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ABSTRACT

The fundamentals of electric circuits and electric machines are presented in the text, with an emphasis on the practical operation rather than on mathematical analyses of theories involved. The material contained in the text includes the fundamentals of both D.C. and A.C. circuits together with the principles of magnetism and electro-magnetic induction, so as to provide a foundation for the understanding of the principles of electric machinery operation. Application of these fundamentals is made in the discussion of D.C. generators, D.C. motors, transformers, A.C. generators, induction motors, synchronous motors, single-phase motors, and polyphase motors. Review questions are included at the end of each lesson for evaluating student progress or for class discussion. (NJ)

State of New Jersey
Department of Education
Division of Vocational Education

INTRODUCTION TO THE CONTROL OF ELECTRIC MOTORS

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March 1975

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NEW BRUNSWICK, NEW JERSEY

INTRODUCTION

In preparing this text the purpose of the author has been to present a concise, practical text covering the fundamentals of electric circuits and machines. To this end detailed mathematical analyses of the theories involved have been omitted.

To achieve a concise text, emphasis has been placed on the presentation of fundamental principles and in so far as possible the physical actions taking place are stressed without rigorous mathematical proofs. The fundamental essentials presented are sufficient to enable the student to gain an understanding of each subject, yet the student and instructor are encouraged to expand on those subjects which are of particular interest.

The material contained in this text includes the fundamentals of both d.c. and a.c. circuits together with the principles of magnetism and electromagnetic induction, so as to provide a foundation for the understanding of the principles of the operation of electrical machinery. Application of these fundamentals is made in the discussion of d.c. generators, d.c. motors, transformers, a.c. generators, induction motors, synchronous motors, single-phase motors, and polyphase motors.

Review questions have been included as a study aid for evaluating a student's progress or they may be used for class discussion.

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LESSON 1 INTRODUCTION TO THE CONTROL OF ELECTRIC MOTORS

OBJECTIVE:

To learn the importance of the electric motor and the manner in which it is controlled.

RELATED INFORMATION:

The control of electric motors has gained an important role in machine design over the years. It ranges from a simple "OFF-ON" switch-type control that is used on such machines as a Bench Grinder, Band Saw, or Drill Press, to systems that will automatically control a machine throughout a complete cycle of operations without the assistance of a machine operator. It is through the use of these automatic controls that industry has managed to free the machine operator from many boring operations. The cost of these controls is justified in that many costly human errors have been eliminated, and production costs are further reduced by allowing the operation of two or more machines by a single operator.

The many different types and wide range of machine sizes that are driven by electric motors is so large that it would not be practical to list them. However, they all have a common denominator in that they are driven from an electric motor. THERE ARE SEVERAL TYPES OF ELECTRIC MOTORS. ALL OF THEM HAVE DEFINITE CHARACTERISTICS THAT MAY OR MAY NOT BE USEFUL IN A GIVEN MACHINE DESIGN. Therefore, the successful operation of each machine is highly dependent on the type of motor selected to drive it and the manner in which it is controlled.

QUESTIONS:

1. Is a simple "OFF-ON" switch considered an electrical control?
2. List three different machines that might use this type of control.
3. When is an electrical control said to be automatic?
4. What advantages can you see in having machines controlled automatically?
5. What denominator is common to the control of most industrial machines?
6. Do all types of electric motors have the same characteristics?
7. Why is selection of the proper type of motor and control important to the successful operation of a machine?
8. What does an automatic motor control do?
9. Do you believe that electric motor controls have a future in industry? Explain your answer.
10. Briefly describe the electrical control of some machine other than those discussed.

LESSON 2 GRAPHIC REPRESENTATION OF TYPICAL ELECTRICAL DEVICES

OBJECTIVE:

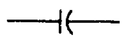
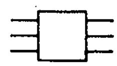
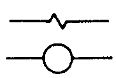
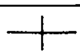
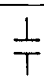
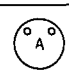
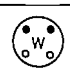
To identify typical graphic symbols.

RELATED INFORMATION:

Graphic symbols are used as a means of identifying electrical devices on wiring diagrams. Early control manufacturers used symbols that strongly resembled the devices that they represented. These symbols were usually difficult to draw and often the different manufacturers would disagree as to how a particular device should be represented. This approach was satisfactory for the relatively simple controls built at that time, but as the controls became more complicated, the wiring diagrams became increasingly more difficult for people who were to use their controls to read. Some machine designs required that controls of different manufacturers function together, and the use of dissimilar symbols added to the difficulty of understanding the combined control functions. Gradually necessity required that some degree of order be brought to the electrical industry. This has largely been brought about by a simplification and standardization of graphic symbols.

A listing of standard industrial symbols is shown in *Fig. 1*. These symbols are not drawn to any specific scale, but are made as small as practical without sacrificing legibility.

STANDARD INDUSTRIAL SYMBOLS

Device	*Standard Industrial Symbol*
Battery	
Capacitor	
Circuit breaker, air, single-pole	
Circuit breaker, oil, three-pole	
Coil, nonmagnetic core	
Coil, magnetic core	
Coil, operating	
Wire crossing, no connection	
Wires connected	
Ground connection	
Contacts, normally closed when device is deenergized	
Contacts, normally open when device is deenergized	
Fuse	
Ammeter	
Voltmeter	
Wattmeter	

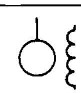
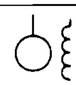
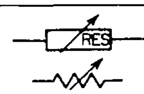
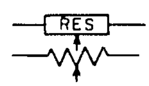
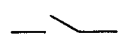
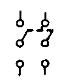
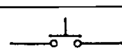
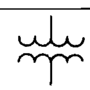
Device	*Standard Industrial Symbol*
DC motor or generator armature	
DC motor or generator shunt field	
DC motor or generator series field	
DC motor or generator commutating (interpole) field	
Three-phase synchronous motor or generator	
Single-phase generator	
Three-phase squirrel-cage motor	
Fixed resistor	
Continuously adjustable resistor	
Adjustable contact, resistor, or rheostat	
Switch, single-pole, single-throw	
Switch, double-pole, double-throw, terminals shown	
Push button, normally open	
Push button, normally closed	
Transformer	

Fig. 1

QUESTIONS:

1. What is a graphic symbol?
2. Why did control manufacturers attempt to simplify and standardize these symbols?
3. What advantages can you see in the standardization of graphic symbols for electrical devices?
4. How large should a symbol be drawn?

ASSIGNMENT:

1. Referring to Fig. 1, sketch the following symbols:
   a. Control transformer
   b. Limit switch (normally open).
   c. Limit switch (normally closed).
   d. Pressure operated switch (normally closed).
   e. Pressure operated switch (normally open).
   f. Push button (single circuit, normally open).
   g. Push button (single circuit, normally closed, with mushroom head).
   h. Relay contact (normally closed).
   i. Half-wave rectifier.
   j. Full-wave bridge rectifier.
   k. Red indicator lamp.
   l. Three-phase motor.
   m. Foot operated switch (normally closed).
   n. Foot operated switch (normally open).
   o. Ground connection.

OBJECTIVE:

To learn about control diagrams and how they are used in industry.

RELATED INFORMATION:

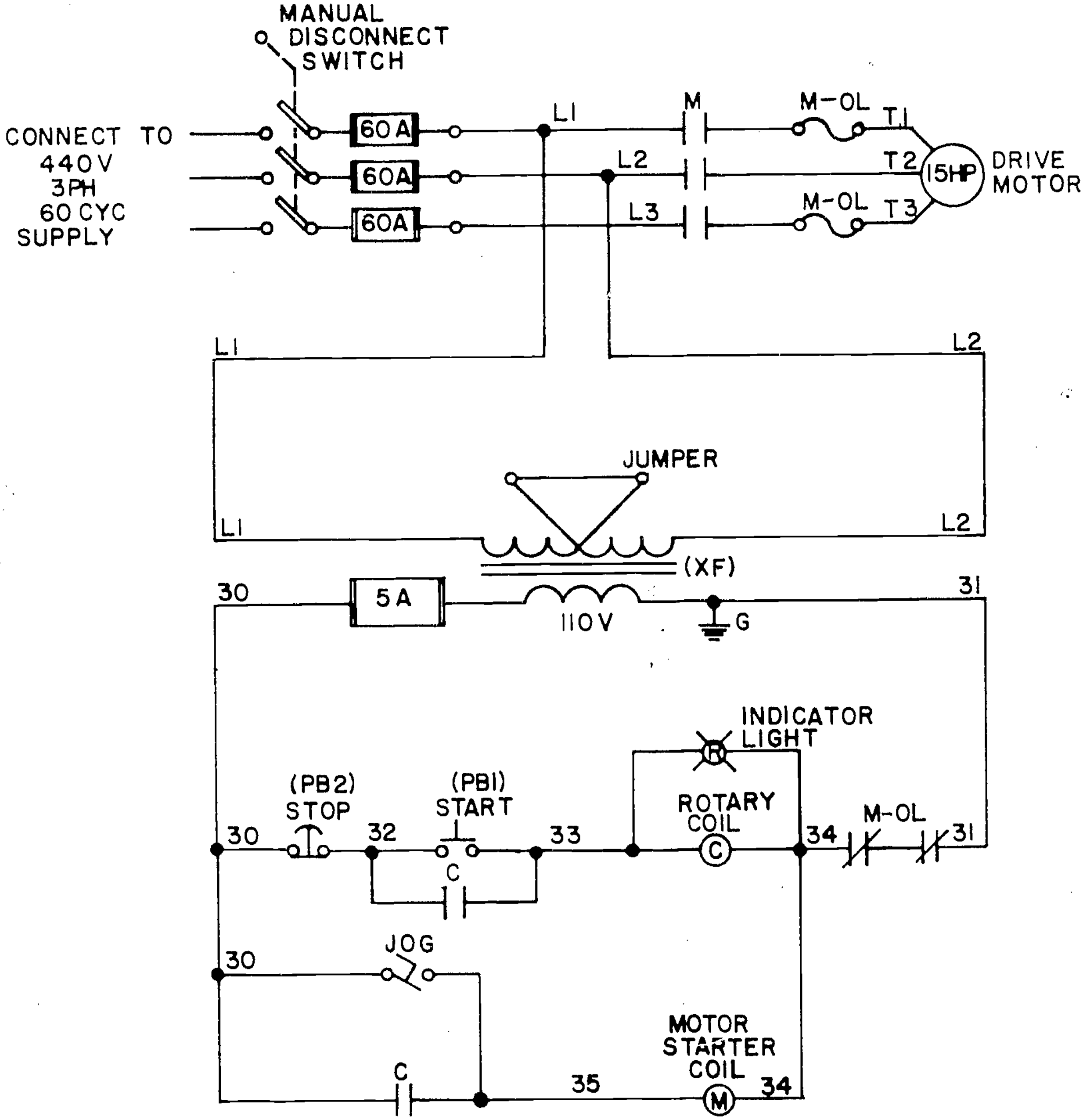
Most of the complicated controls used by industry today are a collection of simple and easy to understand operations that have been arranged to perform a logical sequence of events. The electro-mechanical drafting student would do well to learn to identify and understand simple operations so that he will not be frightened away when he sees them together in a complex control system.

To understand and build these controls, industry puts down a scheme or plan on paper. thus recording the chain of events that is to take place. This drawing is kind of an electrical road map that will indicate the operational path that the machine you are controlling is to take. In other words, it tells you what the machine is supposed to do while it is operating. A drawing that provides this information is called an ELEMENTARY DIAGRAM (or sometimes a SCHEMATIC DIAGRAM). A representive elementary diagram is shown in *Fig. 2.*

Elementary diagrams are to show all of the graphic symbols for the electrical devices to be used in what we call individual circuits. The individual circuits are represented by the horizontal lines shown on the elementary. The vertical lines represent the control circuit power source. The connecting of the individual circuits together in this manner forms a complete control circuit. An elementary diagram must indicate all the electrical connections that are to be made. This is done through the use of numbers that are used to identify the interconnecting wires and the terminal points to which they are connected. You will note that each horizontal line is numbered and that the number changes on opposite sides of a symbol.

The symbols are arranged for convenience in drawing and to simplify the reading of the elementary diagram. No attempt is made to indicate the location of the various devices on the machine being controlled. An elementary diagram is read from left to right. one circuit at a time, similar to reading a printed page. For the sake of uniformity, the operating coils of the various control devices are shown in a vertical line on the right-hand side of the control circuit.

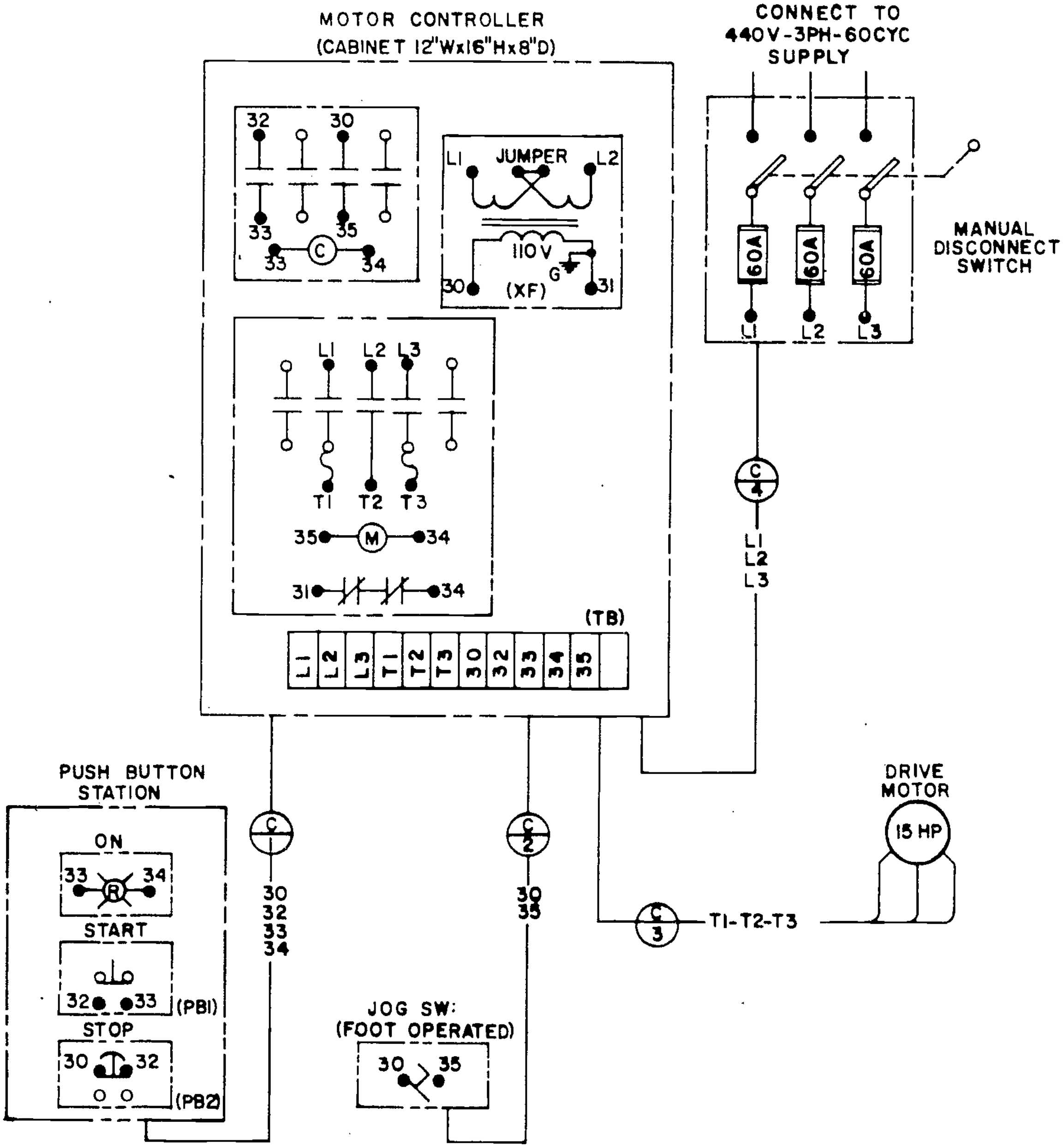
Since the elementary diagram only describes how the individual devices are going to function. you must provide information that will describe where they are to be located and how they are to be connected. A drawing that provides this information is called a CONNECTION DIAGRAM (or sometimes a POINT-TO-POINT). A representative connection diagram is shown in *Fig. 3.*



ELEMENTARY DIAGRAM

Fig. 2

WIRING TABLE		
WIRE No	CONNECTION	SIZE
L1-L2-L3	M-TB	6
T1-T2-T3	M-TB	6
30	C-XF-TB	14
31	XF-M	14
32-33	C-TB	14
34-35	C-M-TB	14



CONNECTION DIAGRAM

Fig. 3

The connection diagram must show the general physical arrangement of all the electrical components indicated on the elementary, and the information that indicates how these devices are to be interwired. Included are the locations of all of the numbered wires and terminal points indicated on the elementary diagram. If the control is to have several controlling devices, as many as can conveniently be grouped together are usually mounted on a panel in a protecting cabinet. The connection diagram must then show the physical layout of the cabinet and all of the internal connections to be made within the control cabinet. These connections are shown on what is called a WIRING TABLE. See *Fig. 3.*

Wiring tables permit the control cabinets to be wired in advance of wiring the machines and insures that the connections made within the panel will be the same regardless of who does the wiring. All devices, wires, and terminals are identified as shown on the elementary diagram. Usually the control cabinets are wired in advance. To accommodate this, the cabinets are provided with terminal blocks on which the individual terminals have been marked with the number of the wire attached. When the remote devices are connected to the controller, the wires from them are simply connected to the terminals with corresponding numbers.

The wires connecting a remote device to the control panel are usually run through a protective covering called a CONDUIT. A conduit can be a system of thin-wall tubing or lengths of flexible armored cable within a flexible plastic hose. Both systems are provided with compression fittings that serve to make the system oil-tight. These runs are identified on the connection diagram with a symbol similar to $\frac{S}{1}$. This symbol indicates that the run is to be shop-connected, and it is the first to be connected. All wires contained are listed either to the right or below the symbol. See Fig. 3. Often runs of conduit are to be made by a customer after he has received the machine. These symbols will be marked with $\frac{C}{1}$, $\frac{C}{2}$, etc.

Dimensions need not be shown, although sometimes it is desirable to include the dimensions of control cabinets, etc. The symbols and numbers used to identify devices, wires and terminals must be identified as shown on the elementary diagram. Study this relationship between Figs. 2 and 3.

The elementary and connection diagrams are both useful during the initial design and manufacture of the control system, and as an aid in servicing or in making future modifications. In many cases the control for a particular machine is simple enough to allow you to put the elementary and connection diagrams on the same drawing. In this case the elementary is always drawn on the left-hand side of the paper. When this is done, the drawing is called a WIRING DIAGRAM.

QUESTIONS:

1. What is the easiest way to understand a complex control system?
2. Describe an elementary diagram.
3. What must an elementary diagram show?
4. How do you read an elementary diagram?
5. Why doesn't an elementary diagram attempt to locate the electrical devices?
6. There are four types of switches shown in Fig. 2. Can you name them?
7. What is a connection diagram?
8. Refer to the connection diagram shown in Fig. 3. If you were trouble-shooting this machine, where would you expect to find the motor starter (M)?
9. Why are the other devices mounted in the same cabinet?
10. Fig. 3 shows a control relay (C) with four contacts. Two are not used and therefore are not shown on the elementary. The two that are used are shown connected to other switch contacts. Using the elementary diagram (Fig. 2), name the switch that is connected with the (C) contact that has wires 32 and 33 connected to it.
11. What is the function of the red indicator light connected to the (C) relay shown in Fig. 2?
12. How many fuses are shown on the elementary (Fig. 2)?
13. Why are wiring tables used on connection diagrams?
14. How many runs of conduit are there between the control cabinet and the remote devices?
15. Who supplies these connections?
16. To what device are the wires in run to be connected upon entering the control cabinet?
17. What are the three wire numbers used to identify the wires that connect the magnetic motor starter (M) to the 15 H.P. motor?
18. How is the run that connects the jog switch with the controller identified?
19. What is the value, in amperes, of the fuses shown in the manual disconnect switch?
20. When might control diagrams, both elementary and connection diagrams, prove useful after the machine has been put in service?

OBJECTIVE:

To learn about the source of electrical energy.

RELATED INFORMATION:

Electricity is a form of energy that can be produced through the proper use of light, heat, magnetism or chemical changes. In turn, this energy can be used to produce light, heat, magnetism, or chemical changes. Although no one knows precisely what electricity is, it has been possible to develop theories about electricity through experiment and by observing its behavior. A satisfactory explanation of this force may be found in the ELECTRON THEORY.

The electron theory explains that the smallest component into which all matter can be divided, and still retain its identity, is called an ATOM. Atoms are made up of particles of electrical energy that are in motion. The core or nucleus of an atom is made up of particles that are tightly held together. These particles are called PROTONS and NEUTRONS. Revolving around the nucleus in eliptical orbits are other particles called ELECTRONS. Each of the orbiting electrons is rotating about its own axis as the nucleus spins in the center. See *Fig. 4*.

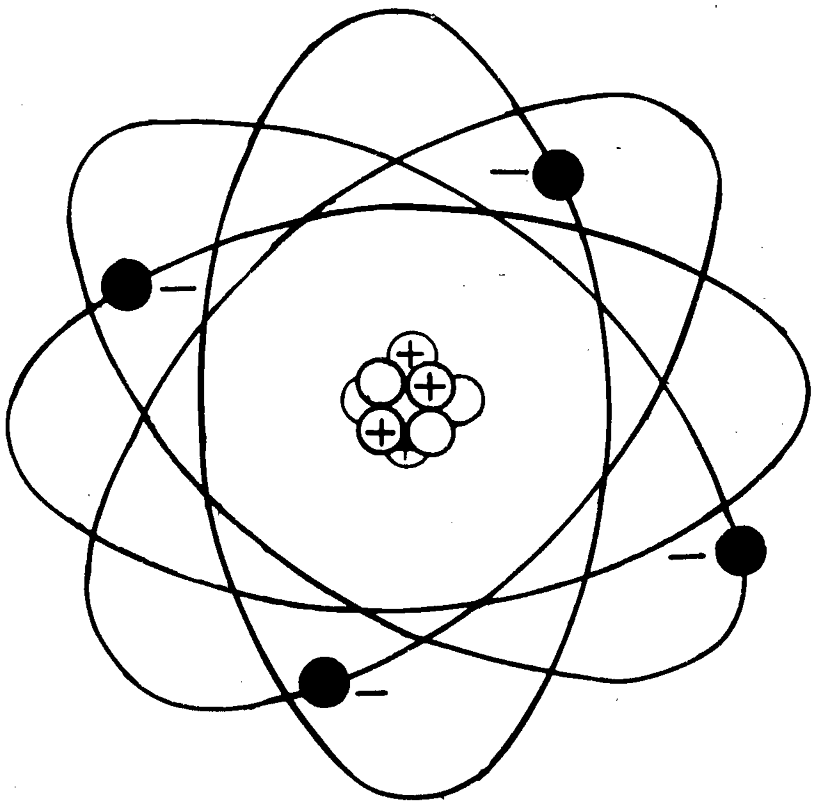


Fig. 4

There appears to be an attracting force acting between the protons of the nucleus and the orbiting electrons. Also, the electrons appear to be exerting a repelling force on one another that causes them to arrange themselves in a kind of a layer of orbits around the nucleus. As a convenience in discussing this behavior, we say that the protons are positively charged, the neutrons are uncharged, and the electrons are negatively charged. In a normal atom, the negative charge of the electrons exactly neutralizes the positive charge of the nucleus, so that the atom itself has no electrical charge.

The structure of atoms that have a great number of electrons, such as those found in metals, is that the electrons are required to form several layers of orbits, each further out from the nucleus than the other. The further out a layer of orbits is, the more electrons it can accept before the repelling action that the electrons exert on one another forces the remaining electrons into a new layer of orbits. The electrons in this outermost layer, being further away from the nucleus, are not attracted as strongly as the electrons in the inner layers, and an electrical force can be applied that will tear a loosely held electron away. This force is called an ELECTROMOTIVE FORCE (E.M.F.), and is expressed by a unit called the VOLT.

When an electron has been torn away from an atom, it is called a FREE ELECTRON. The atomic structure of metals, such as copper and aluminum, that will allow its electrons to be torn away easily produces CONDUCTORS. In materials such as glass and rubber, very high voltages are required. These materials are called INSULATORS.

Atoms that have been distorted by having an electron added are called NEGATIVE IONS and are negatively charged. Those distorted by having an electron torn away are called POSITIVE IONS and are positively charged. The electrical imbalance that exists within the ion produces a force that tries to return it to a normally uncharged atom. This force will be felt by the atoms surrounding the ions. The positive ion will capture a loosely held electron from its neighbor, setting up a chain reaction that will continue until the imbalance has been eliminated. Each of the electrons involved in the exchange has only to move from one atom to another, which it does approximately at the speed of light (186,000 miles per second). The movement of these free electrons is referred to as ELECTRON FLOW. Thus, an electric current is merely the movement of electrons (negative charges) through a conductor.

To do useful work, electrons must move in numbers that are beyond our imagination, forming sort of a current of free electrons. The unit used to express the number of electrons flowing past a given point per second is called an AMPERE. When a current of one ampere is flowing, 6,280,000,000,000,000,000 or (6.28×10^{18}) electrons are flowing past this point each second.

The atoms of all materials offer some resistance to having electrons torn away, some more than others. This characteristic is usefully employed in devices called RESISTORS. The resistance to current-flow is expressed by a unit called an OHM.

QUESTIONS:

1. How can electrical energy be produced?

2. If you were to produce electrical energy through the use of magnetism, could you use this energy to produce light?

3. What accepted theory explains the nature of this force?

4. Name the smallest component that matter can be broken down to without losing its identity.

5. Describe how the electron theory implies that all matter is made up of balanced charges of electricity.

6. What are the parts that make up the core of the nucleus of an atom?

7. Are the parts of the nucleus loosely or tightly held together?

8. Why do we say that the nucleus is positively charged?

9. Why do we say that an electron is negatively charged?

10. What forces are acting upon an electron as it orbits the nucleus of an atom?

11. Is a normal atom positively or negatively charged?

12. The copper atom contains only one electron in its outmost layer of orbits. Why do you believe that this occurs?

13. Why is it easier to tear an electron from an atom if it is in the outermost layer of orbits?

14. What is an electron called after it has been torn from an atom?

15. Name the force required to tear away this electron. What is the unit used to measure it?

16. What do you call materials that require very high voltages before this occurs?

17. What do you call an atom after it has been distorted by having electrons added or subtracted?

18. Describe what would happen within a piece of copper if an electrical imbalance were created at each end.

19. What is the unit used to express the number of electrons flowing past a given point per second?

20. What is the unit used to express resistance to current flow?

OBJECTIVE:

To learn about Series Circuits.

RELATED INFORMATION:

When lamps or other electrical devices are connected end to end we say that they are connected in SERIES. The circuit shown in *Fig. 5* is called a series circuit.

A series circuit is one in which the devices are so connected that it offers only one path for current to flow through it, as indicated by the arrows. It should be mentioned here that this text considers the electron theory – current flow from the negative terminal to the positive terminal. You will encounter people reading current as flowing in the opposite direction – positive to negative. This is called the CONVENTIONAL THEORY OF CURRENT FLOW. There are merits to both theories and truth is yet to be found.

Consider that we want to measure the current that is flowing through the different parts of the circuit. First we must understand that the instrument used to measure electrical current is called an AMMETER. Ammeters are always connected in series with the device through which the current is to be measured.

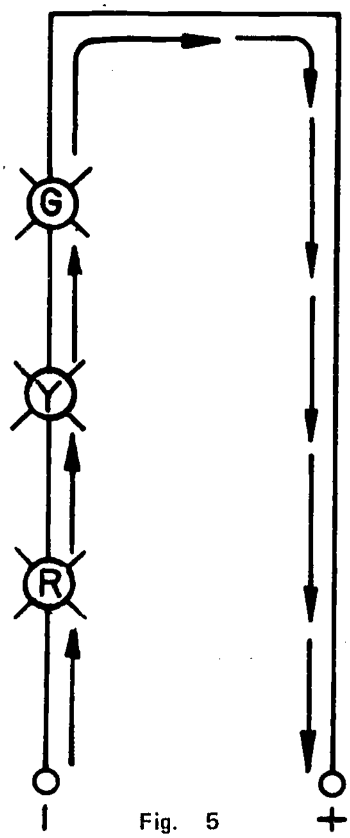


Fig. 5

The circuit in *Fig. 6* is identical to the circuit shown in *Fig. 5* except that we have inserted four ammeters or current-measuring devices in the circuit. When the circuit has been connected to a power supply, or we say that when the circuit has been "energized", you will see that each ammeter is indicating that the same amount of electrical current is flowing through it. This test indicates that a series circuit is one in which the devices are connected so that they will offer only one path for current to flow. As a result, the electrical current remains the same through all parts of the circuit.

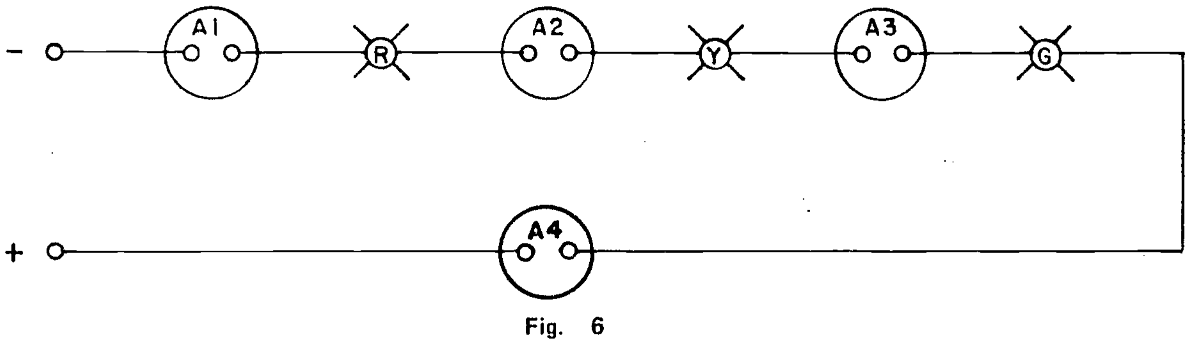


Fig. 6

The total resistance of a series circuit is equal to the sum of the resistances of all the individual parts.

