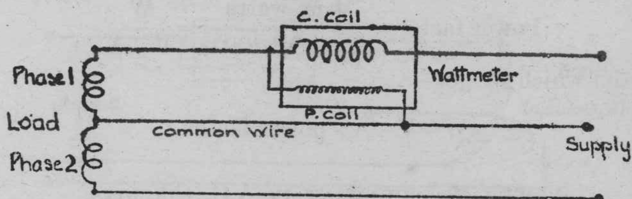

FIG. 3.—Connection of wattmeter to measure the power in a two-phase a.c. circuit, having equal loads on both phases.

Fig. 3 shows the connection of such a meter in a three-wire two-phase balanced supply.

Fig. 4 shows the connection of such meters when the loads

POWER MEASUREMENT IN A.C. CIRCUITS.
TWO-PHASE.

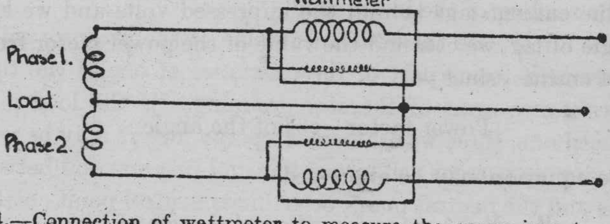

FIG. 4.—Connection of wattmeter to measure the power in a two-phase three-wire a.c. circuit, having unequal loads on the two phases.

are not balanced. In this case the sum of the two meter readings gives the total power or energy in the circuit or system.

Measurement of Power and Energy in Three-phase Circuits.—If the load is a motor load and balanced, and not a lighting or mixed load having the different phases unequally loaded, the measurement of power or energy is simple, and consists in putting a meter with its current coil in one line, and its pressure coil between that line and the neutral point of the system if the latter is accessible.

Fig. 5 represents the connections of a meter to a three-phase balanced system whose neutral point is accessible.

If the neutral point is not accessible, an artificial one may be made by means of three equal resistances.

POWER MEASUREMENT IN A.C. CIRCUITS.
THREE-PHASE.

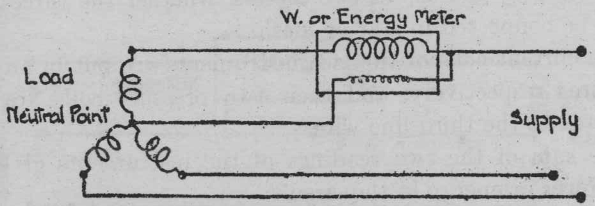

FIG. 5.—Connections of wattmeter in three-phase a.c. circuit, with balanced loads on the three phases, and having an accessible neutral point.

One resistance is connected to each line and the three free ends connected together to form a star, the middle point of the star or common junction being the artificial neutral point.

The meter connected in such a balanced circuit and with such a neutral point is illustrated in Fig. 6.

The total supply of the system in such a case will be three times the reading of the instrument.

In the latter case the resistance value of the pressure coil of the instrument forms part of the resistance of one of the three equal resistance arms of the star grouping. If the load is an unbalanced one, three wattmeters or energy meters may be used, each having its current coil in one line and pressure coil between that line and the neutral point, or artificial neutral point created, by starring the three ends of the similar and equal resistance