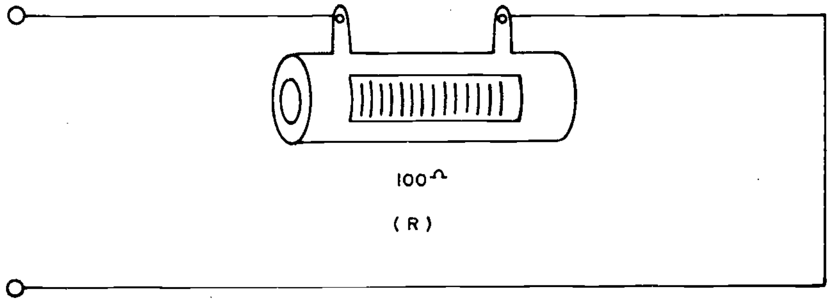


Fig. 7

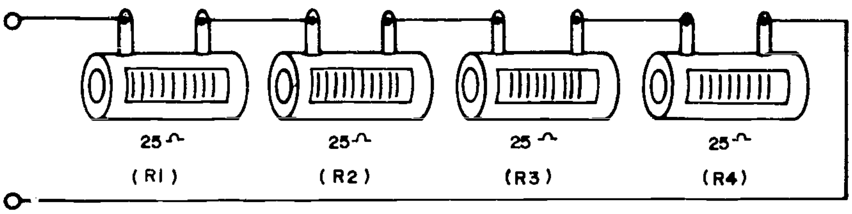


Fig. 8

Consider the circuits shown in *Figs. 7 and 8.* The total resistance of a series circuit is equal to the sum of the resistances of the individual parts. The circuit in *Fig. 7* shows a 100-ohm wire-wound resistor that is in reality a coil of resistance wire wound around a form. If the number of turns on the form produces 100 ohms and we cut the form into four pieces, we will in effect divide the length of resistance wire into four equal parts of 25 ohms each. Therefore, when the four 25Ω resistors shown in *Fig. 8* are connected in series, they are in effect forming one continuous resistor with a value of 100Ω. From this then we arrive at the following formula for the series circuit:

$$\text{Total Resistance} = R_1 + R_2 + R_3 + R_4$$

$$= 25 + 25 + 25 + 25$$

$$= 100 \text{ Ohms}$$

Ohm's Law states that the amount of steady current flowing in a circuit is equal to the applied emf divided by the resistance of the circuit. Written mathematically it is:

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

Where I = current in amperes

E = emf in volts

R = resistance in ohms

Applying Ohm's Law, we see that if the power supply is rated at 220 Volts, the current flowing would be equal to $\frac{E}{R}$ or $\frac{220}{100}$, which is equal to 2.2 amps. Since the voltage applied to a series circuit is divided up among the individual voltage drops across all of the individual resistances in the circuit, the voltage drop across the 100Ω resistor in the circuit shown in *Fig.* 7 could be found by transposing Ohm's Law to read:

$$E = IR$$

$$= 2.2 \times 100$$

$$= 200 \text{ volts}$$

Ohm's law may be applied to the entire circuit or to any part of a circuit. Most of the mistakes in electrical calculations occur because Ohm's law is not used properly. When it is used for the entire circuit, values of current, voltage, and resistance must be used for the entire circuit. When used for a certain part of the circuit, values of current, voltage, and resistance must be used for only that part.

The voltage drop across the first 25Ω resistor (R_1) in *Fig. 8* would equal 2.2 x 25, or 55 volts. We would solve for the voltage drop across each of the remaining resistors in the same manner. Since each of the resistors is equal in value, the voltage drops across each resistor will be equal, and the sum of the voltage drops will equal the applied voltage. The very small voltage drop that will occur across the connecting wires can be ignored.

QUESTIONS:

1. When is a circuit said to be series connected?

2. If a current of 1 ampere is flowing through the RED light in *Fig. 5*, how much current is flowing through the GREEN light? The YELLOW Light?

3. What would happen if the circuit shown in *Fig. 5* were energized and you removed the RED bulb?

4. What instrument is used to measure the flow of electrical current?

5. How should this instrument be connected to measure the current flowing through a particular device?

6. Referring to *Fig. 6*, how many ammeters would be required to measure the total current flowing through all the lights?

7. How many paths are provided for current flow in a series circuit?

8. If the division of the resistances in the circuit shown in *Fig. 8* were $R_1 = 10\Omega, R_2 = 20\Omega$, $R_3 = 30\Omega$, $R_4 = 40\Omega$, what would be the total resistance of the circuit?

9. If you were to insert a 100-Ohm resistor in series with this circuit, what would be the total resistance?

10. If we were to connect the circuit shown in *Fig. 8* to a 440-volt power supply, what would be the voltage drop across the individual resistors?

11. What would be the current flowing through each resistor?

12. If we were to change the power supply to 110 volts, what would be the voltage drop across each resistor?

13. What would be the current flowing through each resistor?

14. Referring to the circuit shown in *Fig. 8*, how would the voltage drop across R_1 be affected if we were to replace R_2 with a 25-Ohm light bulb?

15. If you had an electrical device with an electrical resistance of 25 Ohms that had to be operated on a potential of 55 volts, using the information that you have just learned, sketch a circuit showing how you would connect this device to a 220-volt supply. Indicate all values necessary. Label your calculations.

OBJECTIVE:

To learn how to draw and understand a simple motor control.

RELATED INFORMATION:

By definition a controller is a device for regulating the operation of the apparatus to which it is connected. A starter is a controller whose main function is to start and stop a motor. The controller shown in *Fig. 9* uses a manually operated motor starter to control a ½ H.P. series-wound direct-current motor.

Remember that this elementary diagram shows all of the graphic symbols to be used in what we now recognize to be a series circuit.

On simple wiring diagrams the elementary and connection diagrams are usually shown on the same drawing, with the elementary appearing on the left. The elementary is going to explain how the circuit works, and the connection diagram is going to indicate the location of devices and how they are to be connected.

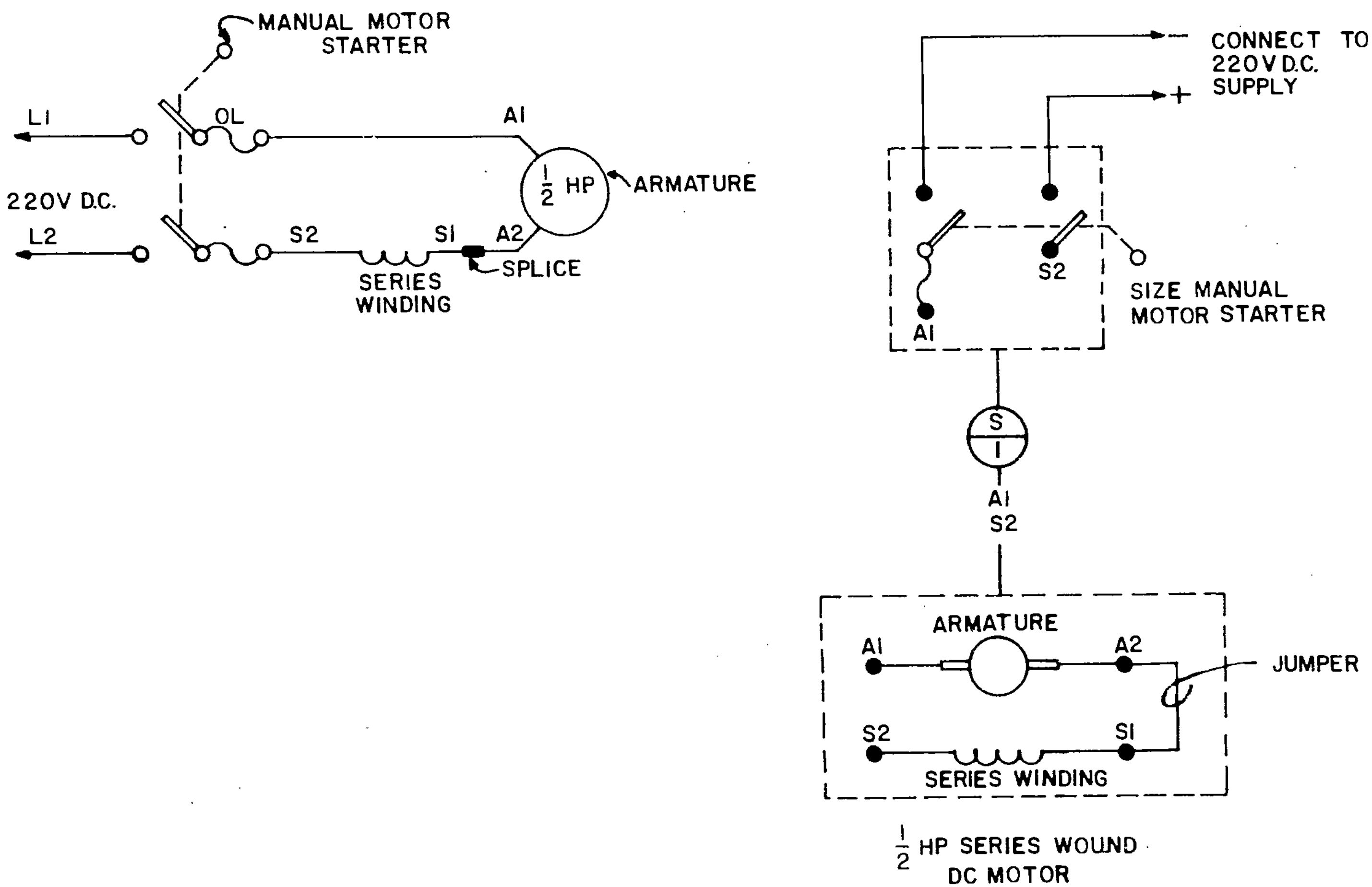
Since wiring diagrams are read like a printed page, start at the upper left-hand corner of the elementary and read the series circuit. First, recognize that the power supply is rated at 220 volts d.c. with the electrical polarity shown. Applied to electrical circuits, the ELECTRICAL POLARITY indicates which terminal is negative and which terminal is positive. The open circles – meaning not filled in – indicate terminals. A terminal is a device for connecting wires. REMEMBER, WHEN YOU SEE AN OPEN CIRCLE YOU CAN CONNECT A WIRE.

Each wire must be identified on an elementary diagram every time that it appears as a horizontal line. By reading the elementary we can tell that a wire identified as (L1) must run from the power source to a terminal on the manual motor starter.

A manual motor starter is a device that will connect or disconnect the motor from the power source, only when someone provides the physical effort to operate it through moving a lever or pushing a button. The symbol for the manual motor starter shown on the elementary, indicates it includes an overload heater (OL).

Overload heaters are basically resistance devices that are designed to heat up as current flows through them. The motor starter is designed to sense this heat and at a predetermined value open the switch contacts. Thus, the switch is equipped to protect the motor from drawing a greater amount of current than it was designed to take. NOTE THAT WHEN OVERLOAD HEATERS ARE SHOWN ON ELEMENTARY DIAGRAMS THEY ARE MARKED (OL).

Continuing to read the elementary, you see that after passing through the starter, the wire connecting it to the motor armature winding is now designated (A1). THE RULE FOR WIRE DESIGNATIONS IS: EVERY TIME A WIRE PASSES THROUGH A SYMBOL, CHANGE THE DESIGNATION.



WIRING DIAGRAM – MANUAL CONTROLLER

Fig. 9

The motor shown is a series-wound direct-current motor. Electric motors convert electrical energy to mechanical energy through the use of magnetic forces. As iron is attracted by, or pulled, toward a magnet before it touches it as the result of the magnetic field, electric motors are possible because an electric current flowing in a conductor or coil of conductors also produces magnetism. The space around the conductors is filled with magnetic lines of force. The area of the magnetic lines of force is called a MAGNETIC FIELD. Two magnetic fields from two conductors or coils can either push away from each other (REPEL) or pull toward each other (ATTRACT). By using these forces, a motor shaft can be made to turn.

All electric motors have two main parts: a rotor, or turning part, and a stator which does not move. A FIELD coil wound on the stator develops a strong magnetic field when current flows in it. An ARMATURE coil is wound on the rotor. When the correct amount of current flows in the armature coil, the magnetic fields will act upon each other and the rotor will begin to turn. The armature winding on a d.c. motor is connected to a switching device, called a COMMUTATOR. The commutator switches the flow of current through the armature winding, so that the magnetic fields will continue to provide the rotating force. The rotor can then be used to drive a machine.

In a series-wound motor the low-resistance field winding consists of a few turns of heavy wire, as the field winding must carry the armature winding current. IN A SERIES CIRCUIT THE CURRENT IS THE SAME IN ALL PARTS OF THE CIRCUIT. Series motors have a very high starting torque which makes them useful for starting automobile engines, driving winches, or cranes, where heavy loads must be moved slowly but where the lighter loads may be moved with greater speed. ANY CHANGE IN LOAD CAUSES A SERIES MOTOR TO CHANGE ITS SPEED.

A series motor does not have a definite no-load speed. Therefore a series motor is usually connected directly to the load rather than through belt or some such device that may break. THE LOAD SHOULD NEVER BE DISCONNECTED FROM A SERIES MOTOR. Without a load, a series motor would rotate so rapidly that the armature may fly apart due to the centrifugal force built up within it.

After passing through the armature the wire designation becomes (A2). At this point a splice is shown. (See *Fig. 9.*) Since all d.c. motor leads from the armature are marked (A1 and A2) and all series-windings are marked (S1 and S2), wires (A2 and S1) will have to be connected together at the motor; this is called a SPLICE. Splices are indicated on wiring diagrams, as shown on the drawing, as an informational note. NOTE THAT LEADERS ARE ALWAYS SHOWN AS IRREGULAR CURVES.

The wire running between the series-winding and the manual motor starter is marked (S2). Finally, the wire from starter to the other side of the power source is marked (L2), thus completing the circuit. The elementary has identified all of the wires to be used, symbols for all of the electrical devices and how the circuit is to function. Namely, when connected to a 220-volt d.c. power source, closing the manual motor starter contacts will energize the ½ horsepower d.c. motor, which will provide mechanical energy to do some useful work. The broken line connecting the two switch contacts together means that they will operate together. Opening the motor starter contacts will de-energize the motor and the mechanical energy will disappear. Also, overload protection is provided for the motor through the selection of the correct overload heater.

The connection diagram is shown on the right side of the paper. Since the connection diagram must show the general physical arrangement of devices shown on the elementary, reading the drawing we would expect to find the conductors (L1 and L2) connecting the starter to the power source projecting through the top side of its enclosure. Enclosures – the metal boxes or cabinets that protect electrical devices – are usually indicated on connection diagrams by using broken lines. The size of the motor starter required to accommodate the motor to be controlled and the recommended heater are shown as informational notes. We would also expect to find the motor starter to be mounted above the motor on this particular machine.

Connection diagrams must also indicate how the devices are to be interwired, including the location of all the wires and terminal points. Note that only one run of conduit $\frac{S}{1}$ is indicated. We would expect to find wires (A1 and S2) in this conduit. The connection of (L1 and L2) between the motor starter and power source is understood, so therefore is not indicated as such. The connection diagram tells us that $\frac{S}{1}$ is a run of conduit that is to be installed between the starter and motor in our shop and that we should find wires (A1 and S2) inside of this conduit. NOTE THAT THE TERMINAL FOR EACH WIRE IS IDENTIFIED AND THE TERMINAL IS FILLED IN WHEN THERE IS A WIRE CONNECTED TO IT.

Since the men who do the actual wiring of the machine work mainly from the connection diagram, note that the splice required on the armature and series winding leads (A2 and S1) have been shown again at the motor location. Finally, the size and type of motor used is indicated. Notice that when elementary and connection diagrams are combined on a single drawing it is referred to as a WIRING DIAGRAM.

QUESTIONS:

1. What is the difference between a starter and a controller?
2. Why is the circuit shown in Fig. 9 a series circuit?
3. How does an elementary help you?
4. In what way does a connection diagram help a person who is to wire the machine?
5. Why do you think the electrical polarity has been shown?
6. How does an elementary indicate that provision has been made for connecting wires?
7. What is the rule for identifying wires on an elementary diagram?
8. Describe the job that is to be performed by a manual motor starter.
9. How are overload heaters indicated on elementary diagrams?
10. When must you change a wire designation?
11. What is the term used to refer to the area of magnetic lines of force?
12. How can two magnetic fields cause a motor shaft to turn?
13. Name the two main parts that all motors have in common.
14. On which part is the field coil usually wound?
15. On which part is the armature coil usually wound?
16. What is the function of a commutator?
17. Why does the series motor have a low-resistance field coil?
18. What happens to the speed of a series motor when the load connected to it changes?
19. Describe what would happen if the load was removed from an energized series motor.
20. Why was it necessary to splice wires (A2 and S1), shown in Fig. 9 together?

21. How does the circuit shown in Fig. 9 work?

22. What does it indicate when electrical devices are connected together with a broken line? The limit switch shown in Fig. 9, for example.

23. How do overload heaters protect motors from drawing excessive current?

24. In what manner are leaders, for informational notes, indicated on wiring diagrams?

25. What are the designations for wires to be found in run $\frac{S}{1}$?

26. Which electrical device, shown on the connection diagram in Fig. 9, would you expect to be mounted in the lowest position?

27. What is indicated on a connection diagram when a terminal has been filled in?

28. Which section of a wiring diagram is most used by the men who do the actual wiring of the machine?

29. Why do you think that series motors are used as automobile starter motors?

30. Explain what would happen to the cranking-speed of an automobile engine if you were to energize the starter motor with the spark plugs removed.

ASSIGNMENT:

1. Redraw the wiring diagram shown in Fig. 9.

   a. Once you have established a size for a particular symbol it must be drawn exactly the same way each time that it appears on the drawing.

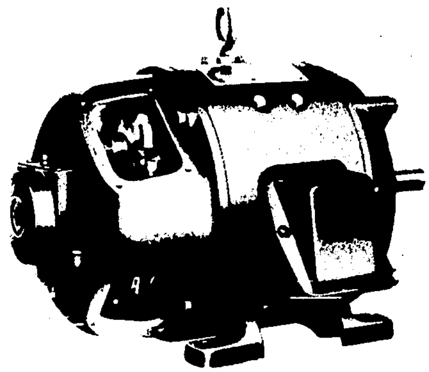
   b. GOOD LUCK ON YOUR FIRST WIRING DIAGRAM.

OBJECTIVE:

To learn about Direct Current Motors.

RELATED INFORMATION:

An electric motor is a machine that converts electric energy to mechanical energy. Electric motors have a variety of applications and may vary in size from 1/100 horsepower to thousands of horsepower. A typical d.c. motor is shown in *Fig. 10.* MOST MOTORS ARE RATED AS TO THE HORSEPOWER THEY CAN DELIVER AT THEIR RATED VOLTAGE AND SPEED WITHOUT OVERHEATING.



A d-c motor. *(Century Electric Co.)*

Fig. 10

Electric motors are used as sources of power for industry and for household work. An electric motor is ready for work instantly. It is clean and economical. Few machines are so important to modern living as the electric motor. Since motors often operate under dusty, wet, or corrosive conditions, they are manufactured in open-type, drip-proof, or totally enclosed enclosures. Open-type motors have screens or similar protection to prevent damage to their rotating parts. A drip-proof motor has its ventilating openings placed so as to protect it against falling liquids. The totally-enclosed motors are completely sealed so that no cooling air can enter the motor. The heat that is generated by the motor must be radiated from the sealed case.

The function of a motor is to develop a twisting effort which is called TORQUE. Thus, torque is the measure of the tendency of a motor shaft to rotate. An explanation of how a motor may produce torque is based on a fundamental law of physics which states as follows: A CONDUCTOR CARRYING CURRENT IN A MAGNETIC FIELD TENDS TO MOVE AT RIGHT ANGLES TO THE FIELD.

The space around a magnet in which the magnetic forces act is called a MAGNETIC FIELD and may be considered to be made up of many lines of force. An excellent graphic demonstration of a magnetic field pattern may be made by placing a sheet of cardboard over a permanent magnet and sifting fine iron filings over the cardboard. The iron filings, becoming magnetized, arrange themselves in definite paths or lines between the poles or ends of the magnet, as shown in *Fig. 11.*

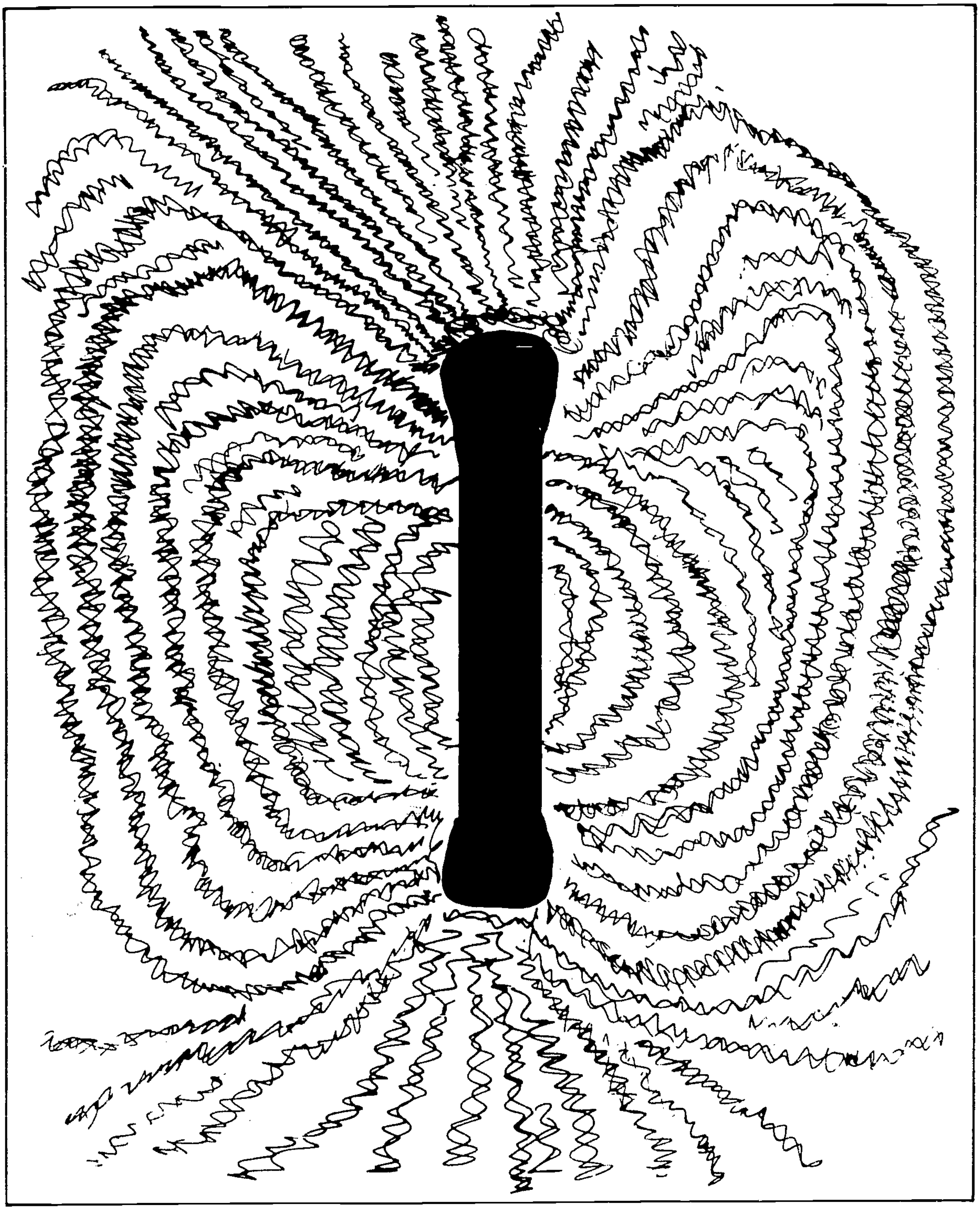


Fig. 11

Turning the magnet on edge will show that a similar field exists, proving that a magnetic field exists in the entire space surrounding a magnet. The entire quantity of magnetic lines of force surrounding a magnet is called MAGNETIC FLUX. The number of lines of force per unit area is called FLUX DENSITY.

The path in which the magnetic lines of force are established is called a MAGNETIC CIRCUIT. The magnetic circuit of a bar magnet consists of the path of magnetic lines through the magnet and the surrounding space. The opposition to the establishment of magnetic lines of force is called the RELUCTANCE of the circuit. Since air has a much higher reluctance than iron or steel, the magnetic circuits used for motors are designed with very small air gaps, the greater part of the path followed by the lines of force being made of iron.

The magnetic circuit of a direct-current motor as shown in *Fig. 12,* is made up of the field yoke, pole cores, air gap, and armature core.

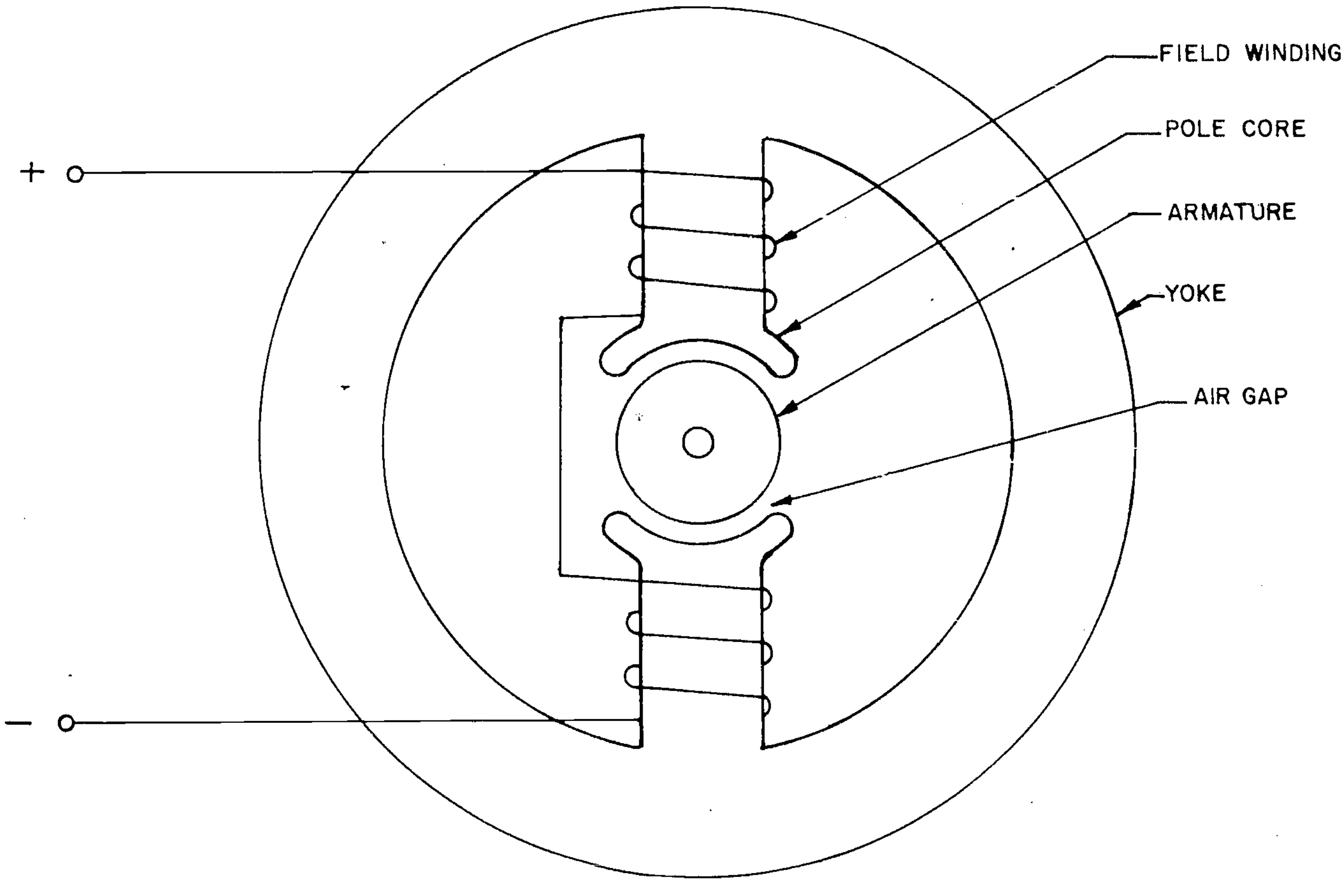


Fig. 12

The FIELD YOKE, or frame, which is usually made of cast or rolled steel, serves as the mechanical support for the pole cores as well as part of the magnetic circuit. End bells, which support the brush rigging and usually the armature bearings, are also bolted to the yoke.

POLE CORES are made of sheet-metal laminations that are insulated from each other and riveted together. The core then is bolted to the field yoke. The pole face, which is the surface of the core next to the air gap, is made larger than the core body. This is to reduce the reluctance of the air gap and to provide a support for the field coils.

An assembled ARMATURE CORE and commutator is shown in *Fig. 13.*

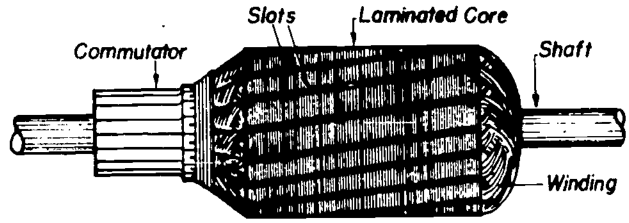


Fig. 13

The core is made up of sheet-steel laminations that are keyed to the shaft. The outer surface of the core is slotted to provide a means of securing the armature coils.

The AIR GAP is the space between the armature surface and the pole face and varies with the size of the motor.

The electric circuits of a d.c. motor are made up of the field winding, commutator, brushes, and the armature winding.

The FIELD COILS are placed around the pole cores as shown in *Fig. 12.* The coils of each of the poles are connected in series to form the field circuit.

The COMMUTATOR consists of a number of copper segments that are assembled into a cylinder which is secured to, but insulated from, the motor shaft. The segments are well insulated from each other, and to these segments are soldered the ends of the armature coils. *Fig. 13* shows an assembled armature core and *Fig. 14* shows a commutator without the armature windings.

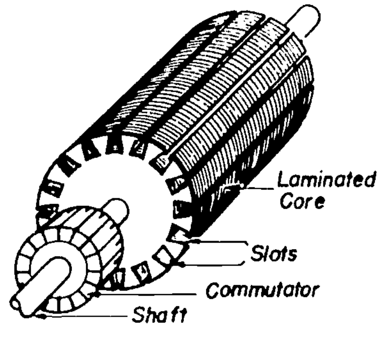
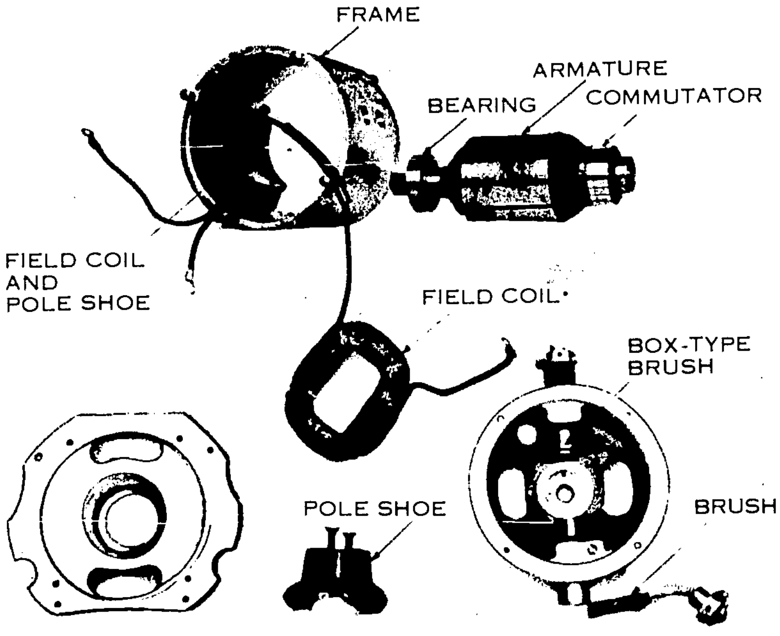


Fig. 14

BRUSHES that rest on the face of the commutator form the sliding electrical connection between the armature coils and the external circuit. Brushes are made of varying degrees of hardness, sometimes being mixed with metallic copper. The brushes are held in place under spring pressure by brush holders, the electrical connection between the brush and holder being made by a flexible copper cable called a PIGTAIL.

Fig. 15 shows a dismantled small d.c. motor. Note that the brush rigging and the bearings are supported by the end bells.



Parts of a Direct Current Motor

Fig. 15

ARMATURE WINDINGS consist of coils that are wound to their correct shape and size on a form, after which they are completely insulated. The formed coils are then slipped into the armature slots and securely wedged into place. Then the coil ends are connected to the proper commutator segments. Small armatures may not be form-wound but are wound directly into the slots of the armature core.

The relationship between electricity and magnetism can be illustrated as shown in *Fig. 16*. When an electrical current begins to flow through a conductor, magnetic lines of force build up around it. If you were to pass a conductor through a piece of cardboard, connect it to the terminals of a battery, and sift fine iron filings on it, you would see that the iron filings will arrange themselves in a circular pattern revealing the force pattern.

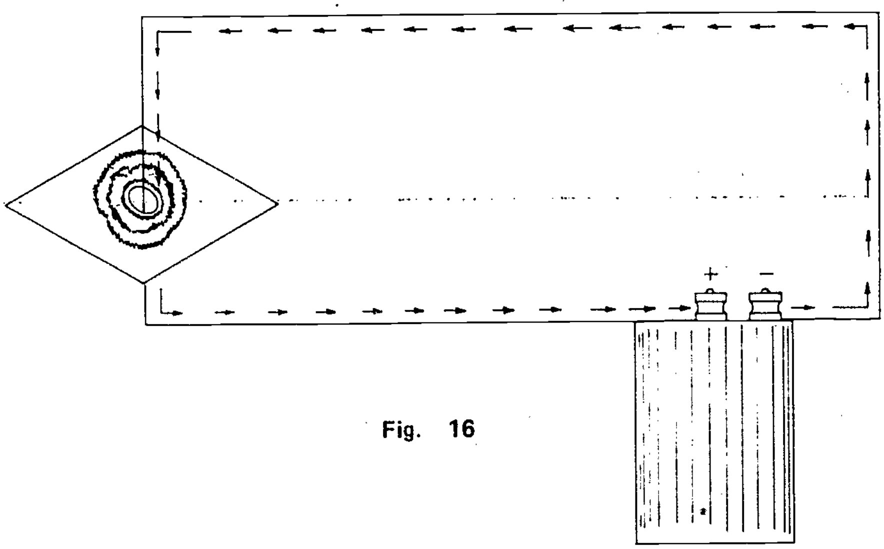


Fig. 16

THE MAGNETISM ASSOCIATED WITH A CURRENT-CARRYING CONDUCTOR CAN BE STRENGTHENED BY FORMING THE CONDUCTOR INTO A COIL OR SOLENOID. An understanding of how a magnetic field is established around a coil can be gained by first considering two parallel conductors carrying current in the same direction, as in *Fig. 17*. Lines of force pass around each conductor in the same direction, resulting in a field that entirely surrounds the two conductors.

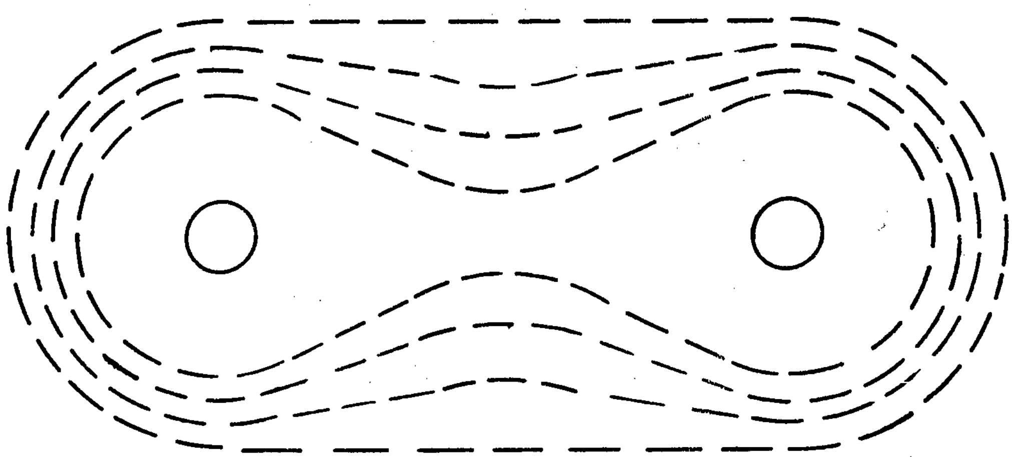


Fig. 17

Likewise the field established by a belt of several conductors, all carrying current in the same direction, completely envelops the conductors as shown in *Fig. 18*.

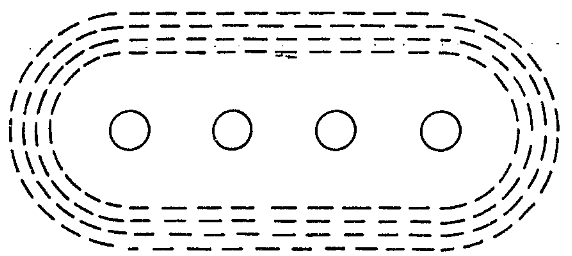


Fig. 18

A coil formed by wrapping a conductor around a hollow insulating tube is shown in *Fig. 19 (a)*. →

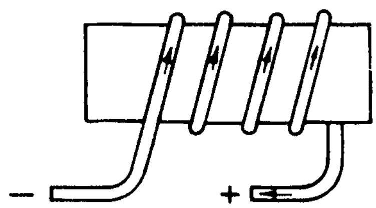
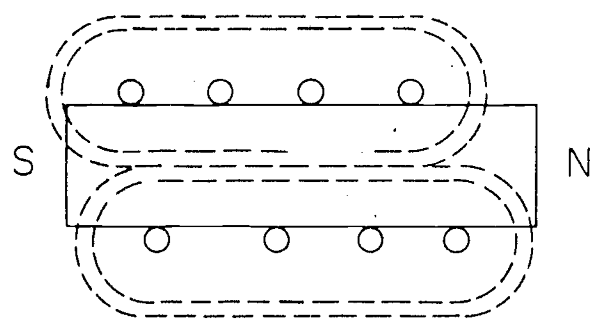


Fig. 19b →



This is further illustrated by *Fig. 19 (b)*, which shows a cross-sectional view of the coil. The field that is established is similar to that of a bar magnet, with the flux emerging from one end of the coil and entering the other. The end of the coil from which the flux emerges is called the north pole of the coil.

The magnetic polarity of any coil may be found by means of the left-hand rule for a coil, stated as follows: GRASP THE COIL IN THE LEFT HAND WITH THE FINGERS POINTING IN THE DIRECTION OF THE CURRENT IN THE COIL; THE THUMB THEN POINTS TOWARD THE NORTH POLE OF THE COIL. Note that when the current is reversed the position of the north pole will be reversed. Applied to magnets, the MAGNETIC POLARITY indicates which pole is north and which pole is south. Also if we were considering the conventional current theory, you would use the right hand.

Electromagnets have a multitude of applications in electrical machinery. One important application is in the field coils that are wound around the pole cores of a d.c. motor.

When voltage is applied to a motor, such as shown in *Fig. 20,* current flows through the field winding, establishing a magnetic field.

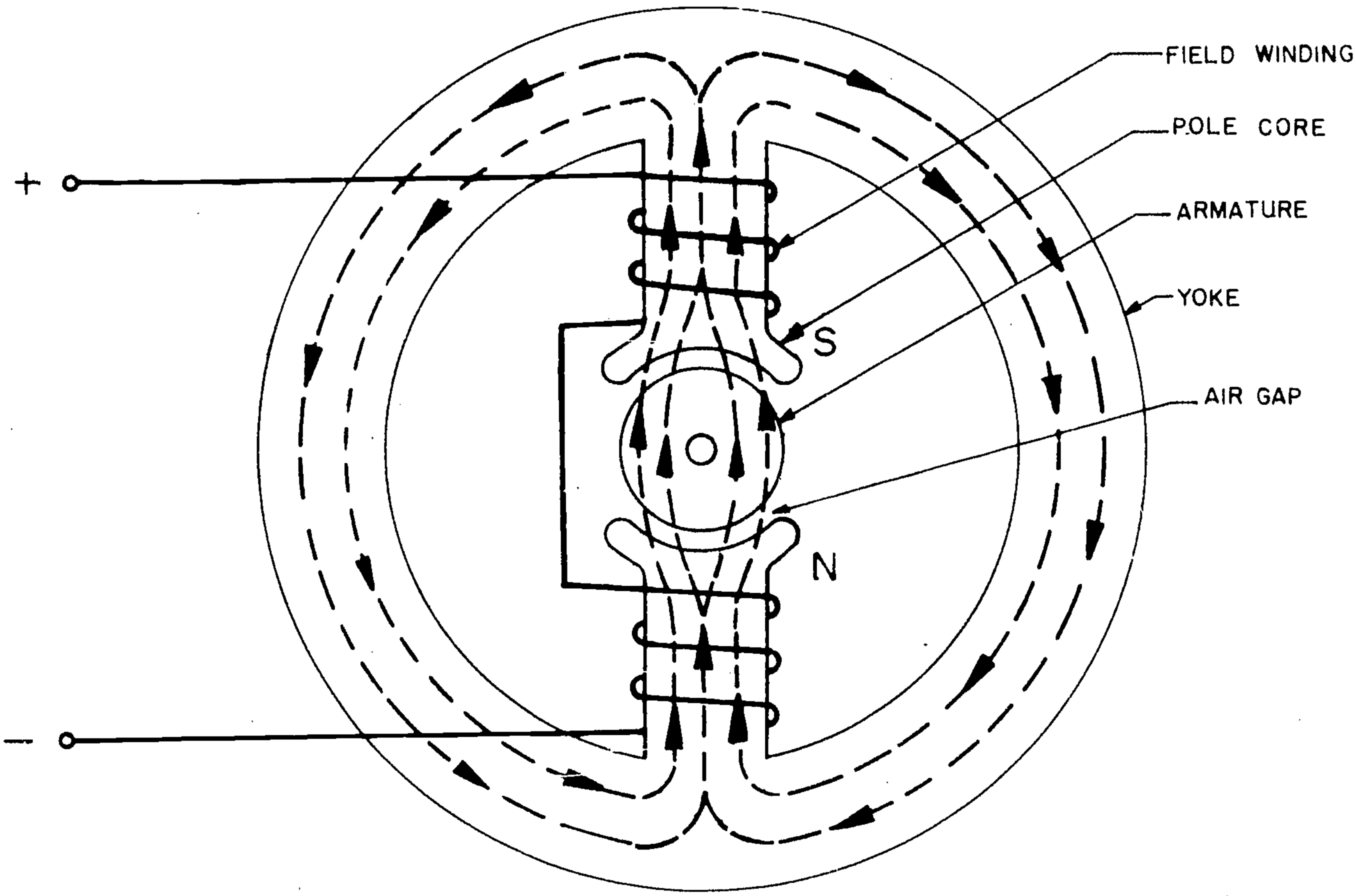


Fig. 20

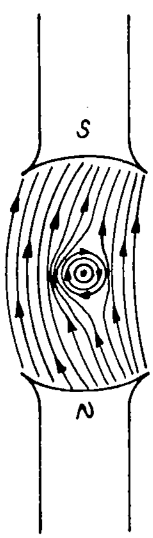
Every conductor carrying a current has a magnetic field around it, the direction of which may be found by another left-hand rule. The left-hand *current* rule states: WITH THE THUMB POINTING IN THE DIRECTION OF THE ELECTRON-FLOW IN A CONDUCTOR, THE DIRECTION OF THE MAGNETIC FIELD IS SHOWN BY THE CURVE OF THE FINGERS OF THE LEFT HAND. The strength of the magnetic field will depend upon the amount of current flowing in the conductor.

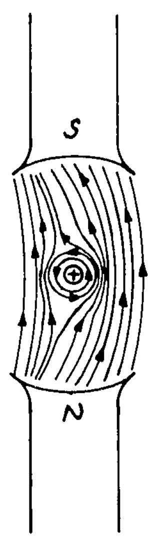
The symbol ⊙ is used in diagrams to show electron-flow toward the reader, and the symbol ⊕ is used to indicate electron-flow away from the reader. *Fig. 21* illustrates the use of the symbol. Don't forget to apply the left-hand rule. Note that we say electron-flow; with the conventional current theory, the current would be considered to be flowing in the opposite direction and you would use the right hand.

Fig. 21

If a wire carrying current toward the reader is placed in a uniform magnetic field, the combined fields will be similar to that shown in *Fig. 22*. Remember like poles repel and unlike poles attract. To the left of the conductor, the clockwise magnetic lines of force from the conductor and those produced by the field winding are in the same direction (like poles). To the right of the conductor the magnetic lines of force from the conductor and the field are in opposite directions (opposite poles). The result is that the flux density (lines per square inch) are increased to the left of the conductor and decreased to the right. Thus, the magnetic lines of force exert a force that would move the conductor shown in *Fig. 22* to the right. If the current through the conductor were reversed, the flux density would increase to the right of the conductor, forcing it to move in the opposite direction. See *Fig. 23*.

Fig. 22 →





← Fig. 23

Torque is defined as the action of a force on a body that tends to cause that body to rotate. Remember, the function of a motor is to develop torque. Motor-armature windings are wound so that when a voltage is applied to the brushes, electrons will flow through the negative brush, through the commutator and armature winding and out the positive brush. Armature windings are wound so that all of the conductors under the south field pole carry current in one direction, while all of the conductors under the north field poles carry current in the opposite direction. *Fig. 24* shows a four-pole-motor armature-current distribution for a given polarity of applied voltage.

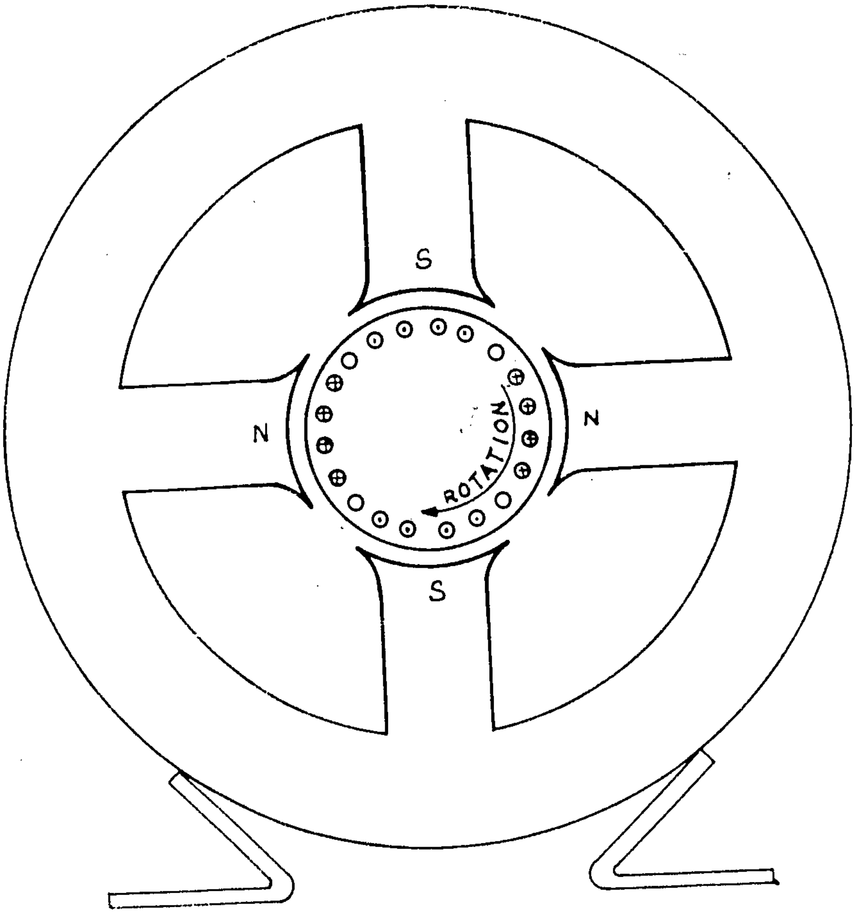


Fig. 24

When a voltage is applied to the motor, shown in *Fig. 24*, electrons flow in the field winding, establishing a magnetic field. Current also flows through the armature winding. Since each armature conductor under the pole faces is carrying current in a magnetic field, each of the conductors has a force exerted on it, tending to move it at right angles to that magnetic field.

Applying the left-hand rule will show that the fields will be strengthened so as to develop a force on all of the active conductors, tending to turn the armature in a clockwise direction. The sum of these forces in pounds multiplied by the radius of the armature in feet is equal to the total torque developed by the motor in POUND-FEET. If the load connected to the armature is not too great, the armature will begin to rotate clockwise.

As the armature rotates and the conductors move from under a pole, the current is reversed in them by the switching action of the commutator. Thus, the conductors under a given pole carry current in the same direction at all times, providing the correct magnetic polarity for developing continuous torque.

If the armature current were to be reversed by reversing the armature leads, but leaving the field polarity the same, torque would be developed in a counter-clockwise direction. However, if both the field polarity and the armature-current direction were changed, torque would be developed in a clockwise direction. THE DIRECTION OF ROTATION OF A D.C. MOTOR MAY BE REVERSED BY REVERSING EITHER THE FIELD OR THE ARMATURE CONNECTIONS. IF BOTH ARE REVERSED, THE DIRECTION OF ROTATION REMAINS UNCHANGED.

Direct current motors are classified into three types, (1) series, (2) shunt, (3) compound. Each type has its distinct characteristics; some are advantages and some are disadvantages.

QUESTIONS:

1. What does a direct-current motor do?

2. How are motors rated?

3. Name the three types of enclosures used on electric motors.

4. What is the term used to refer to the measure of the tendency of a motor shaft to rotate?

5. Describe what happens to a conductor carrying current in a magnetic field.

6. What is the term used to refer to the space around a magnet in which the magnetic forces act?

7. What is meant by the term magnetic flux?

8. Describe a magnetic circuit.

9. What is the term used to describe the opposition to the establishment of magnetic flux?

10. Name the four parts that make up the magnetic circuit of a motor.

11. Name the four parts that make up the electric circuit of a motor.

12. What happens to the magnetism associated with a current-carrying conductor when the conductor is formed into a coil or solenoid?

13. Why is the magnetic field established by a coil of wire, connected to a d.c. power source, similar to that of a bar magnet?

14. How may the magnetic polarity of a coil be found? Consider electron flow.

15. How is the strength of the magnetic field around a conductor affected by the current flowing through the conductor?

16. If the magnetic field can be strengthened without increasing current by adding turns to the coil, how would you increase the magnetic force without adding turns to the coil?

17. When this symbol ⊕ is used to indicate current flow, would you expect a counter-clockwise or a clockwise magnetic field to be present?

18. When a conductor carrying current is placed in a magnetic field, the combined fields act to exert a force on the conductor so as to move it in one direction. What would happen if the direction of current-flow was reversed in the conductor?

19. How is the rotation of a d.c. motor reversed?

20. Name the three classifications for d.c. motors.

OBJECTIVE:

To learn about Parallel Circuits.

RELATED INFORMATION:

When series circuits are connected together so that there are several paths for current to flow through the circuit, we say that they are connected in parallel. THE CIRCUIT SHOWN IN FIG. 25 IS CALLED A PARALLEL CIRCUIT. Sometimes parallel circuits are called SHUNT CONNECTED.

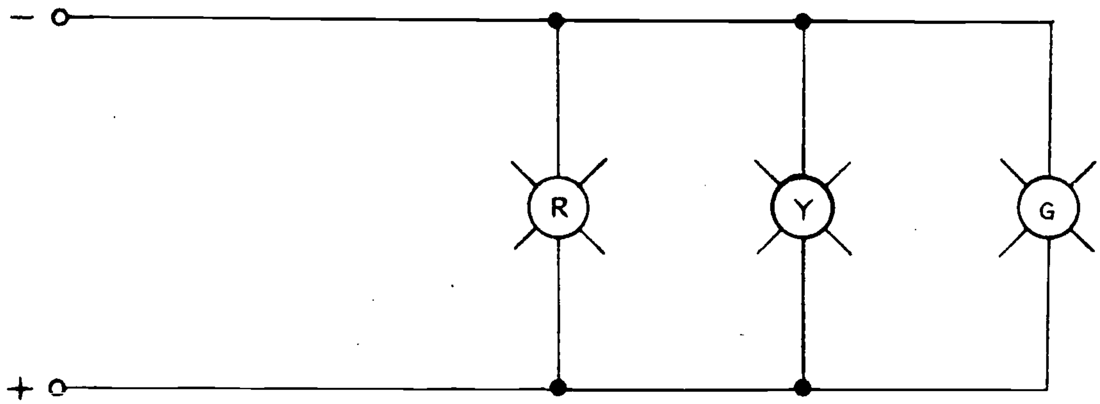


Fig. 25

If we should desire to measure the electrical currents flowing in this type cirucit, we would insert ammeters as shown in *Fig. 26.*

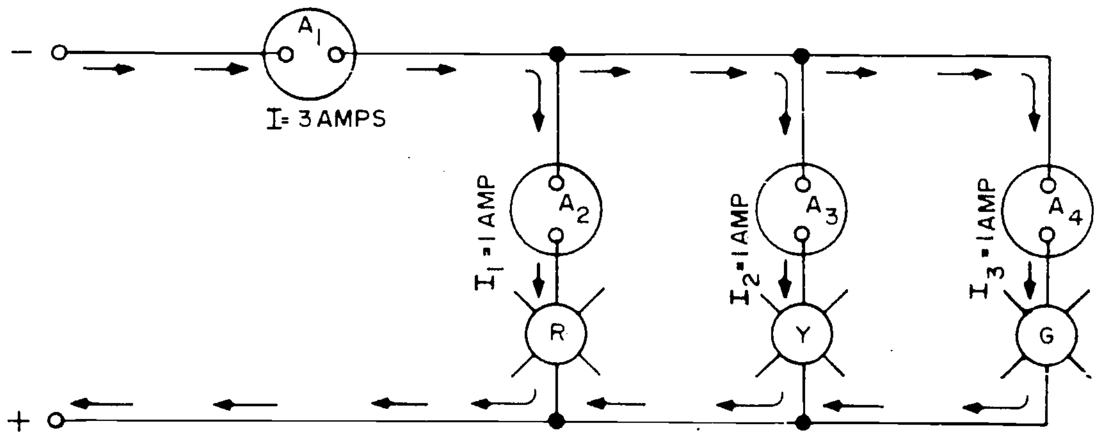


Fig. 26

In this instance Ammeter #1 would measure the total current flowing in the circuit, Ammeter #2 would measure the current through the RED light, Ammeter #3 would measure the current through the YELLOW light, and Ammeter #4 would measure the current through the GREEN light. If the lights were equal in resistance, we would be measuring the same current through Ammeters 2, 3, and 4. Assume this reading to be 1 ampere through each, then we would be reading 3 amperes through Ammeter #1. Therefore: THE TOTAL CURRENT DRAWN IN A PARALLEL CIRCUIT IS EQUAL TO THE SUM OF THE INDIVIDUAL BRANCH-CIRCUIT CURRENTS.

$$I_{total} = I_1 + I_2 + I_3$$
$$= 1 + 1 + 1$$
$$= 3 \text{ amps.}$$

The total resistance of a parallel circuit decreases with an increase in the number of devices and is always less than the smallest individual resistance in the circuit.

The total resistance of the circuit shown in *Fig. 27* may be found easily.

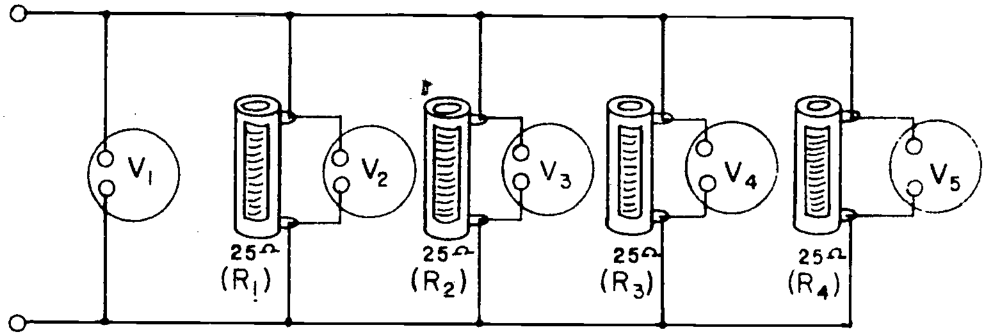


Fig. 27

The voltage distribution in a parallel circuit is such that the applied voltage will appear across each branch circuit. Instruments used to measure electrical voltages are called voltmeters. VOLTMETERS ARE ALWAYS CONNECTED IN PARALLEL WITH THE CIRCUIT TO BE TESTED.

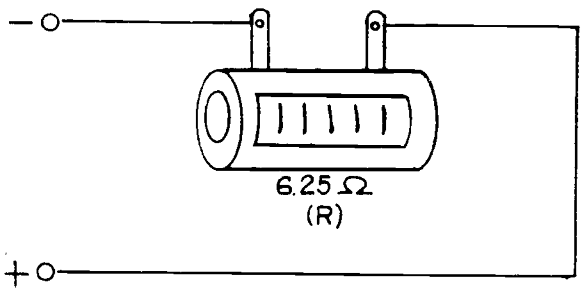


Fig. 28

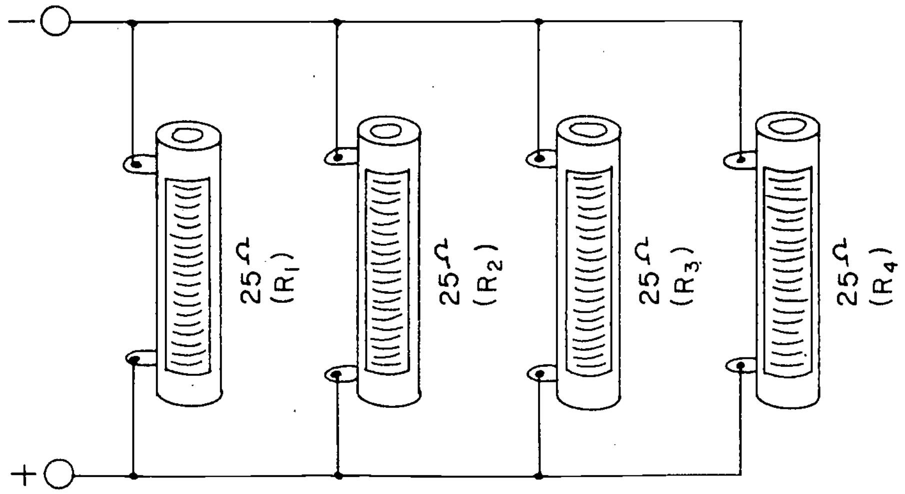


Fig. 29

Consider the circuits shown in *Figs. 28 and 29*. The circuit in *Fig. 28* you will recognize as a series circuit. The parallel circuit in *Fig. 29*, although it is made up of higher resistance values, will present the same total resistance to the power supply as the circuit in *Fig. 28*. The total resistance of a parallel circuit is found by first finding the current flowing through each branch circuit. These are then added together to find the total current flowing through the parallel circuit. The total resistance then equals the voltage applied to the circuit, divided by the total current. R total = $\frac{E\ applied}{I\ total}$.

If the voltage and current are unknown, we may assume one volt and arrive at the total resistance in another way. The resistance of a parallel circuit is the reciprocal of the sum of the reciprocals of the resistances of the individual branches.

$$R_p = \frac{E\ applied}{I\ total}$$

$$= \frac{E\ applied}{\frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}}$$

$$= \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

When the circuit shown in *Fig. 27* is energized, each voltmeter will indicate the same voltage. We have seen then that the power-supply voltage that is measured by voltmeter #1 will appear at each of the voltmeters measuring the branch circuits. IN A PARALLEL CIRCUIT THE POWER SUPPLY VOLTAGE WILL APPEAR ACROSS EACH BRANCH CIRCUIT.

QUESTIONS:

1. When is a circuit said to be parallel or shunt connected?

2. If a current of 1 ampere is flowing in each of the branch circuits, what is the total current flowing through the parallel circuit?

3. What would happen if the circuit in Fig. 1 were energized and you removed the RED bulb?

4. Referring to Fig. 26, how many ammeters would be required to measure the current flowing through the individual lights?

5. How many ammeters would be required to measure the total current flowing through all the lights?

6. How many paths are provided for current to flow in a parallel circuit?

7. If the division of the resistances in the circuit shown in Fig. 29 were 10Ω, 20Ω, 30Ω, and 40Ω, what would be the total resistance of the circuit?

8. If you were to insert a 100-Ohm resistor in parallel with this circuit, what would be the total resistance?

9. If we were to connect the circuit shown in Fig. 27 to a 440-volt power supply, what would be the voltage across each of the branch circuits?

10. What would be the current flowing through each resistor?

11. If we were to change the power supply to 110 volts, what would be the voltage across each branch circuit?

12. What would be the current flowing through each resistor?

13. What would be the total current flowing through the parallel circuit?

14. Referring to the circuit shown in Fig. 29, how would the total resistance of the parallel circuit be affected if we were to replace R_1 with a 25-Ohm light bulb?

15. How many voltmeters would be required to measure the voltage across each of the branch circuits shown in Fig. 27 simultaneously?

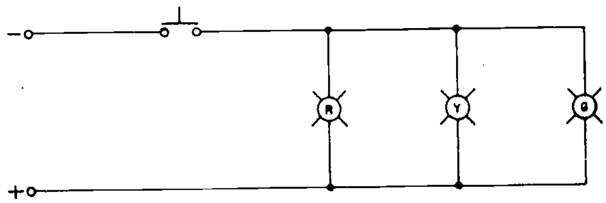
OBJECTIVE:

To learn about Series-Parallel circuits.

RELATED INFORMATION:

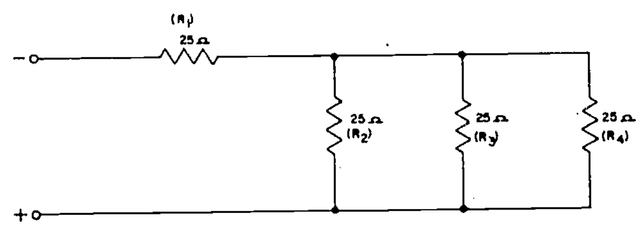
Most circuits used in industry are neither purely a series nor purely a parallel circuit, but are a combination of the two. A convenient method of working with them is to first find the resistance of each group of resistances connected in parallel and then treat the resulting values as a series circuit.

Fig. 30 →



The circuit shown in *Fig. 30* is an example of a series-parallel circuit. While the three lights are in parallel with each other, the switch is in series with all of the lights. ALL OF THE CURRENT FLOWING THROUGH THE LIGHTS MUST FLOW THROUGH THE SWITCH. A series-parallel circuit using four 25-Ohm resistors is shown in *Fig. 31*.

Fig. 31 →



To find the total resistance of this circuit we would first find the total resistance of the group of resistors connected in parallel; namely, R_2, R_3, and R_4.

$$R_p = \frac{1}{\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}$$

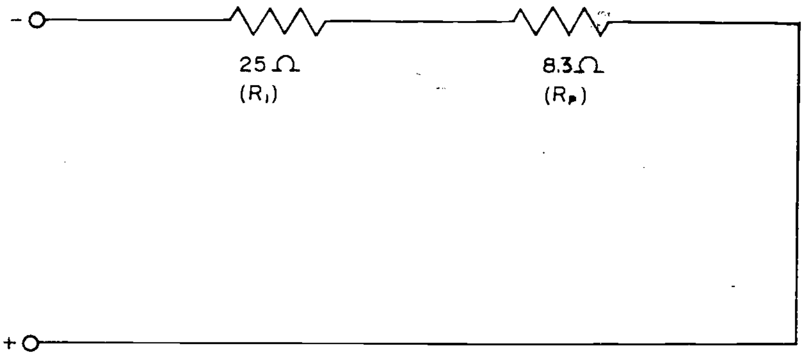
$$= \frac{1}{\frac{1}{25} + \frac{1}{25} + \frac{1}{25}}$$

$$= \frac{1}{.12}$$

$$= 8.3 \text{ Ohms}$$

Having arrived at single resistance value for the three resistors connected in parallel, we may consider them as a single resistor. This is shown in the equivalent series-connected circuit at *Fig. 32*.

Fig. 32→



Remembering that the total resistance of a series circuit is equal to the sum of all the individual parts, we would solve for the total resistance of our circuit as follows:

$$R_t = R_1 + R_p$$

$$= 25 + 8.3$$

$$= 33.3 \text{ Ohms}$$

Assuming that the applied voltage is going to be 220 volts, we may use the values shown in our equivalent series circuit (Fig. 32) to solve for total current (I_t) and voltage distribution. To solve for total current, you should remember that the current remains the same in all parts of a series circuit. Therefore using Ohm's Law,

$$I_t = \frac{E \text{ applied}}{R_1 + R_p}$$

$$= \frac{220}{33.3}$$

$$= 6.61 \text{ amp.}$$

To solve for voltage distribution you would first solve for the voltage drop across R_1.

$$E_1 = I_t R_1$$
$$= 6.61 \times 25$$
$$= 165.25 \text{ volts across } R_1 \text{ in Fig. 31.}$$

Subtracting the voltage across R_1 from the applied voltage will give you the voltage that will appear across the group of resistors that are connected in parallel.

$$E_p = E \text{ applied} - E_1$$
$$= 220 - 165.25$$
$$= 54.75 \text{ volts across } R_2, R_3, \text{ and } R_4. \text{ in Fig. 31.}$$

QUESTIONS:

1. When is a circuit said to be Series-Parallel connected?

2. What would happen to the circuit in Fig. 30 if you removed the RED bulb?

3. If a current of 1 ampere is flowing in each of paralleled resistors in the circuit in Fig. 31, how much current would be flowing through the series resistor?

4. How much current would flow through this circuit if you were to disconnect the series resistor?

5. How much current would flow through this circuit if we were to disconnect one of the parallel resistors?

6. If the division of the resistances in the circuit shown in Fig. 31 were, $R_1 = 10\Omega$, $R_2 = 20\Omega$, $R_3 = 30\Omega$, and $R_4 = 40\Omega$, what would be the total resistance of the circuit?

7. Using the values shown in problem #6, what would be the voltage drop across the series resistor?

8. Using the values shown in problem #6, what would be the current flowing through R_4?

9. If you were to insert a 100-Ohm resistor in series with the circuit in Fig. 31, what would be the total resistance?

10. If you were to insert a 100-Ohm resistor in parallel with the circuit at Fig. 31, what would be the total resistance?

OBJECTIVE:

To learn how to draw and understand a simple reversing controller.

RELATED INFORMATION:

Not every controller has the responsibility of starting the main driving motor of a machine. Some controllers are required to control auxilliary devices such as the reciprocating device indicated on the wiring diagram shown in *Fig. 33*.

A reciprocating device is one that moves back and forth from one point to another in the performance of its job. The control circuit shown on the elementary diagram of *Fig. 33* shows a simple control circuit that will reverse the motor shown at a predetermined time so that it may properly operate the device.

Reading the elementary we see that the circuit shown is essentially a series-parallel circuit. The ON-OFF switch is connected in series with the parallel circuit made up of the motor armature, limit switch and shunt field winding. Since all of the current must flow through the on-off switch, opening the switch contacts will de-energize the parallel-connected motor circuit and closing them will energize it.

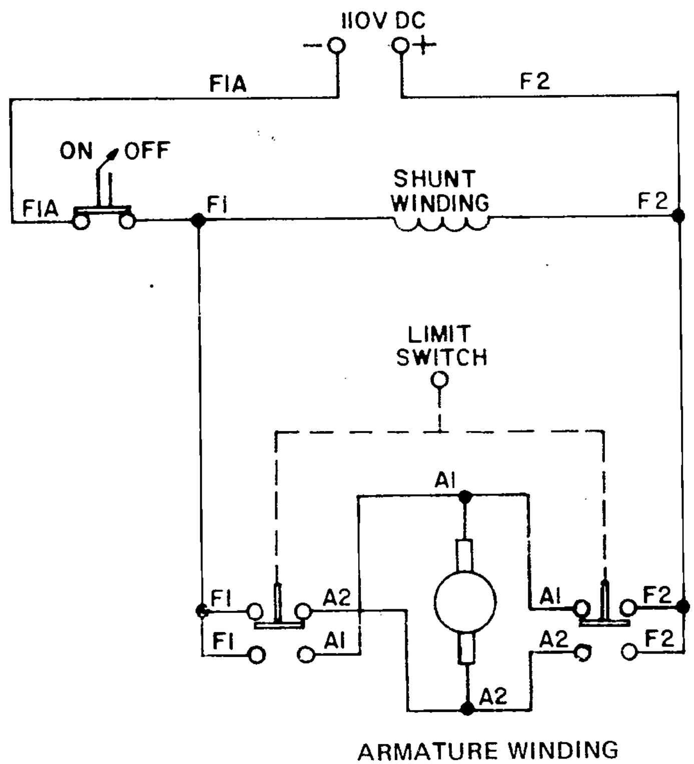
The limit switch is connected so that when its contacts change their position, the polarity of the armature will be reversed. THE DIRECTION OF ROTATION OF A D.C. MOTOR MAY BE REVERSED BY REVERSING EITHER THE FIELD OR ARMATURE CONNECTIONS. In motor-reversing controls, the connections to the armature are usually switched because it is important not to interrupt the magnetic field developed by the field winding.

When control circuits are drawn, the power source is usually shown as two vertical lines rather than the horizontal lines used to indicate the conductors carrying the heavier currents. This has been modified somewhat on *Fig. 33* so that the supply voltage could be indicated clearly. Note that the elementary identifies each wire every time that it appears as a horizontal line.

The d.c. motor used on this device is called a SHUNT-WOUND motor. That means that the field winding is designed to be connected in parallel with the armature. THE MAGNETISM ASSOCIATED WITH A CURRENT-CARRYING CONDUCTOR CAN BE STRENGTHENED BY FORMING THE CONDUCTOR INTO A COIL OR SOLENOID. It follows then that an increase in flux density – magnetic lines of force – could be achieved by either increasing the current or adding more turns to the coil.

Since the field winding of the series motor discussed previously had to carry the heavy armature current, the necessary flux density was achieved with a few turns on the field winding. The shunt motor field, being connected in parallel with the armature, has its own branch current. Therefore, the higher resistance shunt windings are designed to provide the necessary flux density with less current by being designed with more turns of smaller diameter wire. With the field flux density remaining fairly constant with different values of armature current, the shunt-wound motor maintains a fairly constant speed at different loads. A SHUNT MOTOR MAINTAINS A NEARLY CONSTANT SPEED WITH DIFFERENT LOADS. The additional torque required to care for an increased load is obtained by an increase in the armature current alone.

WIRING DIAGRAM
RECIPROCATING DEVICE
$\frac{1}{3}$ HP SHUNT-WOUND DC MOTOR



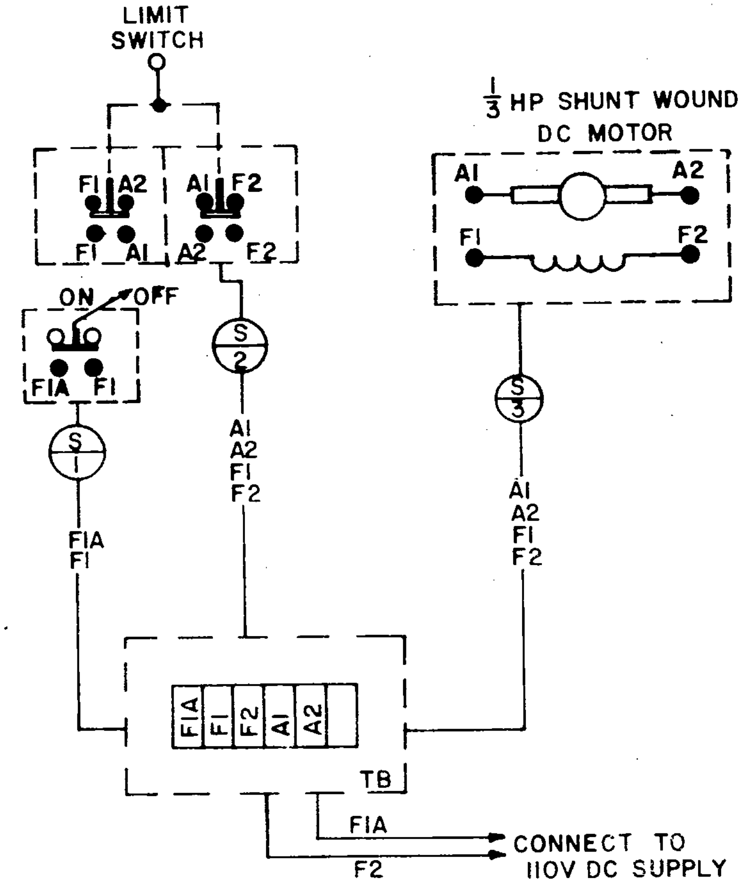


Fig. 33

The shunt motor is the most common type of d.c. motor. They have good starting and operating torque and are used where the loads do not vary greatly or where constant speed is important. CARE MUST BE TAKEN NOT TO DISCONNECT THE FIELD CIRCUIT OF A SHUNT MOTOR THAT IS RUNNING WITHOUT A MECHANICAL LOAD. The loss of field flux would cause the motor speed to increase to dangerously high values.

The connection diagram shown in *Fig. 33* indicates that the limit switch is mounted to the left of the shunt motor, with the ON-OFF switch and a terminal box being mounted below them. Note the broken lines used to indicate the enclosures in each case. The ON-OFF switch indicates that the actual switch has a set of contacts that are not used. No wire numbers are indicated and the terminals are not filled in. WHERE ELEMENTARY DIAGRAMS ONLY SHOW THE PORTIONS OF THE ELECTRICAL DEVICES THAT ARE USED, THE CONNECTION DIAGRAM MUST SHOW ALL PORTIONS THAT ARE ACTUALLY THERE. The reason for this is that they must be recorded so that they may be considered for possible future circuit modifications. Since all of the terminals in the limit switch and the shunt-wound motor are used, all of the wires have been indicated and the terminals have been filled in.

The limit switch has two sections that are GANGED, both actuated by the same operating lever. THE SECTIONS WORK TOGETHER.

There are three runs of conduit to be made by our shop that are connected to a terminal box. A terminal box is a metal enclosure with terminal blocks inside. A TERMINAL IS A DEVICE FOR CONNECTING WIRES. A terminal block is an arrangement whereby one or more terminals are mounted so that they are insulated and protected from the mounting surface – the box – and each other. This arrangement provides a convenient place to make the various interconnections between the electrical device and finally the power supply. Note that terminal blocks are designated T.B. Did you notice that there are six terminals provided? The empty one is left as a spare.

QUESTIONS:

1. Why is the controller described in Fig. 33 considered to be an auxilliary controller?
2. Describe a series-parallel circuit.
3. What does the limit switch shown in Fig. 33 do?
4. Why is it important not to interrupt the magnetic field developed by the field winding?
5. How do you identify the power source on control circuits?
6. When do you identify a wire on an elementary diagram?
7. Why is the d.c. motor shown in Fig. 33 called a shunt-wound motor?
8. When is a magnetic field developed around a conductor?
9. Two methods are discussed for increasing flux; what are they?
10. Is the field winding of a shunt motor designed to carry more or less current than a series motor?
11. How can the higher resistance shunt-field provide the necessary flux density?
12. What happens to the field flux density, in a shunt motor, with a change in armature current?
13. What happens to the shunt motor speed with different loads?
14. How does a shunt motor supply additional torque to take care of an increased load?
15. When should shunt-wound d.c. motors be used?
16. What would happen if the field winding were to be disconnected while the motor was running?
17. On the connection diagram shown in Fig. 33, the symbols for the electrical devices are surrounded by broken lines; what do these broken lines mean?
18. Why is the extra set of contacts shown on the "ON-OFF" switch?

19. What part of a wiring diagram will show all of the equipment actually used?

20. How does an elementary differ in this respect?

21. Explain how you may identify terminals, shown on connection diagrams, that have been used.

22. The limit switch is shown with the moveable switch contacts connected together with a broken line; what does this mean?

23. How many runs of conduit are to be made by the shop?

24. What is a terminal box?

25. Why was a terminal box used on this control system?

OBJECTIVE:

To learn how the speed of electric motors is influenced by generator action.

RELATED INFORMATION:

A machine that converts either mechanical energy to electric energy or electric energy to mechanical energy is called a DYNAMO. The dynamo is a reversible machine. When it is supplied with electric energy and its output is to drive mechanical devices, it is called a MOTOR. If the energy supplied to a dynamo is mechanical and it is to deliver electrical energy, it is called a GENERATOR. A GENERATOR WILL OPERATE AS A MOTOR AND A MOTOR MAY PERFORM AS A GENERATOR. Any physical differences in the two have been developed so that they perform more efficiently in their respective jobs.

It can be shown experimentally that an e.m.f. can be produced in a conductor by moving the conductor through a magnetic field. If the ends of a conductor are connected to a low-reading voltmeter and the conductor is moved into the field of a magnet, as shown in *Fig. 34*, a momentary reading will be seen on the meter. As the conductor is moved out of the magnetic field, the meter will deflect momentarily in the opposite direction. The same results will be obtained if the conductor is held stationary and the magnet moved.

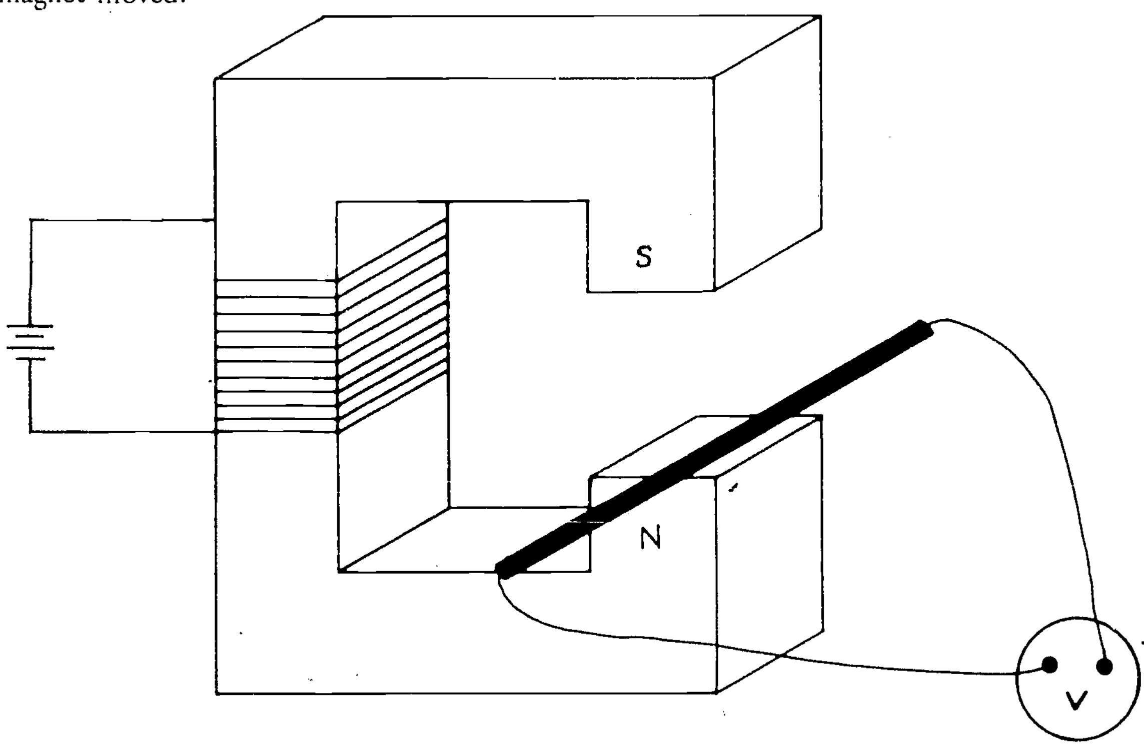


Fig. 34

The voltage that is indicated by the meter reading when the conductor cuts the magnetic flux is known as an INDUCED E.M.F. The current flowing in the conductor due to the induced e.m.f. is induced in a conductor by cutting magnetic lines of force; the phenomenon is called ELECTROMAGNETIC INDUCTION. This principle has led to the development of such electric devices as the electric generator, the telephone, and numerous others.

When the single conductor is wound into several turns as shown in *Fig. 35*, it will be found that a greater meter reading will occur as the coil cuts the magnetic field. Each turn of the coil has an e.m.f. induced in it. The circuit now appears as single-turn coils connected in series. THE TOTAL E.M.F. INDUCED IS THE SUM OF THE E.M.F.'S OF EACH OF THE SERIES-CONNECTED TURNS. The amount of the e.m.f. increases directly with the number of turns on the coil.

Other factors that can affect the induction of an e.m.f. are the speed at which the coil is moved through the field, the strength of the magnetic field (greater flux density), the angle at which the lines are cut, and the length of the section of the conductor that is cutting the magnetic field. All of these factors are concerned with the rate at which the magnetic flux is being cut by a conductor or the rate at which the number of magnetic lines of force that move through a conductor is changing. The E.M.F. INDUCED (OR GENERATED) IN A CONDUCTOR BY ELECTROMAGNETIC ACTION IS PROPORTIONAL TO THE RATE AT WHICH THE CONDUCTOR CUTS MAGNETIC LINES OF FORCE.

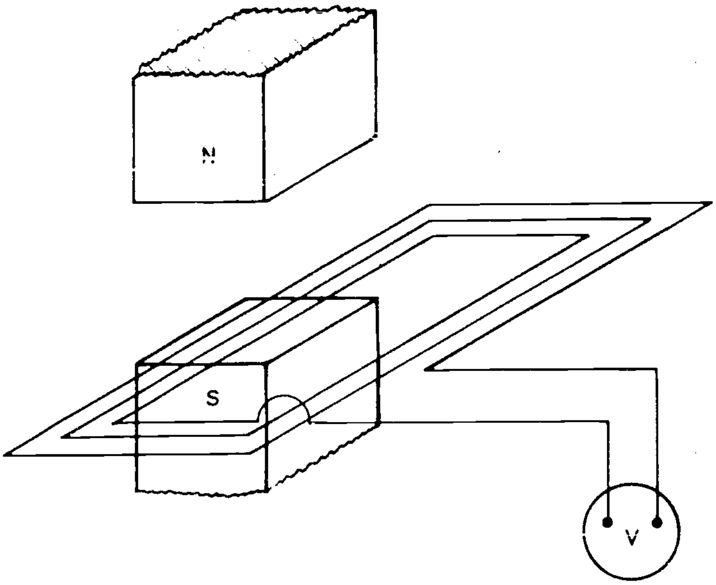


Fig. 35

Inducing an e.m.f. in a conductor by moving the conductor through a magnetic field is used in the d.c. generator. Stationary electromagnets develop a magnetic field through which the conductors of the armature winding are moved, causing an e.m.f. to be induced in them. A GENERATOR IS A MACHINE THAT CONVERTS MECHANICAL ENERGY TO ELECTRIC ENERGY.

As the armature of a generator is rotated by a prime mover, a torque is developed in the generator opposing the action of the prime mover. This countertorque may be considered to be a motor action in the generator. Likewise, a generator action is developed in every motor.

As the armature of a motor rotates, cutting lines of force in the field, a voltage is developed in the armature coils. The current produced by this e.m.f. tends to oppose the flow of current fed to the armature from an outside source. This opposing voltage is called BACK E.M.F. (sometimes counter e.m.f.). Back e.m.f. is directly proportional to the armature speed and the field strength. Remember, the E.M.F. INDUCED IN A CONDUCTOR BY ELECTROMAGNETIC ACTION IS PROPORTIONAL TO THE RATE AT WHICH THE CONDUCTOR CUTS MAGNETIC LINES OF FORCE.

The effective voltage acting in the armature circuit of a motor is the applied or terminal voltage minus the back e.m.f. The armature current by Ohm's Law is:

$$I_a = \frac{E_t - E_g}{R_a}$$

Where I_a = armature current
E_t = motor terminal voltage
E_g = generated back e.m.f.
R_a = armature-circuit resistance

Multiplying both sides of the equation by R_a and transposing gives us:

$$E_t = E_g + I_a R_a$$

This is the fundamental motor equation. Since the back e.m.f. is always less than the applied voltage, there will always be current flow into the motor.

No back e.m.f. exists when the motor is at rest, but it rapidly builds up as the motor gains speed. Once the motor reaches its operating speed, the actual armature current is quite small, since it is the difference between the current fed into the armature and the opposing current due to the back e.m.f. BACK E.M.F. INCREASES WITH AN INCREASE IN FIELD STRENGTH. This decreases the speed of rotation because as the actual armature current is reduced the torque also decreases.

A REDUCTION IN FIELD FLUX OF A MOTOR CAUSES THE MOTOR SPEED TO INCREASE. The reduction of field strength reduces the back e.m.f. of the motor, since fewer lines of force are cut by the armature coil. A reduction in the back e.m.f. permits more armature current to flow. THE INCREASE IN ARMATURE CURRENT DEVELOPS A LARGER TORQUE, AS THE INCREASE IN THE ARMATURE FLUX DENSITY MORE THAN COMPENSATES FOR THE DECREASE IN FIELD FLUX. The increased torque causes the motor speed to increase, thereby increasing the back e.m.f. in proportion. THE SPEED AND THE BACK E.M.F. INCREASE UNTIL THE ARMATURE CURRENT AND TORQUE ARE REDUCED TO VALUES JUST LARGE ENOUGH TO SUPPLY THE LOAD AT A NEW CONSTANT SPEED. This explains why the speed of a series motor varies from a very high speed with a light load to a low speed at full load.

A series motor does not have a definite no-load speed. As the load is decreased, the field flux decreases. THE ARMATURE CURRENT DECREASES AS THE LOAD DECREASES, AND THE FIELD IS CONNECTED IN SERIES WITH THE ARMATURE. If all the load is removed, the field flux drops to practically zero and the motor speed may become dangerously high.

A shunt motor has good speed regulation and is considered to be a constant-speed motor, even though the speed does decrease slightly with an increase in load.

As the load is increased, the motor immediately begins to slow down. The back e.m.f. decreases with the decrease in speed. Remember that in the parallel-connected shunt field, the field flux remains practically constant. THE DECREASE IN THE BACK E.M.F. PERMITS THE FLOW OF AN INCREASED ARMATURE CURRENT. THUS PROVIDING MORE TORQUE FOR THE INCREASED LOAD. The increased armature current causes a larger $I_a R_a$ drop, which means that the counter e.m.f. does not return to its former value but remains at some lower value. As can be seen by the fundamental motor equation:

$$E_t = E_g + I_a R_a$$

Since E_t is constant, the sum of the generated back e.m.f. and the $I_a R_a$ drop must remain constant. If $I_a R_a$ becomes larger, due to an increase in load, E_g must decrease, thus causing a decrease in speed.

The BASIC SPEED of a shunt motor is the full-load speed with full-field excitation. Speed adjustment of these motors may be obtained by inserting a variable resistor in series with the field winding, thereby weakening the field flux. This provides a smooth and efficient method of varying the motor speed from the basic speed to a maximum speed that is set by the motor manufacturer. ALL MOTOR MANUFACTURERS SPECIFY THE BASIC SPEED AND MAXIMUM OPERATING SPEEDS FOR THE MOTORS THEY PRODUCE. Since the reduction of the back e.m.f. causes a motor speed to increase, the loss of the field flux would cause the motor speed to increase to dangerously high values. NEVER DISCONNECT THE FIELD CIRCUIT OF A SHUNT MOTOR THAT IS RUNNING WITHOUT A LOAD.

The speed of a shunt motor may also be changed by inserting a variable resistor in series with the armature winding. This results in a reduced speed due to the reduction in armature current. but this method is less efficient than the shunt-field control and results in very poor speed regulation.

QUESTIONS:

1. Explain why a motor will perform as a generator.
2. What happens when a conductor moves through a magnetic field?
3. Explain the term ELECTROMAGNETIC INDUCTION.
4. What will happen to the INDUCED E.M.F. as turns are added to the coil being moved through the magnetic field?
5. How does increasing the flux density affect the induced e.m.f.?
6. How does increasing the speed at which the coil is moved through magnetic field affect the induced e.m.f.?
7. What is a generator?
8. What is meant by the generator action of a motor?
9. Describe back e.m.f. in a motor.
10. How does the effective armature current change as a motor accelerates?
11. Does an energized electric motor develop a greater torque if the shaft is held stationary or when it is allowed to turn?
12. Why is the speed of a series motor very high with a light load and low with a heavy load?
13. What happens if all load is removed from a series motor that is running?
14. Explain why the field flux decreases in a series motor as the load decreases.
15. Why does the speed of a shunt-wound motor remain practically constant with constant field excitation?
16. Why does the armature current of a shunt motor increase with an increased load?
17. What is meant by the term BASIC SPEED of a shunt motor?
18. How is the speed of a shunt motor normally changed to reach its rated maximum speed?
19. What would happen if the field circuit of a shunt motor were to be interrupted?
20. If the speed of a shunt motor may be changed by reducing the armature current, why isn't this method used more often?

LESSON 12 MANUALLY OPERATED RESISTANCE CONTROLLER FOR A COMPOUND MOTOR

OBJECTIVE:

To learn how to draw and understand a controller with resistance starting and speed control.

RELATED INFORMATION:

COMPOUND MOTORS COMBINE THE ADVANTAGES OF BOTH THE SERIES AND SHUNT MOTORS. The series motor has the ability to provide greater torque without excessive current; in turn the shunt motor offers a more constant speed.

These two desirable features are obtained in the same motor by winding both series and shunt coils on the same field-poles, which provides us with the COMPOUND MOTOR. Usually the shunt and series fields are connected so that the magnetic fields work together so as to increase the total field strength, both windings having current flowing in the same direction. This method of connection forms a CUMULATIVE-COMPOUND MOTOR.

The effect of including the series field is that at heavy loads, when the motor slows down, the increased current through the series winding increases the field strength, providing increased torque. To overcome the over-speeding that would occur, due to the decreased field strength, a shunt field is added to provide a limit on the top speed of the motor. Since the shunt-field current is independent of the armature current, it provides enough flux to control the speed, just as it does in a shunt motor.

Infrequently, a compound motor may be connected with its series field opposing the shunt field, providing a DIFFERENTIAL-COMPOUND MOTOR. With this type of connection the series field BUCKS or tends to weaken the total magnetic field. Excellent speed regulation can be obtained with this type of connection, for as the motor tends to slow down under load, increased armature current will flow, weakening the field strength (REMEMBER, THE SERIES FIELD OPPOSES THE SHUNT FIELD, THEREBY WEAKENING THE TOTAL FIELD STRENGTH), which reduces the back e.m.f., which allows a further increase in armature current, which produces an increase in torque. The result is that the motor accepts the increased load and runs at nearly a constant speed. When the load decreases, the armature tends to rotate faster, increasing the back e.m.f. The increased back e.m.f. decreases the current flowing through the series field, reducing its opposition to the shunt field, resulting in a stronger total field strength. The net result is a decrease in motor speed, again maintaining its constant-speed characteristic.

The differential-compound motor has a nearly constant speed at all loads but has poor torque characteristics at heavy loads. Since shunt motors have a sufficiently constant speed for most applications and much better torque characteristics at heavy loads, use of this motor is limited to applications that require a more constant speed than can be obtained by a shunt motor.

When the shunt field of compound motors is connected across both the armature and series field, the connection is called LONG SHUNT. When the shunt field is connected directly across the armature the connection is called SHORT SHUNT. Usually compound motors are connected long shunt.

Fig. 36 shows schematic diagrams for both long and short-shunt compound motors.

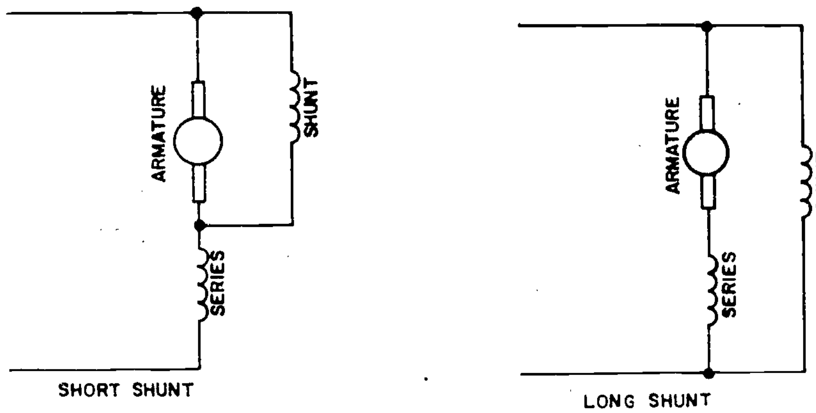
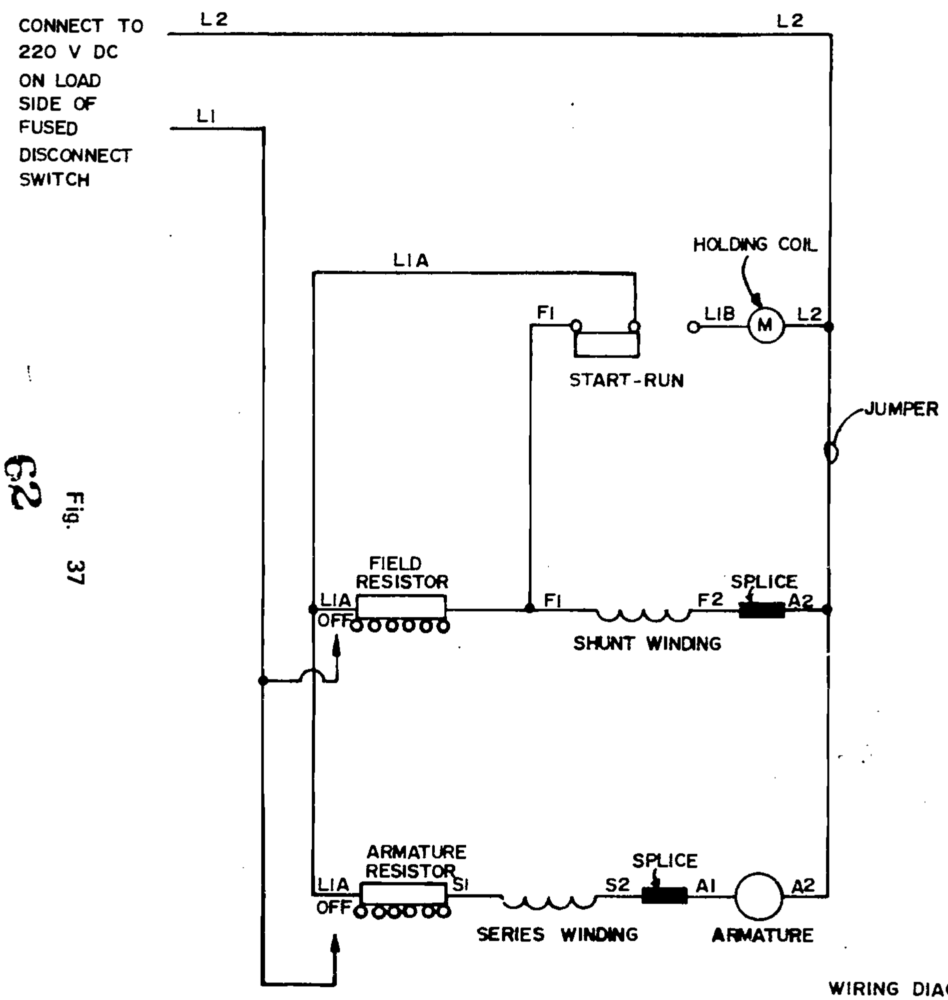
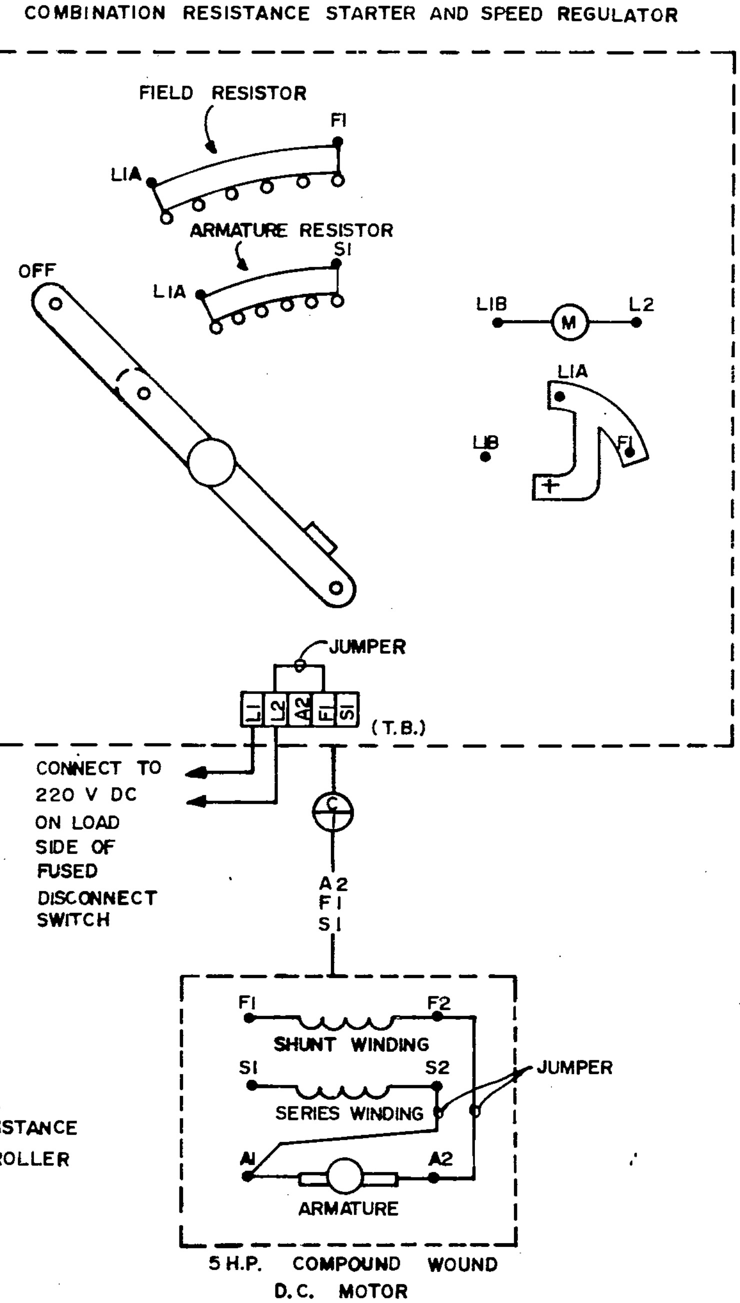


Fig. 36

The four types of compound motors are long-shunt cumulative, long-shunt differential, short-shunt cumulative and short-shunt differential. Compound motors can be designed with characteristics closely approaching those of either series or shunt motors, depending on the design of the series and shunt coils. Usually they are connected as long-shunt cumulative compound motors, which will develop a high torque with a sudden increase in load. Also, this motor has the advantage of having a fixed no-load speed to prevent it from racing to excessively high speed if the load is removed.

The controller shown in *Fig. 37* has been arranged to accommodate a 5 H.P. CUMULATIVE, LONG-SHUNT-CONNECTED COMPOUND-WOUND MOTOR. By definition a controller is a device to which it is connected. D.C. motor controllers perform such functions as starting, stopping, controlling speed, and reversing where necessary.





WIRING DIAGRAM FOR A
MANUALLY OPERATED RESISTANCE
STARTER AND SPEED CONTROLLER

Fig. 37

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A starter is a controller whose main function is to start and accelerate a motor. Since the actual ohmic resistance of armatures is small and time is required for the build-up of the back e.m.f., a heavy current will flow in the armature coil when the motor is first started from rest. During this period there is a chance that the armature winding could overheat and burn out. Thus, two requirements should be met when starting d.c. motors, especially large d.c. motors started under a load.

1. BOTH MOTOR AND SUPPLY MUST BE PROTECTED FROM THE FLOW OF EXCESSIVE CURRENT DURING THE PERIOD WHEN THE MOTOR IS COMING UP TO OPERATING SPEED.

2. THE MOTOR STARTING TORQUE SHOULD BE MADE AS LARGE AS POSSIBLE, TO BRING THE MOTOR UP TO FULL SPEED IN THE SHORTEST TIME POSSIBLE.

Small d.c. motors of ½ h.p. or less use very little current and can therefore be started by placing full voltage across the motor terminals. Larger d.c. motors may be started safely by using a controller, as shown in *Fig. 37*. This controller limits the starting current to a safe value and in addition provides for increasing the motor speed from the basic to the maximum if desired. Since the controller is one that essentially limits current flow through the armature circuit and shunt field circuit, it could be used to control a shunt motor as well as a compound motor.

The starter consists essentially of two tapped resistors, one for connection in the armature circuit and one for connection in the shunt winding circuit. The resistor in the armature circuit limits the starting current, while the resistor in the shunt winding circuit regulates the motor speed only after the motor has reached the basic operating speed. The resistors are tapped at various points, and the connections are brought out to contacts on the face plate, as shown in the connection diagram on *Fig. 37*.

This type of starter has a special handle -- actually two arms on the same axle, one under the other. The starting handle is normally held in the OFF position by a strong spring. When the handle is moved up. both arms are interlocked so that they move together. As the handle is moved clockwise from point to point, the resistance of the armature circuit is decreased. After the handle is brought to the last acceleration point, a coil located on the face plate acts as an electromagnet and holds the arm, shorting out the armature resistor on the last accelerating point. If an increase in speed over normal (BASIC SPEED) is desired. the handle is moved in a counter-clockwise direction. This moves only the arm contacting the field resistor and cuts in the resistance connected in the field circuit.

When the arm is in the OFF position, the shunt-field winding resistor is shorted out by an auxiliary switch contact that is located on the face plate. This contact is movable, so that when the handle is rotated to the last acceleration step, the auxiliary contact opens the short across the field resistor. At the same time the holding coil is energized. The reason for shorting the field resistor is so that the motor is accelerated with full-field excitation so as to quickly build up the back e.m.f. The object in having the handle on the last accelerating step before operating this auxiliary contact is to prevent its use before the armature resistor has been taken out of the circuit.

To operate the controller, the handle is moved to the first contact position. This completes a circuit from the supply L1, through the handle through the entire armature resistor, through the armature circuit, and back to the power supply L2. Also a circuit is completed from the first accelerating contact through the auxiliary contact to the field terminal, through the shunt winding, back to the power supply. After the motor accelerates and the handle has been advanced to the last step, the auxiliary contact opens the short-circuit across the field resistor and energizes the holding coil that will keep the handle in position.

Should the line voltage fail for any reason, current will stop flowing in the coil and spring action will return both levers to the OFF position. Because the holding coil is connected directly across the line and cannot hold the handle in place should the supply voltage drop below a certain value or fail completely, this feature is called UNDERVOLTAGE PROTECTION. Without this protection, the supply voltage might be restored with the starting arm in the RUN position (no resistor in the armature circuit), thereby applying full line voltage to the motor armature, resulting in possible damage to the motor, machine and operating personnel.

If it is desired to increase the motor speed beyond basic operating speed, the main arm may be moved in a counter-clockwise direction, while the arm that is shorting out the armature resistor is held in place by the holding coil. As the main arm is stepped along in a counter-clockwise direction, resistance is being added to the shunt winding circuit, causing an increase in speed up to the maximum allowed by the motor manufacturer.

When the motor is to be de-energized, the main disconnect switch is opened. This removes the supply voltage and the spring action returns both operating arms to the OFF position. Of course the main disconnect switch will have to be reclosed for this controller to be able to restart the motor.

QUESTIONS:

1. Why are compound motors wound with both series and shunt fields?

2. What is meant by the term CUMULATIVE-COMPOUND MOTOR?

3. Describe what happens to the total field strength when the current through the series winding is increased.

4. What is meant by the term DIFFERENTIAL-COMPOUND MOTOR?

5. How does a differential-compound motor maintain a more constant speed than a shunt motor?

6. What is meant by a long-shunt connection?

7. Name the four types of compound motors.

8. What is the difference between a controller and a starter?

9. Name the two requirements that should be met when starting large d.c. motors.

10. How does the controller in Fig. 37 limit the armature current when the motor is started from rest?

11. Explain how this controller provides a speed increase above normal after the motor has reached operating speed.

12. What would happen if the person operating the controller should release the handle, say on the second accelerating step?

13. How is the arm that is shorting out the armature resistor kept on the last accelerating step while the motor is running?

14. Describe what is meant by the term UNDERVOLTAGE PROTECTION.

15. Why is it desirable for this type of control to be provided with undervoltage protection?

16. How does this control prevent the motor from being started with the resistor in the field circuit?

17. Why is it necessary to open the main disconnect switch, on this type of control, in order to de-energize the motor?

18. Who makes the connection between the controller and the motor?

19. What is the value of the applied voltage?

20. If there are six terminals in a compound motor (A1, A2, F1, F2, S1 and S2), why are there only three wires in the run of conduit connecting the motor with the controller?

ASSIGNMENT:

Make a drawing for the controller shown in Fig. 37.

OBJECTIVE:

To learn about current flow in Direct and Alternating systems.

RELATED INFORMATION:

When you provide a path for the transfer of electrical energy between the terminals of a power supply, this path is called a CIRCUIT. The simplest form of electric circuit would be a resistance connected across these terminals. See *Fig. 38*.

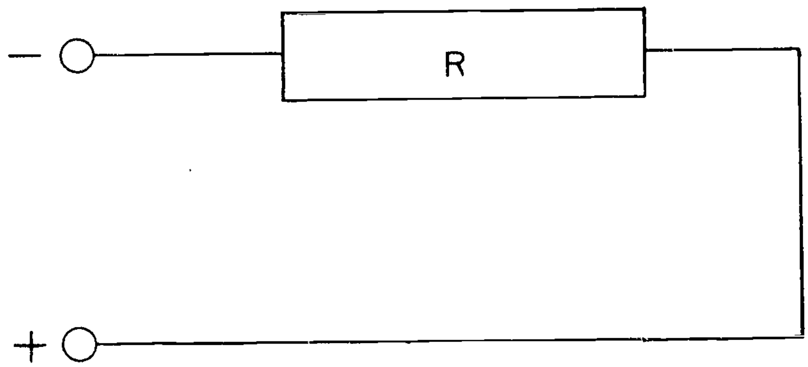


Fig. 38

The values of current, voltage and resistance are dependent upon each other. This relationship is described by OHM'S LAW, which is stated as follows: THE CURRENT FLOWING IN A CIRCUIT IS DIRECTLY PROPORTIONAL TO THE APPLIED VOLTAGE (E.M.F.) AND INVERSELY PORPORTIONAL TO THE RESISTANCE.

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

I = current in amperes
E = applied voltage
R = resistance in Ohms

If you were to apply 100 volts d.c. across the terminals of the circuit shown in *Fig. 38*, you may use the following equation to find the current with a circuit resistance of 20 Ohms.

$$I = \frac{E}{R} = \frac{100}{20} = 5 \text{ amp.}$$

Also, this equation may be transposed to find any of the three when the other two are known.

$$E = IR$$
$$= 5 \times 20$$
$$= 100 \text{ volts}$$

or

$$R = \frac{E}{I}$$
$$= \frac{100}{5}$$
$$= 20 \text{ Ohms}$$

Direct Current (D.C.) systems are those in which the power source is so arranged that the applied voltage will force current to flow through the circuit in only one direction. One terminal will remain negative (−), pushing electrons into the circuit, and the other terminal will remain positive (+), pulling electrons out of the circuit. The minus and plus signs are used to indicate the polarity of the supply, as shown in *Fig. 39.*

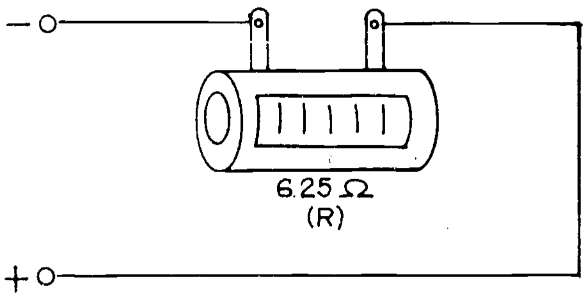


Fig. 39

The current flowing through this type of circuit will obey Ohm's Law.

Alternating Current (A.C.) systems are those in which the power source is so arranged so that the voltage will build up from zero to a maximum value with one polarity across its terminals, then build up from zero with the opposite polarity across its terminals. With this kind of applied voltage the current is forced through the circuit first in one direction and then in the other. Two such reversals are called a CYCLE; in one cycle the force acts in one direction then in the other, and then returns to the first direction to start the next cycle. The number of cycles completed in one second is called the FREQUENCY of the alternating current. Because of the changing polarity of A.C., supply circuits are marked with a sine-wave, as shown in *Fig. 40.*

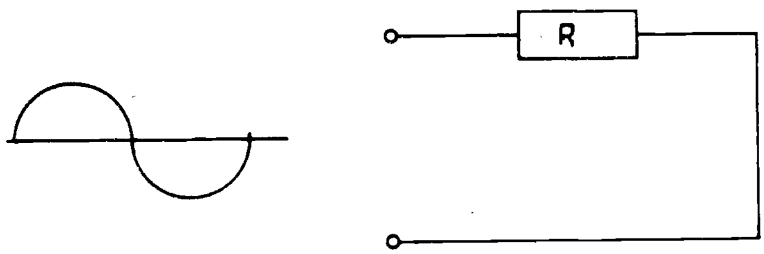


Fig. 40

The difference between Direct Current and Alternating Current can be seen in the graphs shown in *Figs. 41 and 42.* In these graphs the horizontal axis measures time, increasing toward the right (away from the vertical axis). The vertical axis represents amount of current flowing, increasing in either the up or down direction (away from the horizontal axis). If the graph is above the horizontal axis, the current is flowing in one direction (indicated by a +) and if it is below the horizontal axis, current is flowing in the other (indicated by a − sign).

The graph shown in *Fig. 41* indicates direct current. If the circuit is connected to the supply at the time marked (x), the current instantly rises to its maximum value as indicated by height (A).

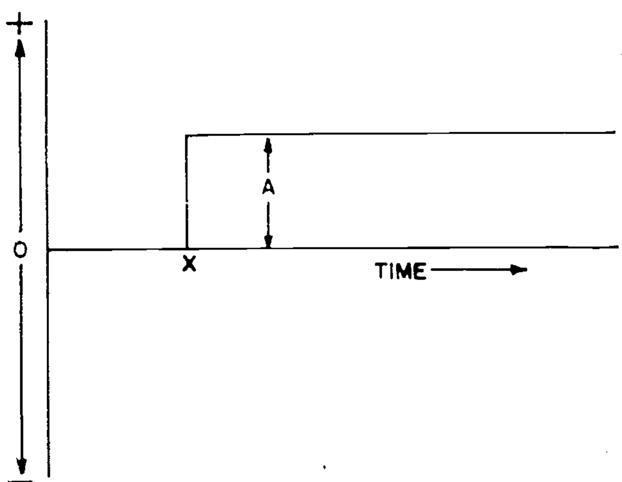


Fig. 41

The graph shown in *Fig. 42* indicates alternating current. If the circuit were connected at the beginning of a cycle, the current would be zero, increasing in strength until it reaches its maximum value (A_1) while flowing in the direction marked (+), then decreasing until it reaches zero again at point (X). At that time the flow of current reverses, indicated by the next part of the graph being below the horizontal axis. The current increases in strength until it reaches its maximum value (A_2) in the opposite direction marked (−), then decreases until it reaches zero for a third time at point (Y) and the current begins a new cycle.

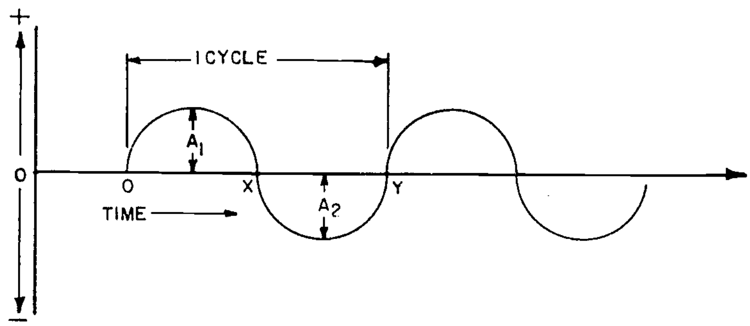


Fig. 42

A.C. circuits are read the same way as D.C. circuits when tracing current paths. The voltage and current in purely resistive circuits will rise and fall together. so they will obey Ohm's Law if the EFFECTIVE VALUES of voltage and current are used. The effective value or R.M.S. (Root mean square) may be found by multiplying the maximum values by 0.707. If the R.M.S. value is known, the maximum value may be found by multiplying the ROOT MEAN SQUARE by 1.414.

Alternating current supplies are rated as to the R.M.S. value and frequency. An example of this is the 110 volt, 60 cycle supply in your home. The maximum value for these supplies is found by:

$$E_{max} = E_{rms} \cdot 1.414$$
$$= 110 \times 1.414$$
$$= 155.5 \text{ volts}$$

Power companies supplying alternating current take great care to control the frequency of their power supplies and usually hold voltages to within plus or minus ten percent of the rated value.

QUESTIONS:

1. What do you call the path that will allow a transfer of energy between the terminals of a power supply?
2. What law describes the relationship between current, voltage and resistance?
3. Describe a D.C. system.
4. Why are the terminals of a D.C. system marked with a plus and minus sign?
5. If you were to connect a 100-Ohm resistor across a 100-V.D.C. supply, how much current would be flowing?
6. How much current would flow in problem #5 if you doubled the D.C. voltage?
7. How much current would flow in problem #5 if you doubled the resistance?
8. How would you reverse the direction of current flow through a D.C. circuit?
9. Describe an A.C. system.
10. How many times during a cycle will the voltage and current reach zero in an A.C. system?
11. What term is used to express the number of cycles per second made in an A.C. system?
12. Why aren't the terminals of an A.C. supply marked with a plus and minus sign?
13. If you were to connect a resistance of 100 Ohms across a 220-V.A.C. supply, what would be the R.M.S. value of the current?
14. What would be the R.M.S. value of the current in problem #13 if the supply was rated at 440 V.A.C.?
15. What would be the R.M.S. value of the current in problem #13 if you doubled the resistance?

OBJECTIVE:

To learn the effect of inductance on current in Direct and Alternating Current systems.

RELATED INFORMATION:

When an electric current begins to flow through a conductor, magnetic lines of force build around it. If you were to pass a conductor through a sheet of cardboard with fine iron filings spread on it and connect it to a battery, such as shown in *Fig. 43,* you would see that the iron filings will arrange themselves in a circular pattern,revealing the force pattern.

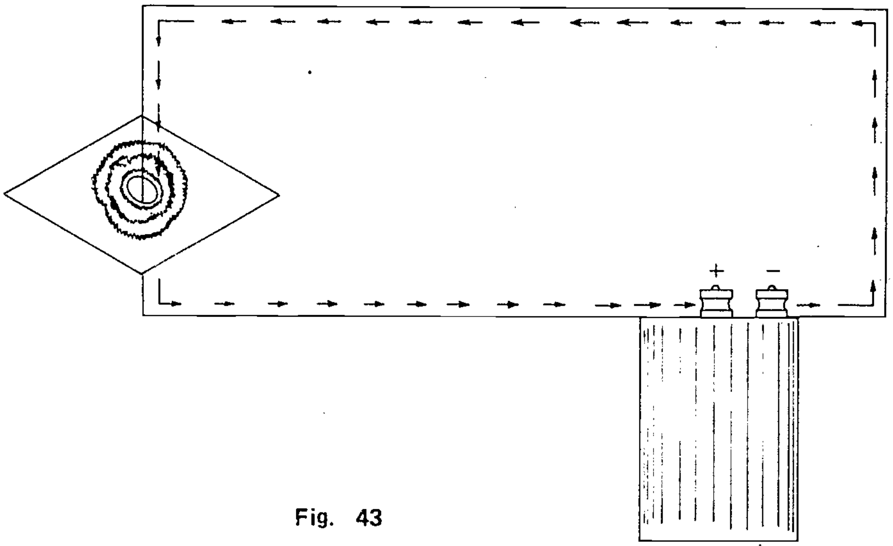


Fig. 43

The magnetic field that develops represents a storage of energy that is being taken from the source of E.M.F. This storage of energy produces a diminishing COUNTER or BACK E.M.F. that tends to cancel the applied e.m.f., resulting in a diminishing voltage drop occurring across the circuit during the time that the field is building up. For this reason, the voltage drop that occurs across an inductor is in no way similar to the voltage drop that occurs across a resistance. WHEN THE CURRENT FLOWING AND THE RESULTING MAGNETIC FIELD BECOME CONSTANT, THE BACK E.M.F. DISAPPERS. The strength of the back e.m.f. is proportional to the rate of change and to a property of the circuit itself called INDUCTANCE. Any circuit capable of producing flux has inductance.

The physical properties of a conductor will determine its inductance; normally in wires used to connect electrical devices together the inductance is small enough to be disregarded, but if you were to wind the wire into a coil, its inductance will increase. If similar in other respects, a coil with more turns will have a greater inductance value than a coil with fewer turns. Devices of this type are called INDUCTORS, and their inductance value is expressed by a unit called the HENRY, symbol (L).

If the current is increasing, the inductance of a circuit will cause energy to be stored in the developing magnetic field. THE INDUCTANCE OF A CIRCUIT PREVENTS THE CURRENT VALUE FROM RISING RAPIDLY. Should the current decrease, the energy stored in the magnetic field returns to the circuit with a polarity that will add to the decaying current being supplied by the source of applied e.m.f. This characteristic tends to keep current flowing through the circuit when the applied e.m.f. is decreasing or is removed entirely, as is demonstrated by the spark that occurs when inductive circuits are interrupted. The thought to remember is, INDUCTANCE SERVES TO OPPOSE ANY CHANGE IN CURRENT FLOW.

While the aforementioned applies directly to the influence that inductance has on D.C. systems, we must introduce other factors to understand its effect on A.C. systems. The first of these you will arrive at by recalling that in A.C. resistive circuits, the voltage and current increased and decreased together; when this relationship exists, you say that voltage and current are in phase. In A.C. systems, the characteristic of inductance to resist a change in current flow, causes the rise in current through the circuit to lag behind and be OUT OF PHASE with the rise of the applied voltage. To compare the relationship of voltage and current in resistive and inductive circuits, you can divide an A.C. cycle into 360 electrical degrees.

In any generator, a conductor must be moved past a north and a south pole to have one cycle generated in it. Therefore, in a two-pole generator, a conductor must make one complete revolution, or pass through 360° in space.

Since the time required to generate one cycle is constant for a given frequency, e.m.f. waves are plotted with time as the horizontal axis. Time in seconds may be used, but it is more convenient to divide the time required to generate one cycle into 360 divisions, called ELECTRICAL DEGREES. It must be kept in mind that electrical degrees used in this sense represent time. See *Fig. 44*.

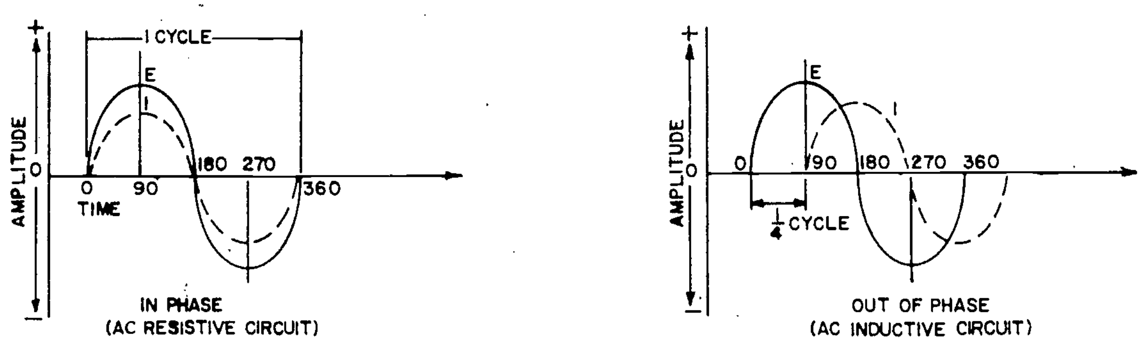


Fig. 44

The back e.m.f. developed in inductive circuits is proportional to the rate at which the current changes, and in A.C. circuits the current is constantly changing at a rate that is determined by the frequency of A.C. source; then the current flow will be inversely proportional to the inductance for an applied voltage and frequency. The combined effect of inductance and frequency will cause the current to lag the applied voltage by 90 degrees. This combined effect is called INDUCTIVE REACTANCE, symbol (X_L). Inductive reactance is expressed by a unit that is also called an ohm.

The other factor is that there is no such thing as a pure inductance, for all circuits contain some resistance. To find the total opposition to current flow in A.C. inductive circuits, you must determine the total effect that the combination called IMPEDANCE, symbol (Z), has on the flow of current.

Since the current in the inductive reactance lags the current in the resistance by 90 degrees, the impedance of the circuit may be determined by the rule that applies to finding the hypotenuse of a right-angled triangle when the base and altitude are known. This relationship is called the IMPEDANCE TRIANGLE.

Z = impedance in ohms
R = resistance in ohms
X_L = inductive reactance

$$Z_{inductive} = \sqrt{R^2 + X_L^2}$$

In A.C. inductive circuits, the impedance (combination of inductive reactance and resistance) will cause the current to lag the voltage somewhere between zero and 90 degrees, depending on the relative amounts of resistance and inductive reactance. Impedance is expressed in ohms, and Ohm's Law may be applied to A.C. circuits containing impedance as readily as those containing resistance.

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

$$E = IZ$$

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

I = current in amperes (R.M.S.)
E = applied voltage (R.M.S.)
Z = impedance in ohms

QUESTIONS:

1. What kind of force builds up around a conductor when current begins to flow through it?
2. What does this force represent?
3. How does the voltage drop that occurs across an inductance differ from that which occurs across a resistance, when they are connected to a D.C. system?
4. What is meant by the term BACK E.M.F.?
5. What determines the strength of the back e.m.f.?
6. How is the back e.m.f. affected when the current flow becomes constant?
7. What determines the inductance of a conductor?
8. What happens to the inductance of wire when it is formed into a coil?
9. Describe the effect the inductance of a circuit has upon current flow when the circuit is connected and disconnected from a source of e.m.f.
10. What is the important characteristic of inductance?
11. How does the relationship between voltage and current differ in A.C.-resistive and A.C.-inductive circuits?
12. Describe the relationship between voltage and current in an A.C. circuit, when they are out of phase.
13. How does the frequency of an A.C. system affect the current flowing through an inductive circuit?
14. What is the term used to describe the combined effect of inductance and frequency?
15. Why is there no such thing as pure inductance?
16. What unit is used to express reactance?
17. What is the term used for the combined opposition of resistance and inductive reactance to current flow?
18. What unit is used to express the term in problem 17?
19. What might be the phase relationship between voltage and current in A.C. circuits containing both resistance and reactance?
20. If the impedance of an A.C. circuit is 40 Ohms and the applied voltage is 220 volts (R.M.S.), what would be the (R.M.S.) value of the current flowing through it?

OBJECTIVE:

To learn how varying the current in one circuit can induce a current in another circuit.

RELATED INFORMATION:

A MAGNETIC FIELD DEVELOPS AROUND A CONDUCTOR WHEN IT IS CONDUCTING CURRENT. If the current is increased,the strength of the field increases. If the current is decreased,the strength of the field decreases. Reduce the current to zero and the magnetic field disappears. WHEN THE CURRENT CHANGES IN STRENGTH THE MAGNETIC FIELD CHANGES IN STRENGTH.

An e.m.f. can be induced in a conductor by moving it into a magnetic field; moving it out of the magnetic field will induce a current in the opposite direction. The same results may be obtained by moving the magnetic field while the conductor remains stationary. AS FLUX CUTS A CONDUCTOR, CURRENT WILL BE GENERATED OR INDUCED IN THE CONDUCTOR.

There is a self-induced e.m.f. that occurs whenever current begins to develop. Flux lines cut the conductor, generating an e.m.f. THIS SELF-INDUCED E.M.F. IS ALWAYS IN OPPOSITION TO THE E.M.F. THAT PRODUCED IT. Since the back e.m.f. is in opposition to the applied e.m.f., the time for the power-supply current to reach its maximum value will depend on the inductance value of the circuit. As the current and magnetic field build to maximum, the rate at which the flux cuts the conductor tapers off and finally disappears. This causes the back e.m.f. to taper off and finally disappear. ONCE THE CURRENT BECOMES CONSTANT, THE ONLY OPPOSITION TO CURRENT FLOW IS THE RESISTANCE OF THE CIRCUIT.

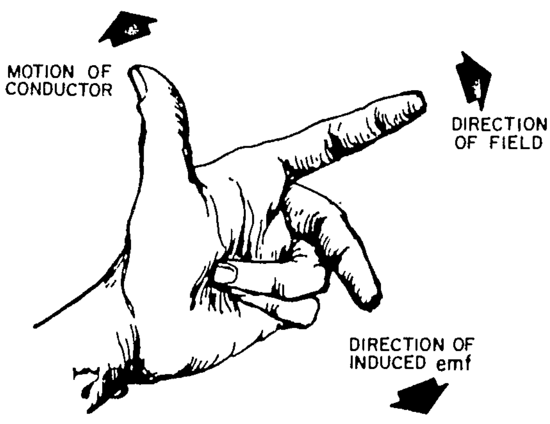
When value of the power-supply current is reduced, the magnetic field begins to collapse. As the flux lines cut the conductor, an e.m.f. is induced in the conductor that will cause an induced current to flow in the same direction as the reduced power-supply current. This property of an electric circuit to oppose any change in current is called SELF-INDUCTANCE.

THE MAGNETISM ASSOCIATED WITH A CURRENT-CARRYING CONDUCTOR CAN BE STRENGTHENED BY FORMING THE CONDUCTOR INTO A COIL. Therefore, a circuit containing a coil will have a much higher value of inductance.

Fig. 45 shows a sectional view of a coil. When the coil is connected to the battery, current will begin to flow through the coil. As the current increases in value, the magnetic lines expand from the center of each turn of the coil and cut across adjacent turns. The resulting induced electron-flow will be against the power-supply current. The relation between the directions of motion, field, and induced e.m.f. is given by the LEFT-HAND GENERATOR RULE:

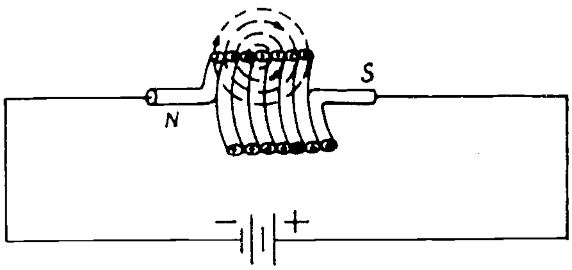
LEFT-HAND GENERATOR RULE

With the thumb, forefinger and middle finger of the left hand placed at right angles to each other, the forefinger gives the direction of the field, the thumb gives the direction of motion of the wire, and the center finger gives the direction of the induced current.



The left-hand generator rule is established for a stationary field and a moving conductor. However, it may also be applied in the case of a moving field and a stationary conductor if the relative motion of the conductor is considered. Although only the flux developed around the cross-section of one conductor is shown in *Fig. 45*, remember that all parts of the coil are producing flux at the same time.

Fig. 45 →



When an inductive circuit is energized, the back e.m.f. tends to oppose the flow of current from the power supply, and the rate at which the current builds to its maximum will depend on the value of the inductance. The inductance of a circuit can be increased by inserting a coil. Once the current reaches a steady value, the only opposition to current flow is the resistance of the circuit. When the current is reduced or a switch is opened, the inductance will oppose the reduction in current. INDUCTANCE SERVES TO OPPOSE ANY CHANGE IN CURRENT FLOW.

Since an e.m.f. can be induced in a circuit by self-induction, why couldn't a change in the magnetic-field strength of one circuit induce an e.m.f. in another circuit? The circuit shown in *Fig. 46* illustrates that as the flux builds up around the primary coil connected to the battery, some of the flux developed will cut the conductors of the secondary coil connected to the ammeter. The induced e.m.f. would tend to cause a current in one direction through the secondary coil as the current built up in the primary circuit, then drop to zero as the battery current reached a steady value. When the primary coil is disconnected from the battery, the magnetic field would begin to collapse. Flux lines would cut the conductors of the secondary coil in the opposite direction, resulting in an e.m.f. that would tend to cause a secondary current in the opposite direction. The coil that produces the original flux is called the PRIMARY WINDING. The coil which is coupled magnetically to the primary is called the SECONDARY WINDING. When an e.m.f. is induced in a secondary by a change in current in a primary, it is said to be induced by MUTUAL INDUCTION.

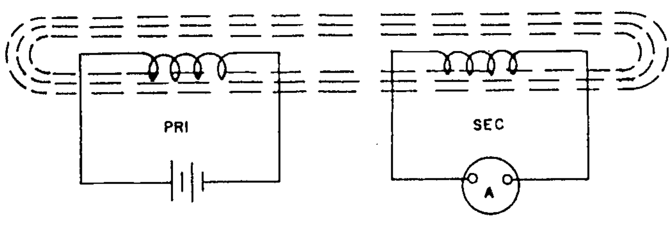


Fig. 46

The induced voltages in the primary and secondary are directly proportional to the number of turns.

Example: $$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

$$\frac{12v}{24v} = \frac{10t}{20t}$$

The ampere-turns of the primary and secondary are equal.

Example: $I_p N_p = I_s N_s$

2 amp X 10 turns = 1 amp X 20 turns

The reluctance of the magnetic circuit is often reduced by winding the primary and secondary on a single iron core; see *Fig. 47*.

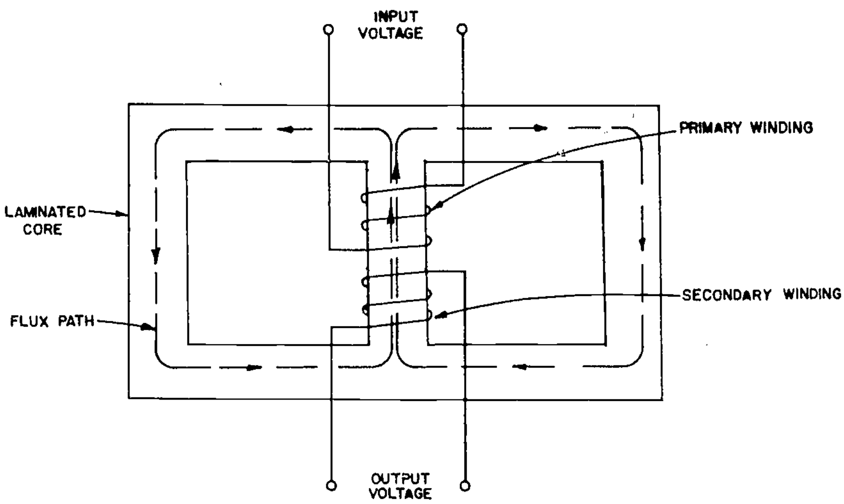


Fig. 47

Also, the field established by the primary may be made to vary by one of the following methods:

1. PERIODICALLY ENERGIZING AND DE-ENERGIZING THE PRIMARY CIRCUIT. This is the method used in ignition systems for most automobiles. *Fig. 48* shows an elementary diagram of a four-cylinder automobile-engine ignition sytem.

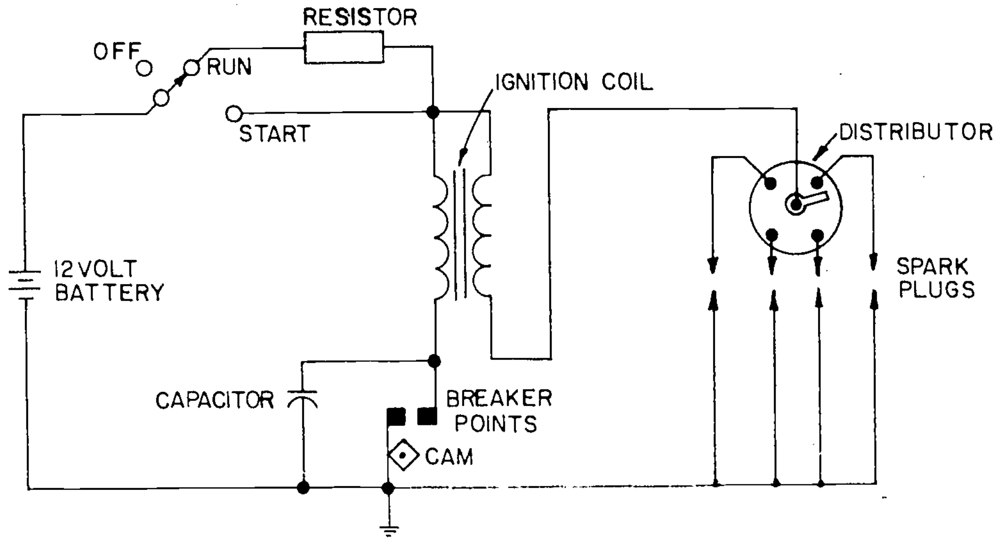


Fig. 48

An ignition coil consists of a primary coil of a few turns of heavy insulated wire wound around an iron core and a connected secondary of many turns of fine insulated wire wound directly around the primary. The primary is energized by connecting it to a 12-volt storage battery. Breaker points are connected in series with the primary circuit and are periodically opened and closed by a mechanically driven cam. Current will flow in the primary circuit, developing a magnetic field that will couple both the primary and secondary together. At a predetermined instant the breaker points are opened, de-energizing the primary circuit. At the same instant the distributor rotor arm connects the secondary to the correct spark plug. Thus, as the field collapses around the many turns of the secondary coil, the high voltage induced in the secondary is applied across the spark-plug gap. This causes an arc to occur which ignites the fuel mixture in the combustion chamber.

A capacitor is connected across the breaker points to prevent an arc from forming between the breaker points due to the inductance of the primary circuit. Since a capacitor functions as a kind of storage tank for electrical current, the capacitor momentarily provides an easier path for the induced primary current to flow. Once the capacitor is charged, the primary current comes to an abrupt stop, the field collapses very rapidly, inducing a secondary voltage high enough to establish the arc at the spark-plug gap. The E.M.F. INDUCED IN A CONDUCTOR BY ELECTROMAGNETIC ACTION IS PROPORTIONAL TO THE RATE AT WHICH THE FLUX CUTS THE CONDUCTOR.
The capacitor is discharged by the closing of the breaker points, and the sequence of events is repeated as the next lobe on the cam opens the points and the distributor rotor arm moves to connect the next spark plug. The system may be expanded to accommodate six- and eight-cylinder cars by simply adding lobes to the cam, extra distributor positions and additional spark plugs. Also, note that a resistor is shown in the primary circuit while running, but is shorted out while starting. This is done so as to allow sufficient current to flow in the primary with the low battery voltages that occur when the cranking-motor load is applied and prevents excessive primary current when the cranking-motor load is not being applied.

2. VARYING THE INTENSITY OF THE PRIMARY CURRENT. A telephone is a good example of this method. The primary of an induction coil, battery and telephone transmitter are connected in series as shown in *Fig. 49*.

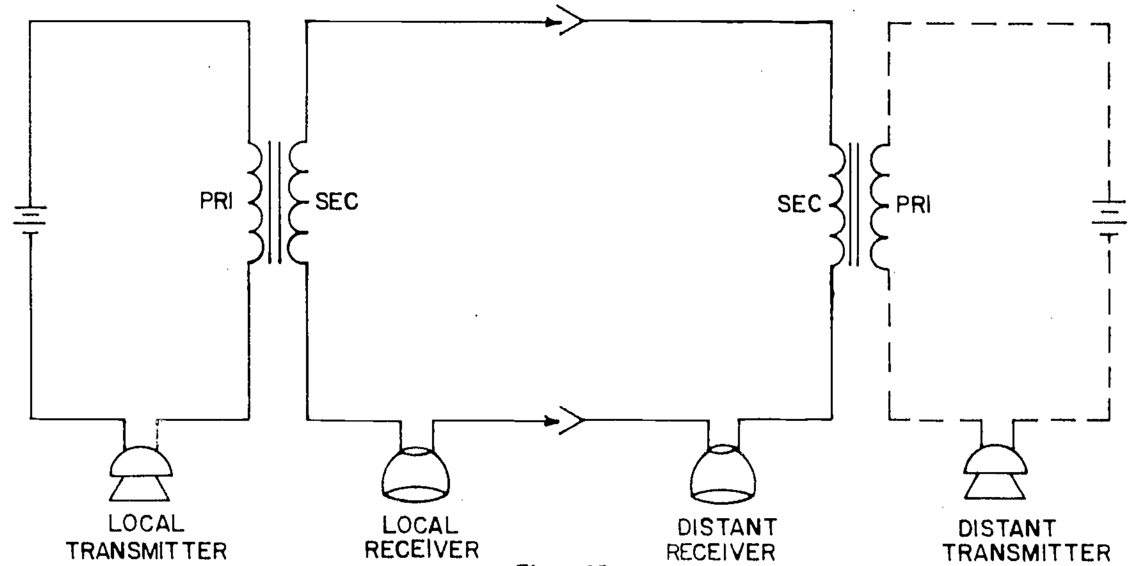


Fig. 49

The resistance of the transmitter varies in response to the speaker's sound waves, increasing and decreasing the current flow in the primary circuit. The varying primary current causes corresponding variations in the magnetic field coupling the primary to the secondary. Since the magnetic field is alternately building up and collapsing, an alternating e.m.f. is induced in the secondary circuit, causing an alternating current to flow through the distant receiver that has been connected in the circuit.

3. PERIODICALLY REVERSING THE PRIMARY CURRENT. A mutual-induction device that is used for changing the value of an alternating voltage is called a TRANSFORMER. In its simplest form it consists of a primary and a secondary wound on the same iron core. When an alternating e.m.f. is applied to the primary circuit, the current will flow first in one direction then in the other. The flux produced in the core will increase, decrease and reverse with the changes in the primary circuit, inducing an alternating e.m.f. in the secondary winding. The value of the secondary voltage will be in direct proportion to the turns ratio of the primary and secondary windings.

Transformers may increase or decrease voltages. When they are used to reduce voltages they are called STEP-DOWN TRANSFORMERS. If they are used to increase the voltage, then they are called STEP-UP TRANSFORMERS. Any transformer may operate as either a step-down or step-up transformer provided that the voltage for which the transformer windings are designed is not exceeded.

To transmit a given amount of energy, less current is required as the voltage is increased. This means that step-up transformers can be used to increase the generated alternating e.m.f. to several hundred thousand volts. Then at locations where the energy is required, step-down transformers may be used to reduce the high transmission voltage to values that would be safe and practical to use. *Fig. 50* shows an elementary diagram of a step-down transformer.

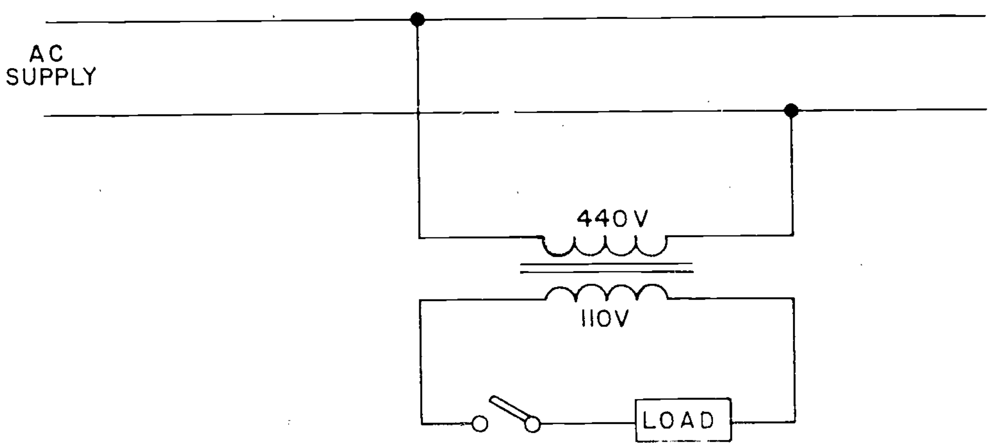


Fig. 50

QUESTIONS:

1. What happens to the magnetic field around a conductor when the current flowing in it is increased?
2. Describe what happens when flux cuts the conductor of a circuit.
3. How does the self-induced current flow in a circuit prevent the current from building up rapidly?
4. Why does the self-induced back e.m.f. disappear once the current becomes constant?
5. What limits the current flow once the magnetic field becomes fixed in strength?
6. How does reducing the power supply affect a circuit that has inductance?
7. Define the term SELF-INDUCTANCE.
8. How would you increase the inductance of a circuit?
9. In what way does increasing the inductance of a circuit affect the current flow of a circuit?
10. How does an inductor oppose any change in current flow?
11. What is meant by primary circuit?
12. How is current induced in the secondary?
13. What kind of a circuit couples the primary winding to the secondary winding?
14. Explain what is meant by the term MUTUAL INDUCTION.
15. If 240 volts were applied to a primary winding with 300 turns, how many volts would be measured across a secondary with 150 turns?
16. If 12.5 amperes were flowing in the primary circuit, how many amperes would be flowing in the secondary circuit?
17. How may the reluctance of the magnetic circuit of a mutual-inductance device be decreased?
18. Explain why automobile ignition systems will not work if the capacitor across the breaker points becomes shorted.
19. Why does the person hear himself through the local receiver as he is talking into the local transmitter?
20. In what way are the three methods used to vary the magnetic field similar?

OBJECTIVE:

To learn about universal, synchronous, shaded-pole and split-phase motors.

RELATED INFORMATION:

The term PHASE in alternating-current systems refers to the time or electrical angle between some electric value and a reference point such as zero. Introducing reactive components such as inductors and capacitors, currents may be caused to lag behind or lead the applied voltage. In a single-phase system only one such phase relationship can exist. The current is either in or out of phase with the voltage.

Alternating currents are generated by a.c. generators or ALTERNATORS. Alternators of the type that are used on automobiles today are similar to d.c. generators in that they have a d.c.-excited stationary field winding and a rotating armature. Since the alternator produces alternating current, the armature doesn't have to be switched. Thus, the commutator is replaced by slip rings so that a sliding connection can be made to the rotating armature winding. The alternating current is then changed to direct current by a device called a RECTIFIER.

Large alternators are constructed with stationary armatures called STATORS and a revolving field known as a ROTOR. Because alternating current is usually transmitted at very high voltages, the alternators are usually designed to generate e.m.f.'s of several thousand volts. Since the stationary armature does not have to be switched as was the case with the d.c. generator, it can be connected directly to the load. This also eliminates the problem of having to bring the high voltages generated through sliding contacts. Thus, the windings are relieved from being subjected to centrifugal forces and vibrations due to rotation. The rotating field can easily be supplied with the required lower voltage d.c. excitation required to develop the necessary flux through brushes and slip-rings.

Remember that d.c. series and shunt motors rotate in the same direction regardless of the polarity of the power supply. Since at any given instant a.c. can be considered to be d.c. in that there will be a value of current flowing in one direction, you would expect that these motors should perform on alternating current. Actually, a d.c. shunt motor develops very little torque when connected to alternating current. The very high inductive-reactance of the shunt field causes the field current to lag behind the armature current by such a large amount that it results in a very low torque. However, in the case of the series motor, the field and armature currents are in phase. This results in a much greater torque than could be obtained with the shunt motor.

In actual practice special considerations are taken in motors that are to operate on both a.c. and d.c. supplies. Since the current is constantly changing in an alternating system, the inductive-reactance of the series winding would tend to reduce the current flow through the armature. To increase the torque, the series windings of these motors are designed with as few windings as possible, and with a special laminated field core to provide a low-reluctance magnetic circuit. When so designed these motors are called UNIVERSAL MOTORS.

The operating characteristics of universal motors are quite similar to d. c.- series motors. The torque is high for high armature currents, providing the motor with a good starting torque. Also, as the load decreases the speed increases. For this reason the universal motor is connected directly to the load. Universal motors are used mostly in vacuum cleaners, sewing machines, and portable tools.

Some applications, such as clocks, timing devices and phonographs, require special motors that will provide an absolutely constant speed drive. These motors are called SYNCHRONOUS MOTORS.

Though there are several types of synchronous motors, the one discussed is called the Warren Synchronous motor, shown in *Fig. 51*.

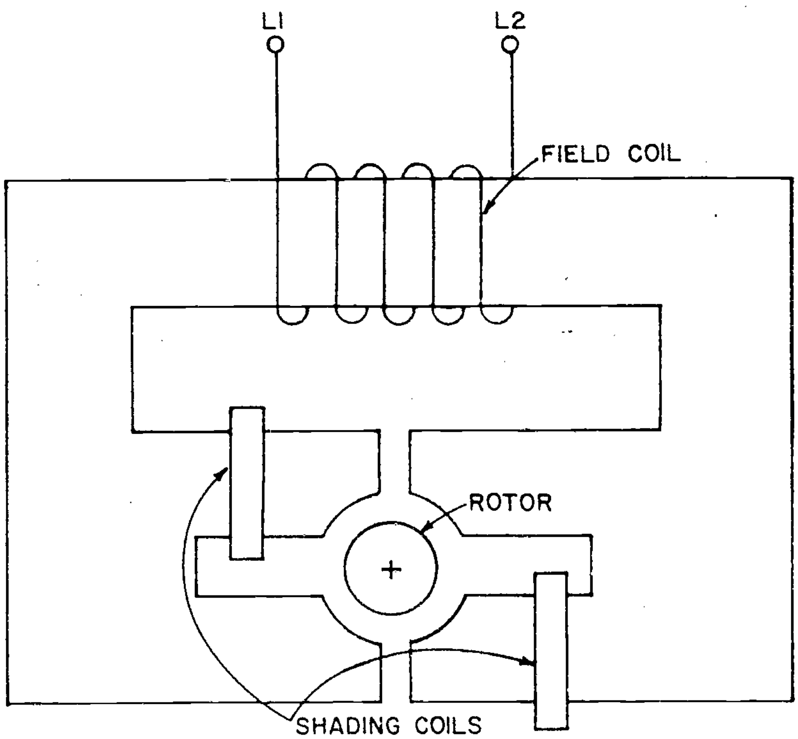


Fig. 51

This motor has two field poles, each divided into two sections. A heavy copper loop, known as a shading coil, is placed over half of each pole. The presence of the copper loop serves to shift the field flux to the half of the pole face without the copper loop as the field builds up; through both halves when the field is at maximum; then through the half with the copper loop as the field collapses, thus producing the effect of a rotating field.

The rotor for this motor is made up of hardened steel disks pressed on to the rotor shaft. A starting torque is developed by circular currents in the rotor, called EDDY CURRENTS, and losses due to magnetizing the rotor disks, called HYSTERESIS LOSSES. When the rotor accelerates to synchronous speed, the rotor becomes magnetized in one direction and locks in synchronism with the rotating stator field. While the operating speed for this type of motor is 3600 r.p.m., the torque produced is very small. But when the rotor speed is geared down through a gear train, sufficient torque is available to drive clocks and other timing devices at the synchronous speed.

Torque-producing single-phase motors that are designed to have their field windings connected directly to the power supply are called INDUCTION MOTORS. In these motors the magnetic field induced in the rotor is caused by currents flowing in the stator. There is no electrical connection between the rotor and the power supply. The revolving rotor consists of a cylindrical core made up of steel punchings or laminations.

Copper bars are mounted near the surface of the rotor, which are brazed or welded to two copper end rings. In some motors the rotor is cast from aluminum as a one-piece unit. The rotor bears a resemblance to the exercise wheel in a squirrel cage. For this reason motors using this type of rotor are referred to as SQUIRREL-CAGE MOTORS. A rotor of the squirrel-cage type is shown in *Fig. 52.*

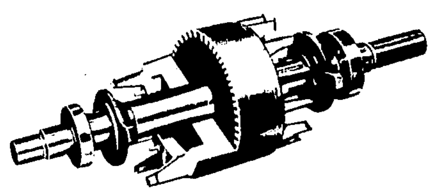


Fig. 52

Induction motors are actually a form of transformer; the stator serves as the primary and the rotor serves as a short-circuited secondary. As in a transformer, an e.m.f. is induced in the secondary circuit, in this case the rotor conductors. The field established is similar to that shown in *Fig. 53.*

During the half cycle when the stator current is flowing in the direction indicated, a south pole is established on the stator surface at A and a north pole at C. During the next half cycle, the stator poles are reversed. Although the stator field strength is varying and reversing its polarity periodically, its action is that of a pulsating stationary field along line A C. Since the induced rotor currents are induced to flow as shown in *Fig. 53*, they will establish poles that line up with line A C. THEREFORE A SINGLE-PHASE INDUCTION MOTOR IS NOT SELF-STARTING.

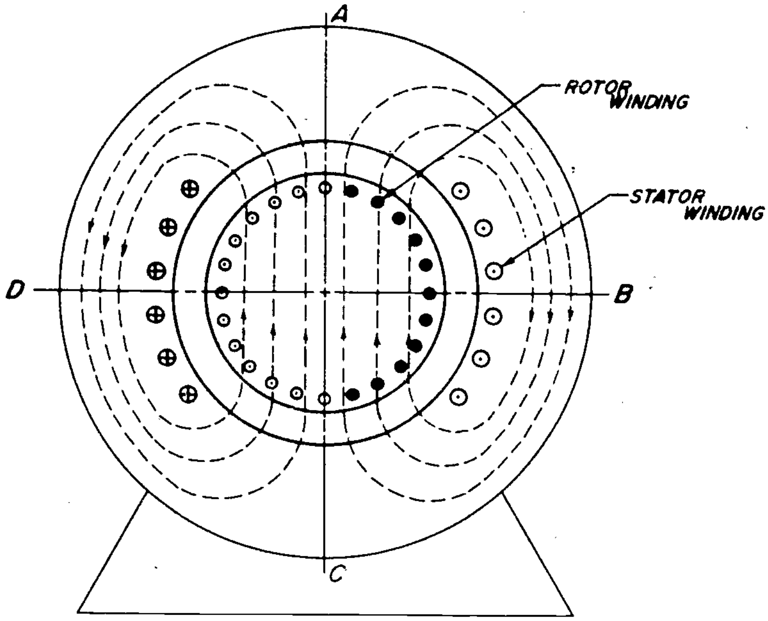


Fig. 53

Once rotating however, the rotor conductors cut across the stator field, causing an e.m.f. to be generated in them. *Fig. 54* shows the relationship as the rotor is being turned in a clockwise direction.

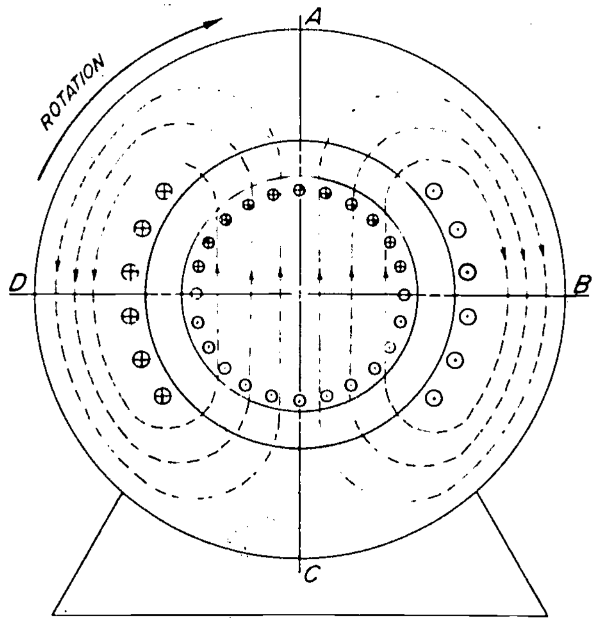


Fig. 54

At the instant shown, the direction of the generated rotor currents, determined by the left-hand rule, will be toward you in the upper half of the rotor and away from you in the lower half. A half cycle later the polarity of the generated e.m.f. will be reversed. *Fig. 55* shows that the generated rotor voltages vary in phase with the stator current and flux.

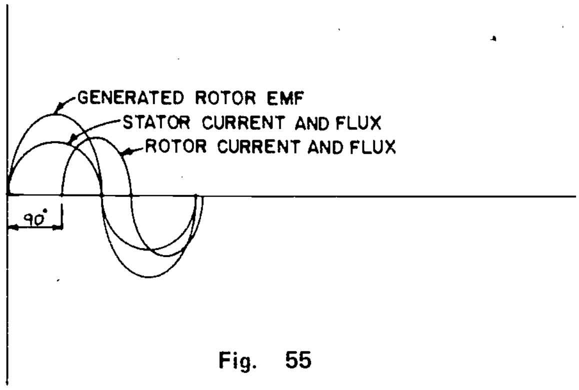


Fig. 55

The phase relationship shown illustrates that because of the high rotor inductance, the rotor current lags the voltage by almost 90 degrees.

The field produced by the generated rotor currents reaches its maximum value one-quarter cycle later; when the rotor field is at right-angles to the stator field, the fields are crossing each other. Since the rotor currents are alternating, the field resulting from these currents also alternates and its action is always along DB, as shown in *Fig. 56*.

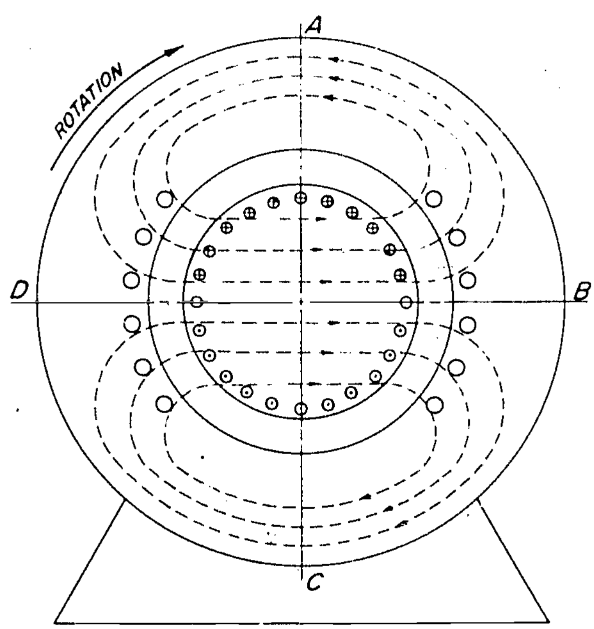


Fig. 56

This crossing field produces the effect of another stator winding at points A and C, that would be energized by an e.m.f. lagging 90 degrees behind the actual stator winding. Since the crossing field and the development of the field lags the stator field by 90 degrees, the two fields combine to form a resultant rotating field that revolves at a speed that is determined by the number of stator field poles and the frequency of the alternating current. This is called the SYNCHRONOUS SPEED.

Remember that the resultant rotating field is produced by the generator action of the motor and is only present when the rotor is turning. Therefore, at the synchronous speed, the field created by the crossing field is almost as strong as the stator field. But in order to develop torque, the full-load speed of a motor is somewhat lower than the synchronous speed. At the actual operating speed of the motor, the rotating field is irregular in strength. Therefore, the torque developed is pulsing in nature. For this reason single-phase induction motors are provided with mountings that are designed to reduce the vibrations that develop from this action. REMEMBER THAT A SINGLE-PHASE INDUCTION MOTOR IS NOT SELF-STARTING.

Single-phase induction motors of 1/20 h.p. and smaller are sometimes started by the use of SHADING COILS on one side of the pole faces as shown in *Fig. 57*. The shading coil is a low-resistance copper loop. As the current in the stator winding increases, the stator flux increases, which induces a current in the shading coil on each pole face. The induced current in the shading coil produces a magnetic field. The field produced by the shading coil is in such a direction as to oppose any increase in the main field flux through the loop. This causes the flux to increase on the other section of each pole face as shown by *a* in *Fig. 57*.

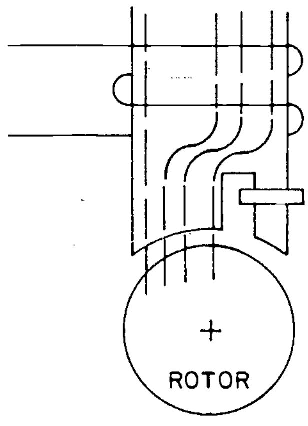


Fig. 57a

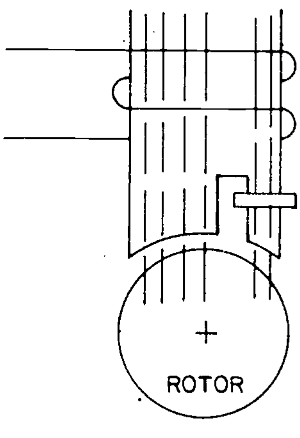


Fig. 57b

As the stator current and flux reach their maximum value, there is no change in current or flux. The result is that the induced current in the loop will disappear. At this point the opposing magnetic field developed by the loop current disappears, and the stator flux becomes uniform across the pole face, as illustrated by *b* in *Fig. 57*. When the stator current and field flux decrease, the induced current in the loop sets up a field that aids the stator field. This results in the field decreasing less rapidly in the section of the pole face on which the shading coil is mounted; see *c* in *Fig. 57*. The effect of the shading coil is to cause the field flux to shift across the pole face somewhat like a rotating field, thus producing a small starting torque. Once the operating speed is reached the motor operates as an induction motor; it is called a SHADED-POLE MOTOR. Shaded-pole motors are used extensively in applications requiring a small starting torque, such as on small fans and blowers.

Another method of producing the effect of rotating field is placing a second winding 90 degrees away from the main winding, points A and C on *Fig. 56*. Energizing this field with an e.m.f. that lagged 90 electrical degrees behind the alternating e.m.f. that is energizing the stator winding would produce the effect of a rotating field similar to that generated when the induction motor is running. The phase difference or lag between e.m.f.'s is created by designing the starting winding with a relatively high impedance. This principle of causing the currents to differ in phase is called PHASE-SPLITTING. Split-phase induction motors consist of five essential parts:

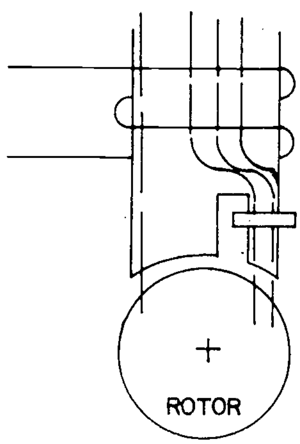


Fig. 57c

1. A stationary part called a STATOR.
2. A revolving part called a ROTOR.
3. A CENTRIFUGAL SWITCH that is located inside of the motor.
4. A STEEL FRAME into which the stator is pressed.
5. Two END SHIELDS bolted to the steel frame so as to provide for mounting the bearings that will support the rotor shaft.

In practice, the STARTING WINDING is designed to have a high resistance by using smaller diameter wire so that its resistance is increased. The low-resistance winding is called the MAIN WINDING. At the instant of start, however, the phase difference between the currents in the starting winding and main winding is small, resulting in a rotating field that will start the motor as long as the torque requirements are not too great. Since the currents in the two windings are not equal, the resulting rotating field is not uniform and the starting torque is small.

Normally the design of starting windings will only permit them to be energized for periods of less than a minute before they will overheat and burn out. For this reason the starting winding is disconnected from the power supply when the rotor reaches approximately 75 percent of its full-load speed. This is accomplished by a centrifugally operated switch. *Fig. 58* shows an elementary diagram of a RESISTANCE-START SPLIT-PHASE INDUCTION MOTOR .

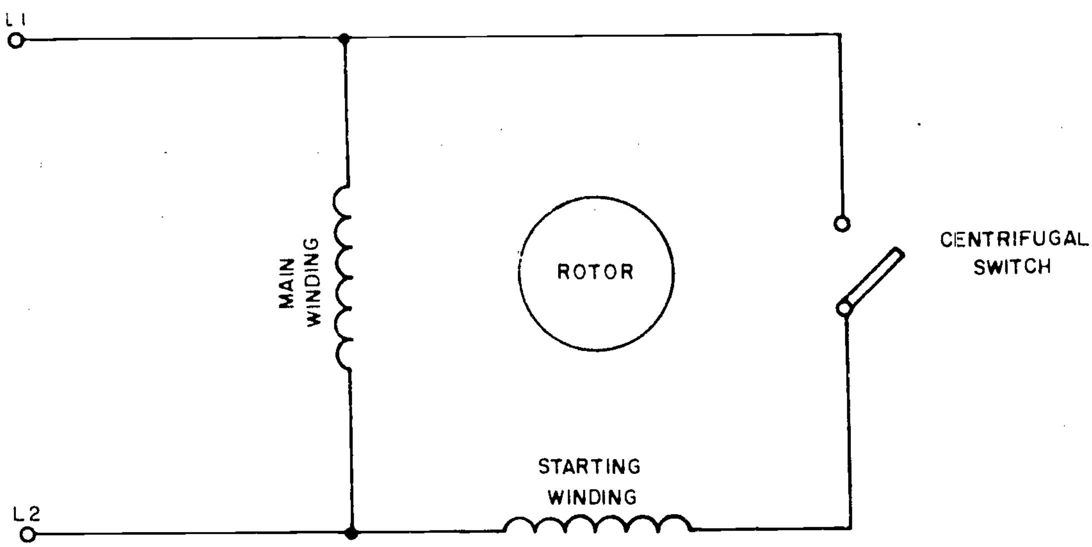


Fig. 58

Because of its low starting torque, this motor is usually used for easily started loads under ½ horsepower. The resistance-start motor is widely used for driving oil burners, washing machines, dryers, grinders and wood-working tools. *Fig. 59* shows a resistance-start split-phase induction motor.

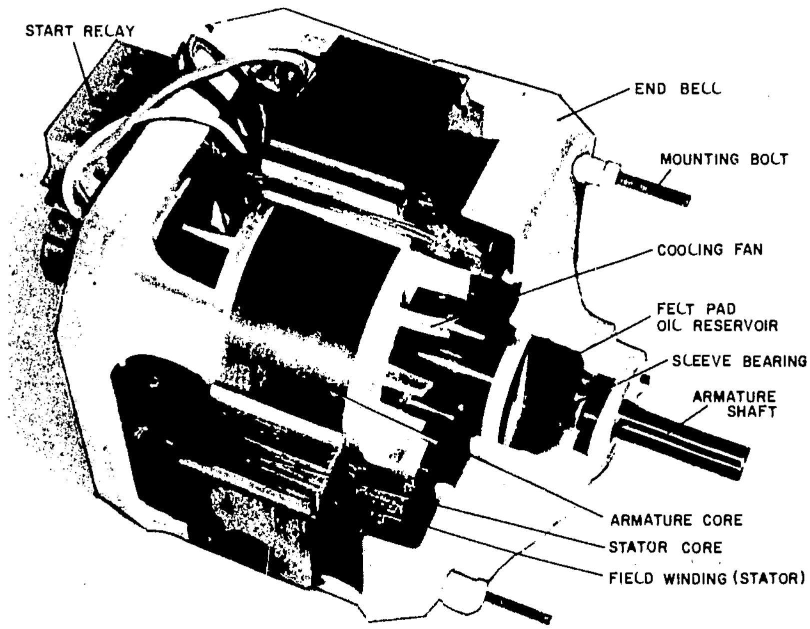


Fig. 59

Where increased starting torque is required, a capacitor may be connected in series with the starting winding. This type of split-phase motor is called a CAPACITOR-START MOTOR. The current in the main winding lags the applied voltage as in the resistance-start motor. The capacitor with the correct storage capacity will cause the current in the starting winding to lead the applied voltage. In this way the currents of the two windings can be made almost 90 degrees. This provides a more even rotating field, resulting in a higher starting torque than could be obtained with the resistance-start motor.

The capacitor-start motor also has a centrifugal switch for disconnecting the starting winding as the rotor approaches its operating speed. *Fig. 60* shows an elementary diagram of a capacitor-start motor.

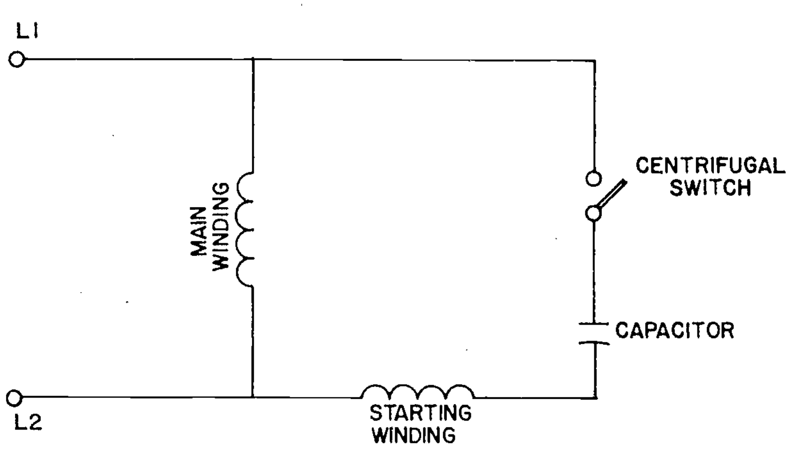


Fig. 60

QUESTIONS:

1. What reactive components may be introduced into a single-phase circuit to cause the current to be out of phase with the voltage?

2. If an automobile alternator produces an alternating current, how can it be used to charge a battery that requires direct current?

3. Why are large alternators built with a revolving field winding and a stationary armature winding?

4. Can you reverse the direction of rotation of a d.c. motor by reversing the polarity of the power supply?

5. Why does a d.c. shunt-wound motor develop very low torque when connected to an alternating current?

6. What special provisions allow universal motors to operate on both a.c. and d.c. power supplies?

7. Why is it dangerous to operate a universal motor without a load?

8. On what devices might a universal motor be used?

9. Why are synchronous motors used to drive clocks and phonographs?

10. What is the function of the shading coil on the synchronous motor discussed?

11. Is the synchronous motor discussed self-starting?

12. How is the magnetic field produced in the rotor of an induction motor?

13. Why are some induction motors called squirrel-cage motors?

14. Why isn't the induction motor shown in Fig. 53 self-starting?

15. Describe the LEFT-HAND RULE as applied to a conductor.

16. Describe the LEFT-HAND RULE as applied to a coil.

17. What is meant by PHASE-SPLITTING?

18. Why is it necessary to limit the time that the starting winding is energized on a resistance-start split-phase motor?

19. On devices, where might you find a resistance-start motor?

20. What type of split-phase motor is used when increased starting torque is required?

OBJECTIVE:

To learn about magnetically operated across-the-line starters.

RELATED INFORMATION:

A measure of the ability of a coil to produce flux, magnemotive force (m.m.f.) corresponds to e.m.f. in electric circuits and may be considered a magnetic pressure. just as e.m.f. is considered an electric pressure. The M.M.F. OF A COIL VARIES DIRECTLY WITH THE CURRENT FLOWING IN IT AND THE NUMBER OF TURNS IN THE COIL. The product of the current in amperes and the number of turns is called the AMPERE-TURNS of the coil. The ampere-turn is the practical unit of m.m.f.

A coil with a given amount of m.m.f. is able to produce a much greater amount of flux when an iron core is inserted into the coil, since the permeability of iron is much greater than air. Very powerful magnets called ELECTROMAGNETS may be made by placing a coil around an iron core.

THE STRENGTH OF AN ELECTROMAGNET DEPENDS ON THE NUMBER OF AMPERE-TURNS OF THE COIL AND ON THE PERMEABILITY OF THE CORE. Soft iron is usually used for the core of an electromagnet because of its high permeability.

Whenever it is desired to operate devices from a remote point, electromagnets are usually employed. Electromagnets have two advantages over permanent magnets: (1) they may be magnetized or demagnetized by turning the current on and off, and (2) they can be made stronger than permanent magnets. *Fig. 61* shows the type used on large industrial hoists.

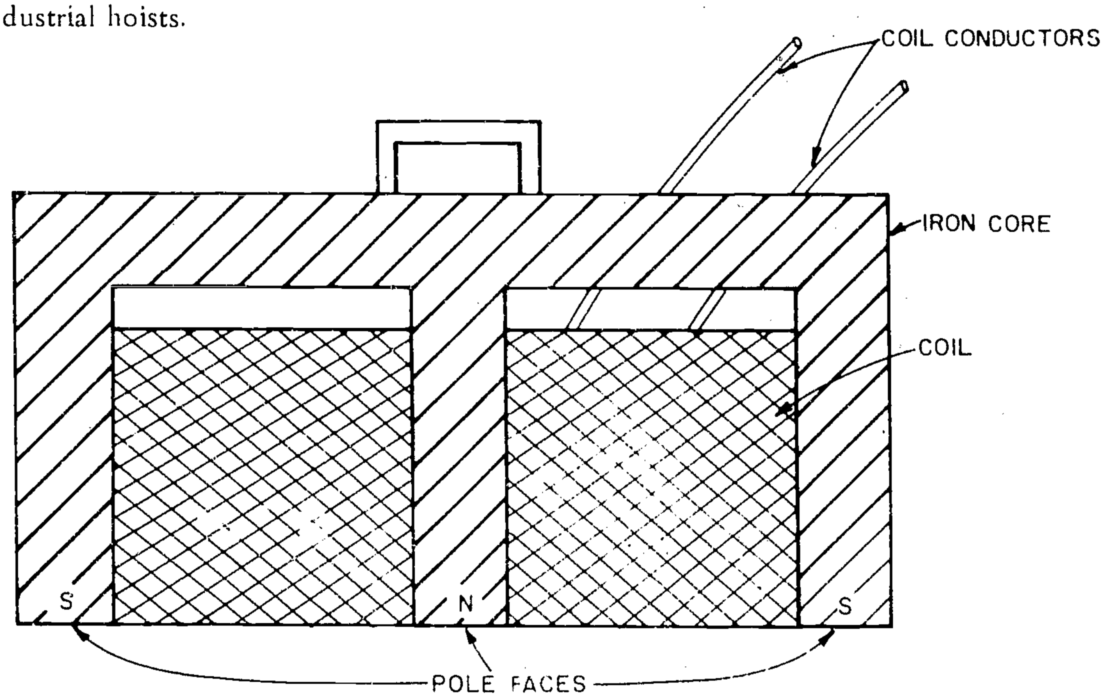


Fig. 61

These magnets are coil conductors used for lifting scrap iron, steel plates, castings, etc. The electromagnet is made by winding coils of wire around a soft iron core as shown in *Fig. 61*. The high permeability of the core allows the electromagnet to be a magnet only when current is flowing through the coil. When the current is turned on the iron core becomes a strong magnet, as the iron or steel objects help complete the magnetic circuit. Each square inch of the pole face is capable of lifting over 100 pounds. To release the iron, the current is turned off. A typical industrial electromagnet operates on 230 volts d.c. with approximately 45 amperes of current.

Whenever a piece of soft iron is placed in the field of a coil it becomes magnetized, as shown in *Fig. 62*. The iron core is pulled into the magnet until the centers of the coil and the iron plunger nearly coincide. The strongest attraction exists when the center of the iron nearly meets the center of the coil.

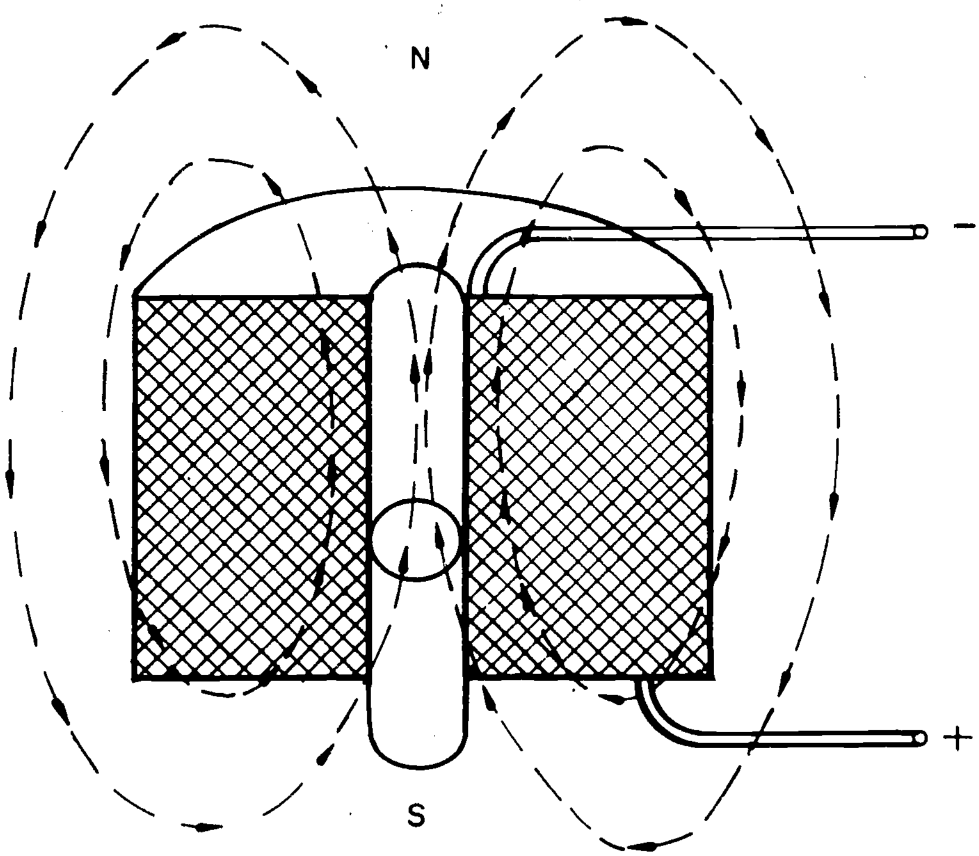


Fig. 62

Solenoid-plunger magnets are used to operate electric door chimes, as shown in *Fig. 63*. Closing the switch allows a current to flow in the solenoid coil, strongly magnetizing the iron plunger and causing it to be drawn upward into the hollow core of the solenoid. The sliding plunger has a tip which strikes the chime bar, producing a musical note. Opening the switch de-energizes the solenoid and the plunger drops.

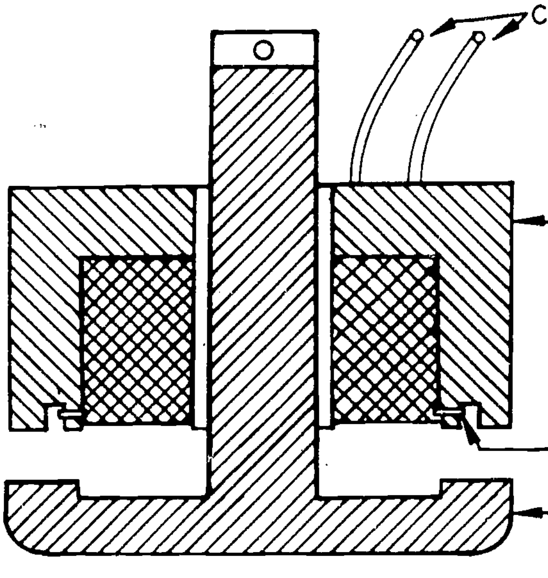


Fig. 63

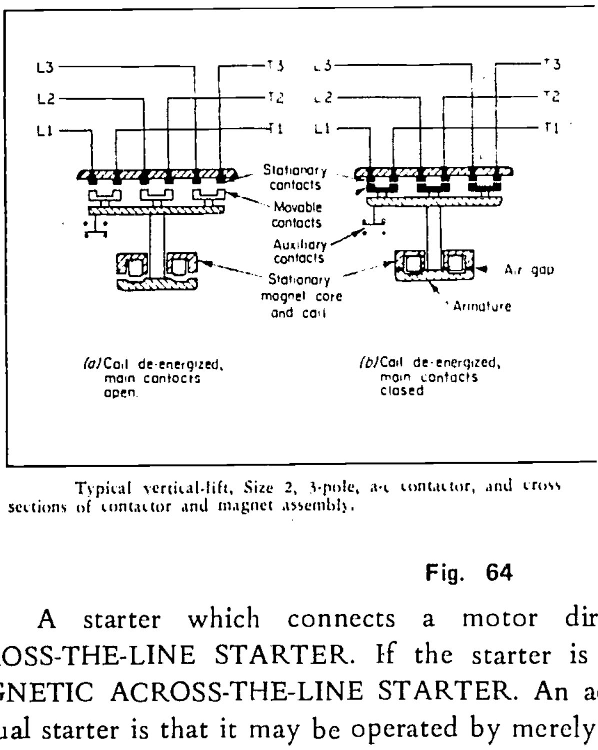
Motor starters that are designed to connect a motor directly across the line are called ACROSS-THE-LINE STARTERS. If these starters are operated magnetically they are called MAGNETIC ACROSS-THE-LINE STARTERS.

The basic part of all magnetic controllers is the MAGNETIC CONTACTOR. Contactors are designed with MAIN CONTACTS, which when closed connect the electrical device they are controlling to the power supply. Usually other smaller contacts are provided to perform auxiliary functions. These contacts are called AUXILIARY CONTACTS. Each set of contacts or POLES has a movable part and a stationary part. The stationary part is called STATIONARY CONTACT, which is mounted to the contactor's insulated base. The movable part, called a MOVABLE CONTACT, is assembled to an insulating bar which moves with the plunger of the solenoid. When the solenoid is energized by a current flowing through its coil, the plunger moves upward, closing the main and auxiliary contacts at the same time. De-energizing the coil opens the contacts by the force of gravity on the plunger assembly. Some contactors are designed with a spring to help gravity along where necessary.

In actual practice solenoids that are used to operate contactors use a design that resembles the electromagnet shown in *Fig. 61* and the solenoid shown in *Fig. 63*. The operating coils of contactors that are to operate on a.c. are energized by a pulsating current; therefore the pull is not continuous, but alternates according to the frequency of the current. This tends to cause a machine-gun-like chattering. To overcome this condition, the core of the electromagnet is equipped with a SHADING COIL, which produces an OUT-OF-PHASE FLUX—the shading coil being a copper loop imbedded around a portion of the core pole-face. The current induced in the shading coil is sufficient for the solenoid to keep the plunger from falling during the reversal of the current. A sectional view of this type of solenoid is shown in *Fig. 63*.

Magnetic Contactors are used when it is desired to control a motor or some other electrical device from a remote point. Since it is not necessary to run the main supply lines to the control point, only the small wire required by the operating-coil current need be run. Also, often the operating solenoids are connected to a lower voltage than the main power supply, offering further protection to the machine operator.

Contactors offer the control of very heavy currents by the machine operator opening and closing a small switch that will control the relatively small current required to energize the solenoid coil. *Fig. 64* shows a magnetic contactor.



Typical vertical-lift, Size 2, 3-pole, a-c contactor, and cross sections of contactor and magnet assembly.

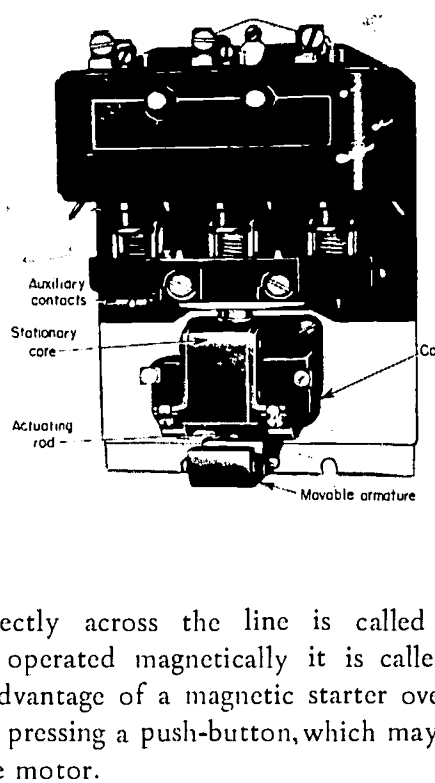


Fig. 64

A starter which connects a motor directly across the line is called an ACROSS-THE-LINE STARTER. If the starter is operated magnetically it is called a MAGNETIC ACROSS-THE-LINE STARTER. An advantage of a magnetic starter over a manual starter is that it may be operated by merely pressing a push-button, which may be located some distance away from the starter and the motor.

Magnetic starters consist basically of a contactor to which overload relays have been added. These relays are thermally operated. *Fig. 65* shows a thermal-operated overload relay. This relay consists essentially of a small heater coil which is connected in series with the line. The current flowing through the heater generates heat, in an amount determined by the current through the heater. Mounted in such a way as to be exposed

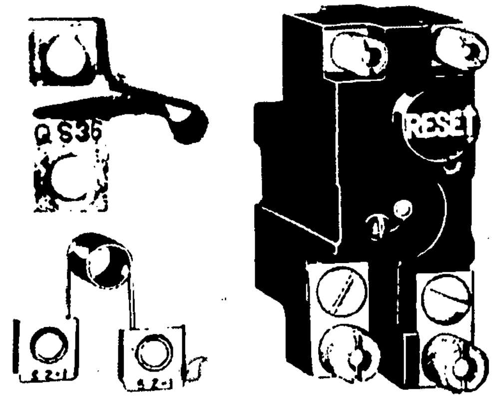


Fig. 65

to this heat is a strip formed of two metals. The strip is fixed on one end and is free to move on the other. The two metals have different degrees of expansion, so as to make the strip bend when heated. The free end normally keeps two contacts that are connected in the control circuit closed. When an overload occurs, the coil heats the thermostatic bimetal so that it bends and opens the contacts, thereby de-energizing the control circuit and stopping the motor. *Fig. 66* shows an elementary diagram for a single-phase magnetic across-the-line starter.

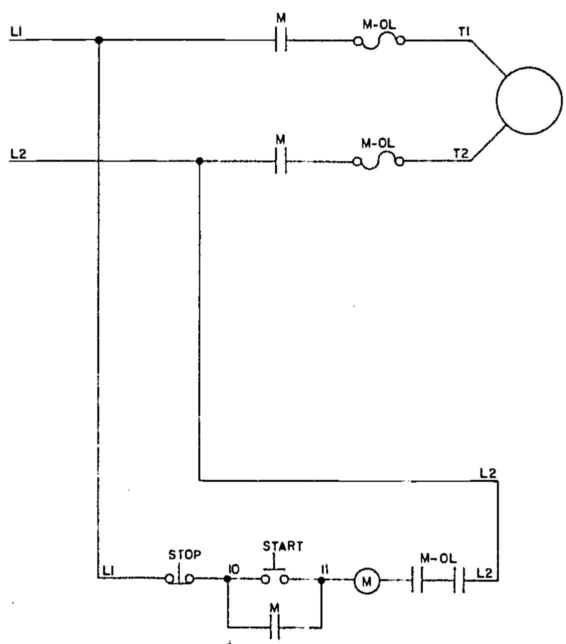


Fig. 66

The circuit shown in *Fig. 67* is similar, except a disconnect switch has been connected between the power supply and the motor starter. The disconnect switch is a two-pole, single-throw enclosed switch with quick-break spring action and is operated externally. There are three cartridge fuses included in the disconnect switch for short-circuit protection of the power supply.

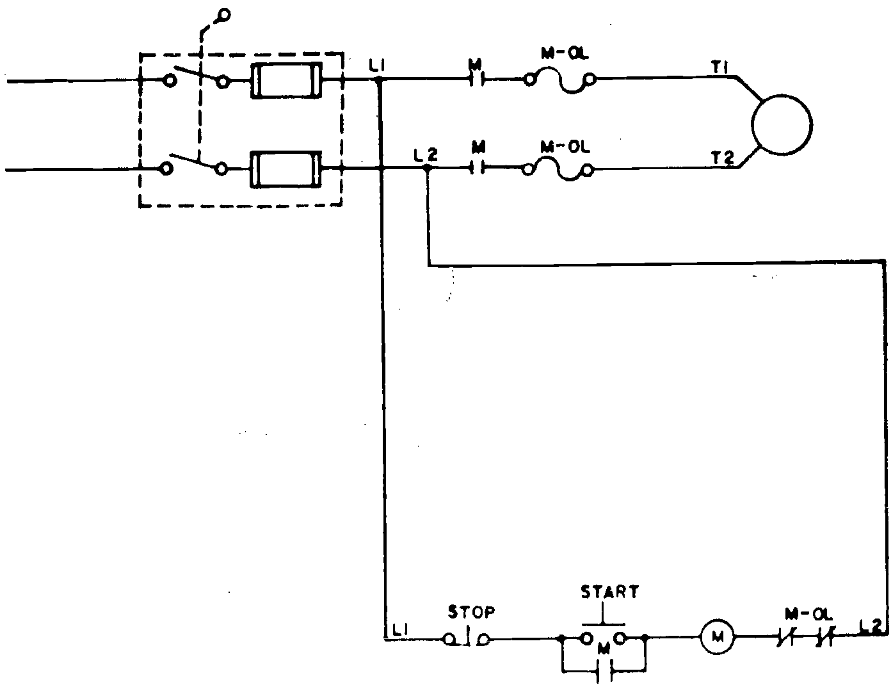


Fig. 67

The two (M) contacts connected in series with lines L_1 and L_2 are the main contacts and are designed to switch the load current. Note all contacts for the starter and its operating coil are marked with the symbol (M). Since magnetic motor starters are designed with the overload heaters connected in series, no designation has been given to this connection, as it has already been wired by the starter manufacturer.

The designation (M-OL) means that it is part of the overload relay for starter (M), in this case the overload heater. (T_1 and T_2) are the connections to the motor. The control circuit is drawn below the load circuit and consists of the normally closed stop pushbutton, normally open start pushbutton, normally open auxiliary contact on the (M) starter, the operating coil on the (M) starter and the series-connected, normally closed contacts of the overload relay. Since the overload contacts are connected in series with the operating coil at the factory, no designation is made for this connection.

This control will provide across-the-line starting in one direction of rotation when the controller has been connected to the specified power supply. The cartridge fuses will allow sufficient current to flow in order to accommodate the starting surge to the motor, but will open the circuit to protect the system from any damage that might be caused by defective wiring or faults in the motor windings. Running overload protection is provided by the overload relays.

Operation of the circuit is as follows: Closing the disconnect switch connects the circuit to the power supply. When the machine operator pushes the normally open START button, the power supply e.m.f. is connected across the starter operating coil through the normally closed STOP pushbutton, manually closed START pushbutton, and the normally closed overload contacts. Upon energization, all contacts on the magnetic motor starter (M) change from their de-energized position to their energized position. In this circuit the two main (M) contacts and the auxiliary (M) contacts close. The two overload contacts (M-OL) do not change, as they are only operated by excessive heat from the overload heater.

Once the normally open (M) contacts close, the motor is connected to the power supply, and the auxiliary (M) contact that is connected in parallel with the START push-button provides a path around the pushbutton so that the circuit becomes self-holding. When the auxiliary contact is used in this manner it is called a HOLDING CONTACT. All this has taken place in an instant and the operator can release the push-button and the system will remain energized.

The motor can be de-energized by pushing the series-connected STOP button, which is the normal operating procedure, opening the disconnect-switch contacts, blowing a fuse, or opening the overload relay contacts. Or an interruption of voltage or insufficient voltage will allow the starter contacts to open. The desirable feature of this circuit is that once the circuit is de-energized it returns to the OFF position and cannot be started again unless the operator takes certain necessary steps.

Operation of the STOP button would only require the pushing of the START button for re-starting. Blowing a fuse would require replacement and necessary fault corrections before pushing the START button would re-start the motor. Operation of the overload relay would require that the machine operator push the reset button on the starter before the START button would become effective.

The circuit shown in *Fig. 66* could be used to start small d.c. motors or single-phase a.c. motors. The power-supply ratings of both the motor and starter operating coil would have to accommodate the supply used.

Most of the industrial applications employ motors that are energized by a three-phase power supply. This type of supply is essentially three single-phase systems that operate together. The advantage of this system is that, by starting the build-up of current in each phase 120 electrical degrees behind the other, a more constant torque is achieved than can be developed with a single-phase system.

A similar control system but for a three-phase motor is shown in *Fig. 67*. The first phase relationship occurs between wires L_1 and L_2, the second between L_2 and L_3, and the third between L_1 and L_3. Note that the control circuit has been connected across one of these single-phase supplies, L_1 and L_2.

QUESTIONS:

1. What is the term used to identify the magnetic equivalent of e.m.f.?

2. If a given field strength is to be retained, what must be done if the turns of the coil were to be reduced?

3. Why is soft iron chosen for use in the core of electromagnets?

4. How can the strength of an electromagnet be improved without increasing the AMPERE-TURNS?

5. What is the difference between an electromagnet and a solenoid-plunger magnet?

6. How are these two types combined to operate magnetic contactors?

7. In what way does a contactor differ from a starter?

8. Each POLE of a contactor is made up of two parts; name them.

9. The contacts on a contactor are usually closed by a solenoid; what opens them?

10. How does a shading coil permit the use of a solenoid on the pulsating alternating current?

11. What is the advantage in using magnetically operated switches?

12. How do overload relays serve to protect the motor from excessive currents?

13. What electrical device protects the power supply from excessive currents, such as might be caused by short circuits?

14. All of the contacts mounted on a motor starter (M) change from their normal position to the energized position, when the operating coil is connected to the power supply, except those marked (M-OL). Why?

15. How does an overload relay protect the motor from overload?

16. Why is the elementary diagram for a d.c. magnetic across-the-line starter identical to a single-phase magnetic across-the-line starter?

17. The circuit shown automatically returns the controls to the OFF position if the circuit is de-energized for any reason. How does it provide this safety feature?

18. What is the function of a HOLDING CONTACT?

19. What advantage is gained by using three-phase supplies in most industrial applications?

20. The operating coils of a.c. magnetic motor starters are energized by single-phase current. How may this be accomplished with a three-phase power supply?

LESSON 18

POLY-PHASE A. C. TRANSFORMERS AND INDUCTION MOTORS

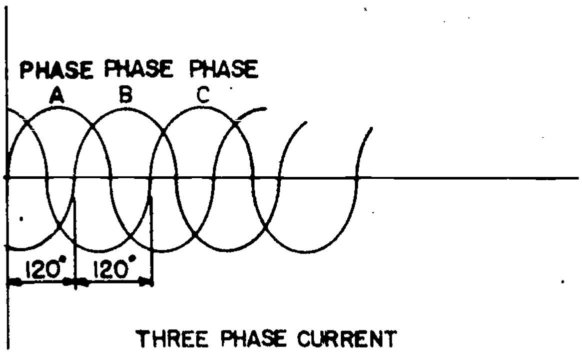
OBJECTIVE:

To learn about poly-phase transformers and poly-phase inductor motors.

RELATED INFORMATION:

In poly-phase systems there is always current in one or more phases. *Fig. 68* shows the output of a three-phase alternator. Note that the current impulses are 120 electrical degrees apart.

Fig. 68 →

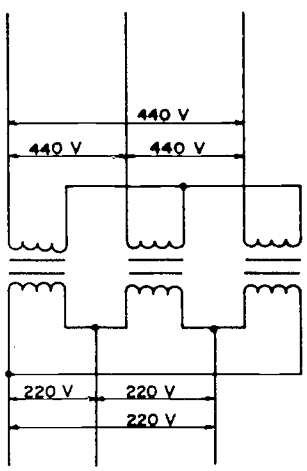


THREE PHASE CURRENT

This has an advantage when used for power purposes, as the overlapping current impulses produce a more constant torque than single-phase current. Three-phase current is produced by an alternator that has three sets of armature and field coils, which produce alternating currents at different intervals of time. Another advantage of the three-phase system is that the motors and transformers of the same rated capacity are smaller and lighter than for single-phase systems. In addition to these advantages is the fact that the distribution system requires only three-fourths as much copper in the line conductors as does a single-phase system of the same power.

Three-phase voltages may be transformed by means of three-phase transformers. Single-phase transformers may be connected in transformer banks to raise or lower the voltages of a three-phase system. *Fig. 69a* shows the connections for the single-phase transformers and *Fig. 69b* shows the three-phase equivalent.

Fig. 69a →



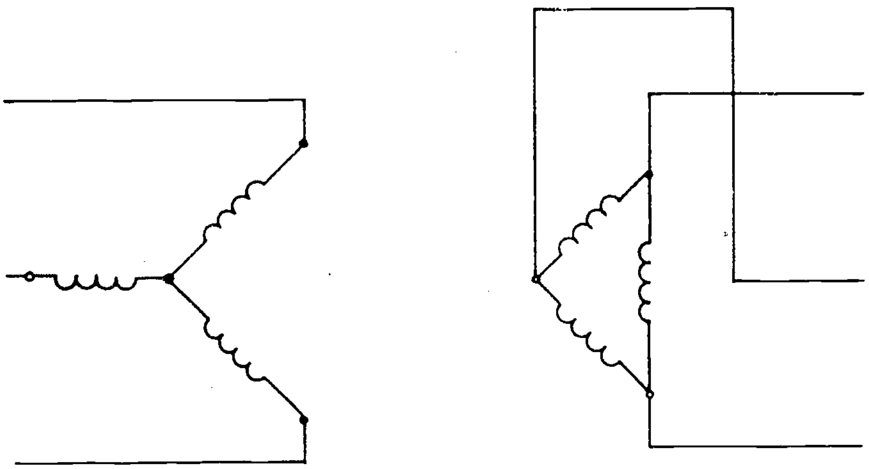


Fig. 69b

The laminated core of a three-phase transformer is made with three legs, a primary and secondary winding for one phase being wound on each leg. These transformers can be built with only these legs since the fluxes established by the three windings are 120°apart in time-phase. Two core legs act as a return for the flux of the third leg. Since the flux will be at maximum value in one leg at some instant, the flux is at half that value in the opposite direction through the other two legs at the same instant. *Fig. 70* shows a three-phase transformer with the flux path described.

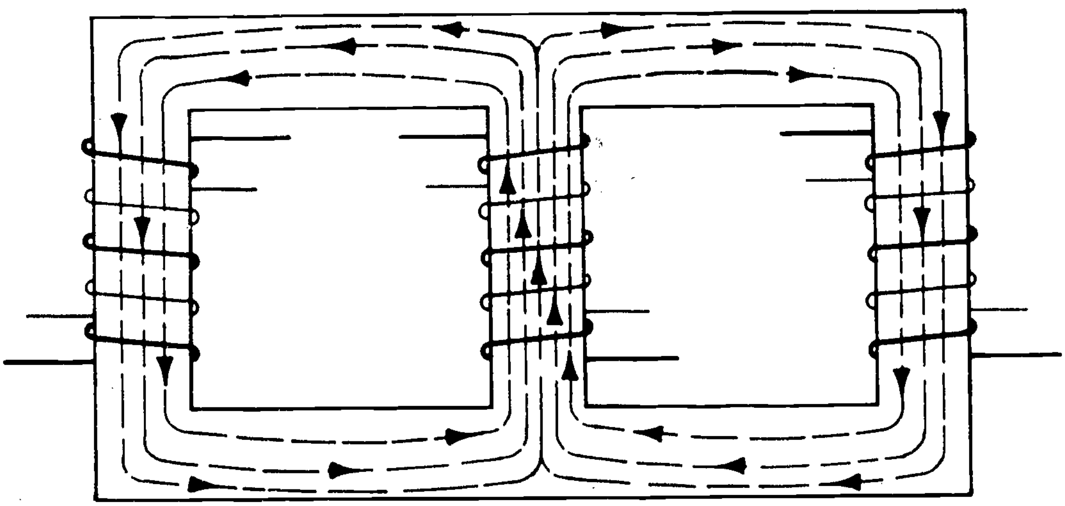


Fig. 70

Because the three windings can be placed on a single core, the three-phase transformer is slightly more efficient and occupies less space than would be required by three single-phase transformers with the same ratings.

Three-phase induction motors are simple and rugged in construction. They have good operating characteristics and hence are the most commonly used type of a.c. motor. Poly-phase induction motors consist essentially of a stationary part called a STATOR, a revolving part called a ROTOR, and two end shields that house the bearings that support the rotor shaft. The stator is connected to the a.c. supply. The rotor is of the squirrel-cage type, and current is induced in it by transformer from the stator. Because of this, the stator is referred to as the primary and the rotor as the secondary. *Fig. 71* shows the essential parts of a POLYPHASE SQUIRREL-CAGE INDUCTION MOTOR.

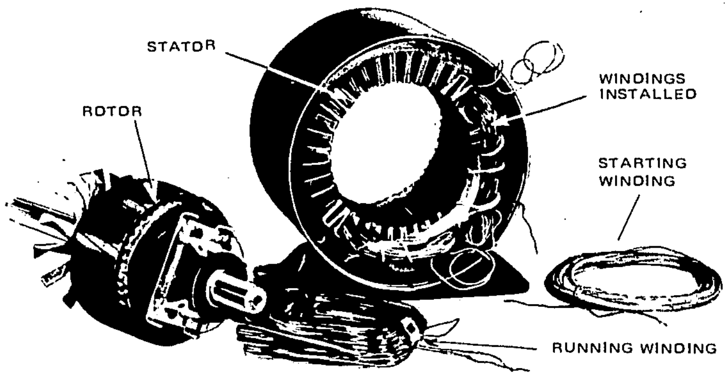


Fig. 71

The stator core is made up of slotted sheet-steel laminations that are supported in a stator frame. The winding itself consists of formed coils that are spaced in the stator slots so that they are 120 degrees apart. The three separate single-phase windings may be connected in either wye or delta.

The rotor of a squirrel-cage motor is constructed of a laminated cylindrical core with conductors embedded in the surface of the core. The conductors are placed approximately parallel with the shaft and are not insulated from the core. This is not necessary, as the currents will naturally follow the path of least resistance, namely, the rotor conductors. At each end of the rotor, the rotor conductors are short-circuited by two end rings. *Fig. 72* shows a squirrel-cage rotor with the rotor conductors skewed. This provides a more uniform torque and reduces the magnetic humming noise when the motor is energized.

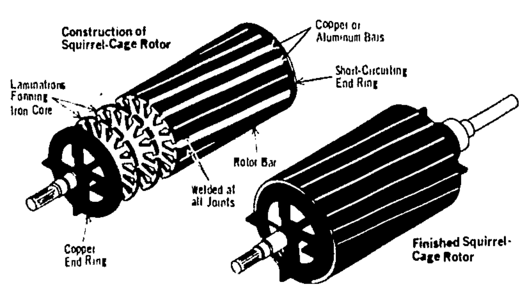


Fig. 72

The synchronous speeds of three-phase induction motors with different numbers of poles and operating frequencies of 25, 50 and 60 cycles per minute are given in the table shown in *Fig. 73*.

POLES	SPEED IN R. P. M.		
	25 CYCLES	50 CYCLES	60 CYCLES
2	1500	3000	3600
4	750	1500	1800
6	500	1000	1200
8	375	750	900

Fig. 73

Reversing any two of the supply lines to the stator will reverse the phase sequence of the stator currents, thereby causing the magnetic field to rotate in the opposite direction. Since the rotor always turns in the same direction as the magnetic field developed by the stator, THE DIRECTION OF ROTATION OF A THREE-PHASE MOTOR MAY BE REVERSED BY INTERCHANGING ANY TWO OF THE THREE STATOR SUPPLY LINES.

Fig. 73 shows that the speed of the rotating field is dependent on the frequency of the supply and the number poles wound in the stator windings. As the field travels it cuts the copper conductors of the rotor and induces an e.m.f. in the squirrel-cage winding. This sets up currents in the rotor conductors which create a field on the rotor. The attraction between the rotating stator field and the rotor field causes the rotor to follow the stator field. THIS MEANS THAT POLY PHASE INDUCTION MOTORS ARE SELF-STARTING.

An induction motor cannot run at synchronous speed. If it were possible for the rotor to achieve synchronous speed, the rotor would be cutting the rotor conductors, no rotor current would flow, and no torque would be developed. The rotor must always turn at a speed less than the synchronous speed of the stator field. Actually, the rotor speed even at no load is slightly less than synchronous speeds in order to produce the torque required to overcome the mechanical losses in the motor. As the mechanical load applied to the rotor shaft is increased, the rotor speed will decrease. Since the stator field is rotating at a constant synchronous speed, the flux can cut the rotor conductors at a faster rate per second. This induces a greater current flow in the rotor, increasing the rotor field. The result of this change is to produce a greater torque at a slightly reduced speed. The construction of squirrel-cage rotors results in a very low impedance. Therefore, a slight decrease in speed results in a large increase in rotor current. Because of this the speed regulation of squirrel-cage induction motors is very good.

The difference between the synchronous speed and the rotor speed is called SLIP. Slip may be expressed in r.p.m. but is more commonly expressed as a percent of synchronous speed. The synchronous speed of the stator's rotating field is used as a reference point, as it remains constant. Subtracting the rotor speed from the synchronous speed will provide the difference which is the number of revolutions per minute that the rotor slips behind the rotating stator field. For example, if a four-pole 60-cycle squirrel-cage motor has a full-load speed of 1750 r.p.m., the slip may be found as follows:

$$\text{synchronous speed} = \frac{120 \times 60}{4} = 1800 \text{ r.p.m.}$$

$$\text{r.p.m. slip} = 1{,}800\text{-}1740 = 60 \text{ r.p.m.}$$

For this motor the percent slip is:

$$\text{percent slip} = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{Synchronous Speed}} \times 100$$

$$= \frac{60 \times 100}{1800} = 3.33\%$$

The smaller the value of slip, the better the speed regulation. The percent slip of most squirrel-cage induction motors averages around 3 percent. BECAUSE THESE MOTORS HAVE A RELATIVELY SMALL DECREASE IN SPEED BETWEEN NO-LOAD AND FULL-LOAD, THEY ARE CONSIDERED TO BE CONSTANT-SPEED MOTORS.

When a pair of stator poles passes a given rotor, one cycle of e.m.f. is induced in that conductor. The motor in our example has a slip of 60 r.p.m. This means that the rotor slips behind the stator field 60 revolutions per minute. Because the flux of the four stator poles passes a given conductor only 60 times per minute, the frequency of the induced e.m.f. and current will be very low. The rotor frequency for this instance, according to the formula for alternators is:

$$F = \frac{PS}{120} = \frac{4 \times 60}{120} = 2 \text{ cycles per second.}$$

Since there are two pairs of stator poles, a pair of stator poles will be passing a given rotor conductor only two times per second. Thus, the rotor frequency must be 2 cycles per second. Increase the slip and the frequency will increase. Therefore, THE GREATER THE SLIP, THE GREATER THE ROTOR FREQUENCY.

The rotor frequency is an important factor, as a change in rotor frequency will vary the inductive reactance of the rotor ($X_L = 2\pi FL$). The resulting change in the rotor impedance will affect both the starting and running characteristics of the motor.

QUESTIONS:

1. Why is current always flowing in one or more phases of a three-phase supply that is supplying power to a load?

2. How is three-phase current generated?

3. Copper is expensive; how do three-phase distributions offer an advantage in this respect?

4. What are the two methods used to connect three-phase windings?

5. How can single-phase transformers be used to transform three-phase voltages?

6. Why can the windings of a three-phase transformer be wound on a single laminated core?

7. What advantage does a three-phase transformer have over using three single-phase transformers with the same ratings?

8. Why are three-phase induction motors used in most industrial applications?

9. Explain why the stator of an induction motor is referred to as the primary and the rotor is referred to as the secondary.

10. Why are the conductors of a squirrel-cage rotor skewed?

11. What are the two connections that may be used for the three single-phase windings of the stator?

12. How does the stator of a three-phase induction motor produce a rotating field?

13. What is meant by the term SYNCHRONOUS SPEED?

14. Why are polyphase induction motors self-starting?

15. How is the direction of rotation reversed on these motors?

OBJECTIVE:

To learn about push-button stations, and reversing polyphase motors.

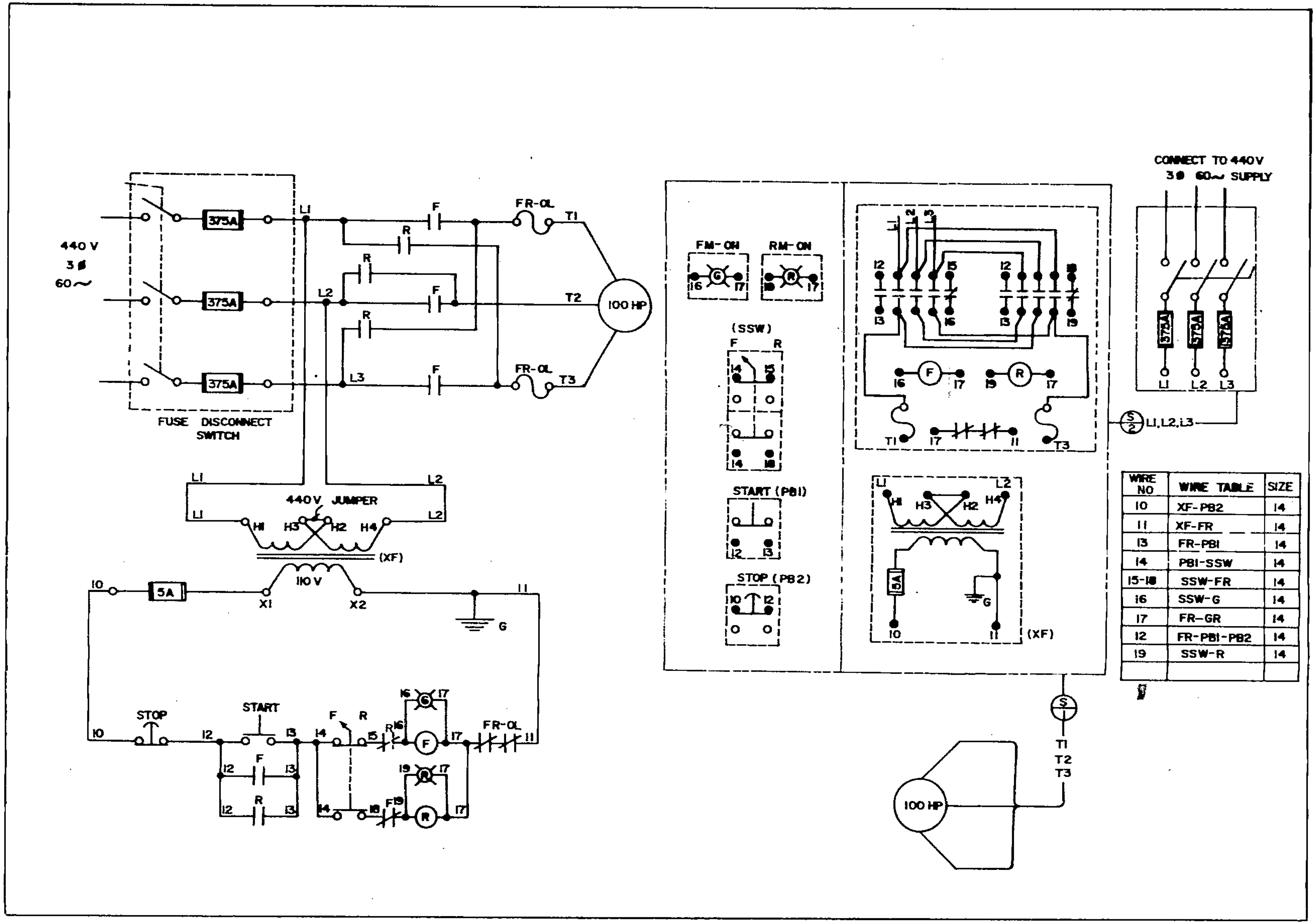
RELATED INFORMATION:

The operation of some industrial machines requires that direction of rotation of a squirrel-cage motor be reversed. Since the reversing of a three-phase motor requires the interchanging of any two of the three line leads, special motor starters are manufactured to accommodate this requirement. *Fig. 74* shows an elementary diagram of a controller using this type of starter. When the three main REVERSE contacts are closed, the phase sequence at the motor leads is different from that when the three main FORWARD contacts are closed. Two of the line leads are interchanged when the REVERSE contacts are closed. For example, in forward positions, (L_1) is connected through the (F) contact and overload heater to (T_1). In reverse position, (L_1) is connected through the (R) contact and overload heater to (T_3), thereby changing the lead. A similar change takes place at (L_3). (L_2) is always connected to (T_2), as contacts (F) and (R) are connected in parallel on this lead.

Reading the diagram, we see that there is a disconnect switch connected between the power supply and the reversing starter main contacts. SAFETY SWITCHES or disconnect switches are manually operated switches that are used to isolate or disconnect branch circuits from the power supply, thus allowing the motor or controller to be serviced or repaired without cutting off the power to other machines.

Basically, a disconnect switch consists of a single to four-pole single-break snap acting knife switch. Disconnect switches are available with or without provision for short-circuit protection for the power supply. However, the fusible type or the more expensive circuit-breaker type are normally used.

Next are the normally open main contacts of the reversing starter. Two sets of starter contacts are connected to the motor through overload heaters and one set is not. When you consider that two phases function as the return for the other, all leads are being protected from overload currents. Most starter manufacturers supply starters with only two overload relays; however, the third will be supplied on request. Also, since the forward and reverse contacts are both controlling the same motor, it is not necessary to switch to other overload relays with a different size heater installed. A reversing starter consists of two contactors that are mounted on a single mounting plate, each connected to a common set of overload relays. Usually reversing starters are provided with a mechanical interlock. These are so arranged that once the contacts of one contactor are closed the other will be physically prevented from closing its contacts. Both electrical and mechanical steps are taken with starters in order to prevent short-circuiting the power supply.



WIRE NO	WIRE TABLE	SIZE
10	XF-PB2	14
11	XF-FR	14
13	FR-PB1	14
14	PB1-SSW	14
15-18	SSW-FR	14
16	SSW-G	14
17	FR-GR	14
12	FR-PB1-PB2	14
19	SSW-R	14

Fig. 74

The power supply rating for this installation is 440 volts, 3 phase, 60 cycles. This voltage could cause the machine operator serious injury, so the controller has been supplied with a step-down transformer (XF). This is a single-phase transformer, as all a.c. magnetic switches operate on single-phase current. SINGLE-PHASE CURRENT MAY BE OBTAINED FROM A THREE-PHASE SUPPLY BY CONNECTING TO ANY TWO OF THE THREE SUPPLY LEADS. In this case connecting the primary of the transformer to L_1 and L_2 will provide the primary with 440 volts, single-phase 60-cycle current. The secondary of the transformer will reduce the voltage to 110 volts, single-phase, 60 cycles. The lower voltage plus the isolation from the power supply provided by the transformer, provides a much safer condition for the machine operator. The transformer offers short-circuit protection with a fuse and fuse holder that is mounted on the transformer.

The selection and energization of the correct operating coil is controlled by push-buttons. This type of manually operated switch is usually of the momentary-contact double-make, double-break contact arrangement. It includes a combination of both, as in the FWD-REV. switch. The STOP and START switch is of the momentary-contact type, which means that the contacts will change their condition only while the button is being pushed and return to the normal condition as soon as the button is released. The FWD-REV switch is a TWO-POSITION SELECTOR SWITCH.

A selector switch is a maintained-contact switch that is used to shift circuits in sequence. When the FWD-REV switch is in the FWD POSITION, the STOP and START buttons are shifted so as to control the (F) contactor operating coil. Moving this switch to the REV POSITION will shift the STOP and START buttons so as to control the (R) contactor.

Operation of the controller is as follows:

I. Manually closing the safety switch contacts will connect the power supply to the controller.

II. Operation in the FORWARD direction.
   a. Selector switch is placed in the forward position.
   b. Pushing the START button connects the (F) contactor operating coil and the GREEN indication light to the control-circuit power supply through the normally closed STOP switch, manually closed START switch, maintained-closed FWD-REV switch contact, normally closed (R) auxillary contact and, on the return side, the normally closed overload contacts (FR-OL). Energization of the (F) contactor operating coil causes all of the normally open (F) contacts to close and the normally closed (F) contact to open. The closing of the (F) main contacts causes the motor to rotate in the forward direction. Closing the (F) holding contact seals the circuit around the START push-button so that the machine operator may release it. The opening of the normally closed (F) contacts prevents the energization of the (R) contactor coil, thus providing an ELECTRICAL INTERLOCK.
   c. The machine may be stopped in any of the following ways:
      1. The motor is normally de-energized by pressing the STOP push-button.

Since this contact is in series with the (F) contactor coil it will become de-energized, opening all of the (F) contacts and returning them to the normal condition. This disconnects the motor from the supply and interrupts the holding circuit around the normally open START push-button contact. The control is returned to the OFF condition.

2. Blowing a fuse in the main disconnect switch will return the controller to the OFF condition. The fuses in series L_1 and L_2 would immediately de-energize the control circuit, thereby disconnecting the motor from the power supply. Blowing the fuse in one of the line leads would bring about a condition that is called SINGLE-PHASING. Since only two line leads would be connected to the motor, it would continue to rotate as a single-phase motor at greatly reduced power. The excessive current that would flow under this condition would eventually cause the overload heaters to trip one of the overload relay contacts. The opening of the series-connected (FR-OL) contact would return the controller to the OFF condition. Once stopped, the motor could not be restarted. A SINGLE-PHASE INDUCTION MOTOR IS NOT SELF-STARTING, WITHOUT SPECIAL PROVISIONS. Unless the condition was corrected, the excessive current drawn by the motor would keep tripping the overloads, returning the control to the OFF condition each time.
3. Blowing the fuse in the transformer (XF) secondary circuit would return the control to the OFF condition, by de-energizing the starter operating coil. The machine could not be restarted until the problem had been corrected.
4. Changing the selector switch from the position that it was in when the motor was started will return the control to the OFF condition, by de-energizing the starter operating coil previously selected. The operating coil for the opposite direction would be prevented from being energized by the electrical and mechanical interlocks on the reversing starter.

III. Operating in the REVERSE direction.

a. Place the selector switch in the REVERSE position.
b. Pushing the START button connects the (R) contactor operating coil and the RED indicator light to the control-circuit power supply, through the normally closed STOP switch, FWD-REV switch contact, normally closed (F) auxiliary contact and, on the return side, the normally closed overload contacts (FR-OL).
c. Stopping in the REVERSE direction is identical to FORWARD except that it is the REVERSE contactor that is de-energized.

QUESTIONS:

1. How is the direction of rotation of a three-phase induction motor reversed?
2. What is a SAFETY SWITCH?
3. Why are safety switches used?
4. What is the purpose of making safety switches snap-acting?
5. Explain the use of fuses in a safety switch.
6. Why are at least two and sometimes three of the main contacts of magnetic motor starters connected through overload heaters?
7. What is the reason for supplying only one set of overload relays with two magnetic contactors on reversing starters?
8. How is the closing of both the forward and reverse contacts prevented on these starters?
9. Why has a control transformer been supplied on this control?
10. The control transformer is of the single-phase type; how is the required 440 volt-1PH-60 cycle obtained from the three-phase supply?
11. How is the machine operator protected from the dangerous 440-volt supply e.m.f.?
12. What method is used to protect the control-circuit transformer from the excessive currents that would be caused by a short circuit?
13. Which switch determines the direction in which the motor will rotate when energized?
14. How does using a momentary-contact switch contribute to the under-voltage protection feature of the circuit?
15. Why is the selector switch a maintained-contact switch?
16. What would you do to correct this condition? The motor rotates in the reverse direction when started, but the selector switch is in the forward direction.
17. If you push the START button and the motor hums loudly but will not rotate, what would you suspect is happening?

18. What will happen to this circuit if there is an interruption of voltage?

19. Describe an electrical interlock.

20. How would you go about correcting this condition? With the selector switch in the forward position, the motor will start when the start button is pressed. Releasing the start button stops the motor. If the selector switch is placed in the reverse position the control functions normally.

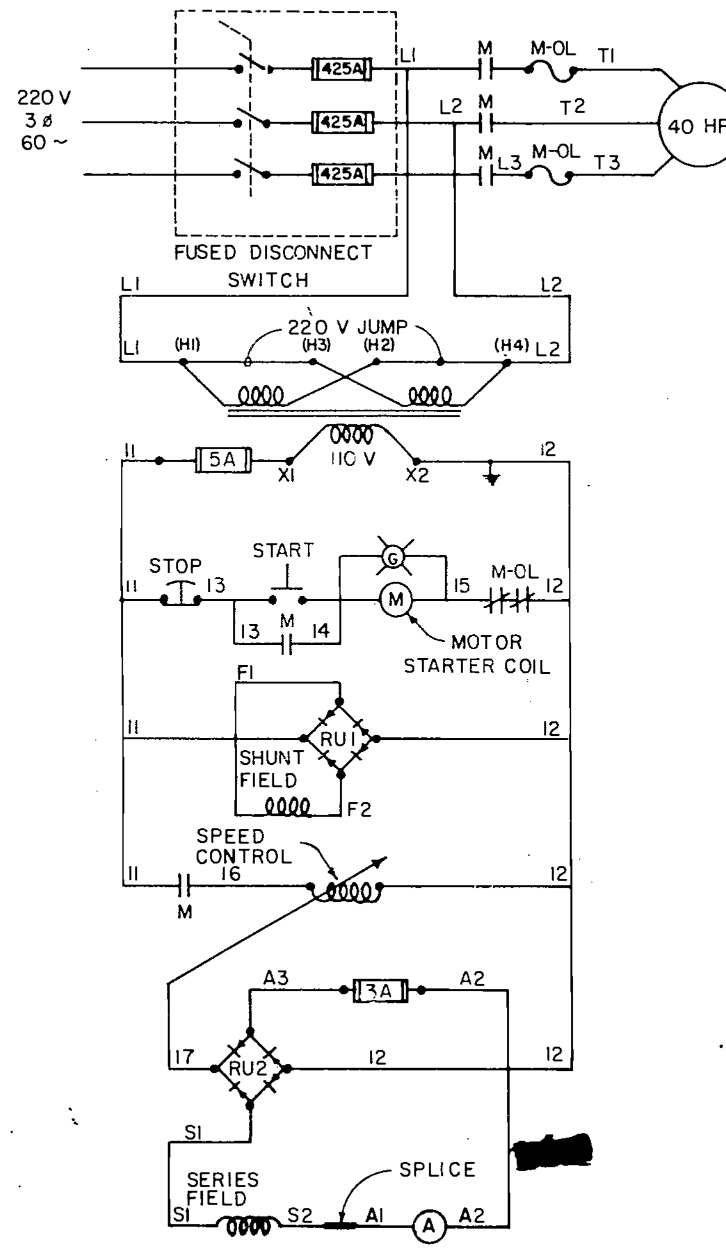
ASSIGNMENT:

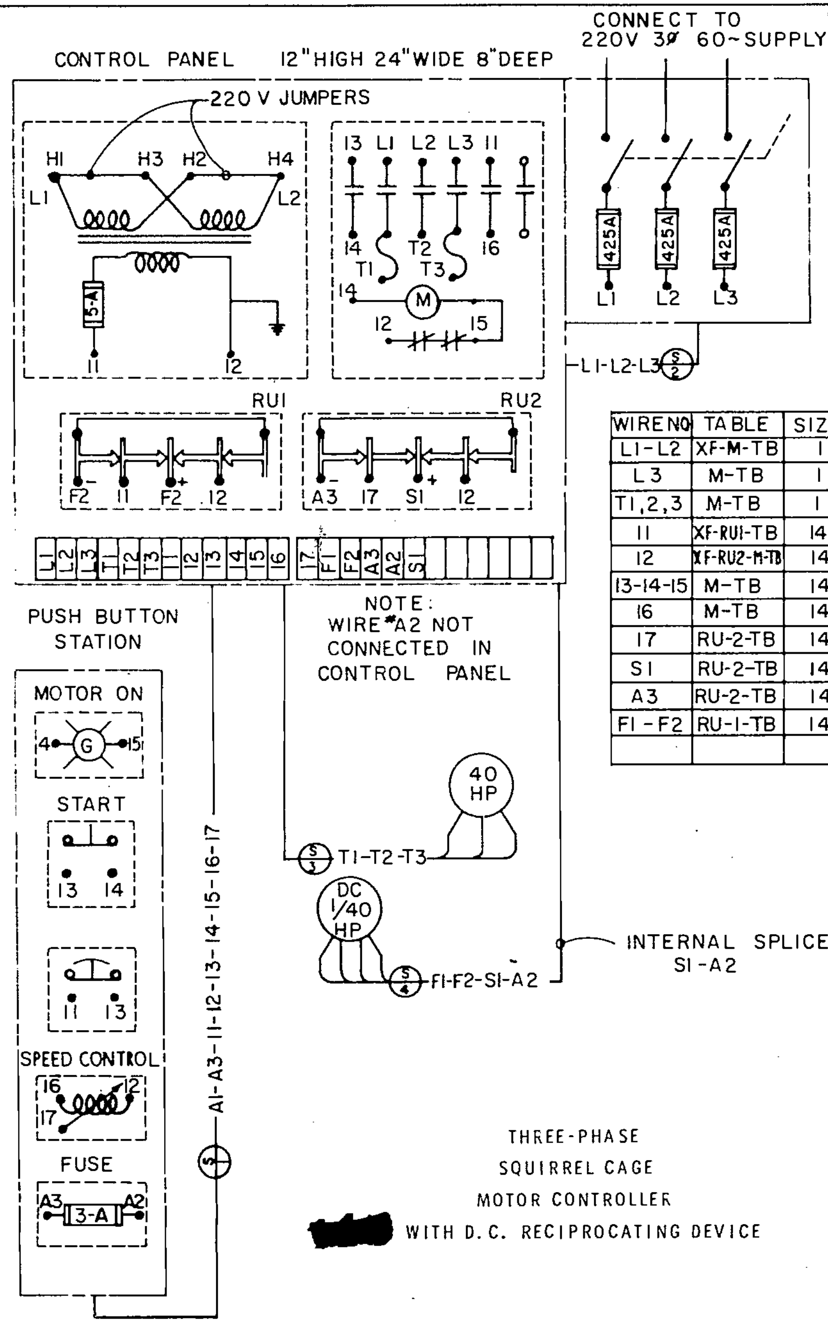
Make separate elementary and connection diagrams to accommodate the wiring diagram shown in *Fig. 74*. Note that in this diagram the switches are mounted in the cabinet door, which is shown in the open position. This means that you are looking at the rear of the switches. Also, you are to indicate all of the wire numbers that are required on the connection diagram.

WIRING DIAGRAMS FOR ADDITIONAL DRAWING PRACTICE

OR

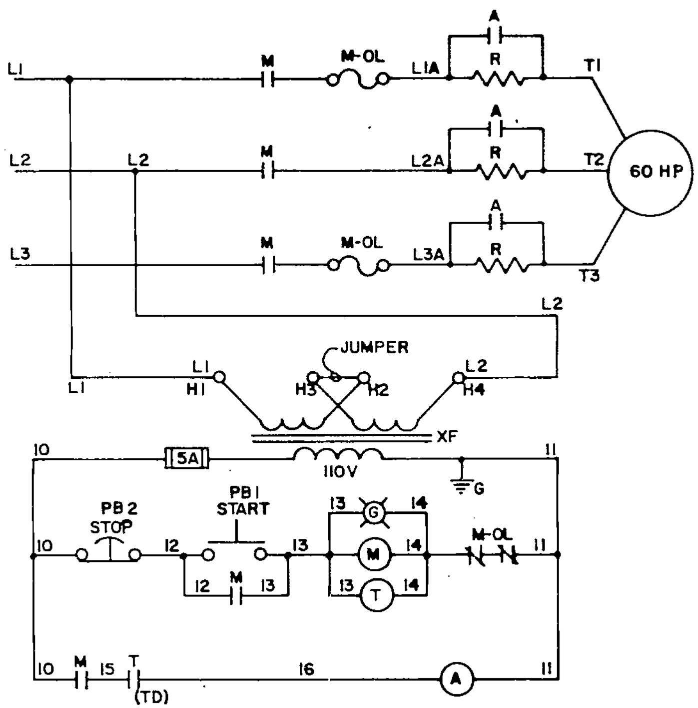
CONTROL INTERPRETATION BY THE ADVANCED STUDENT



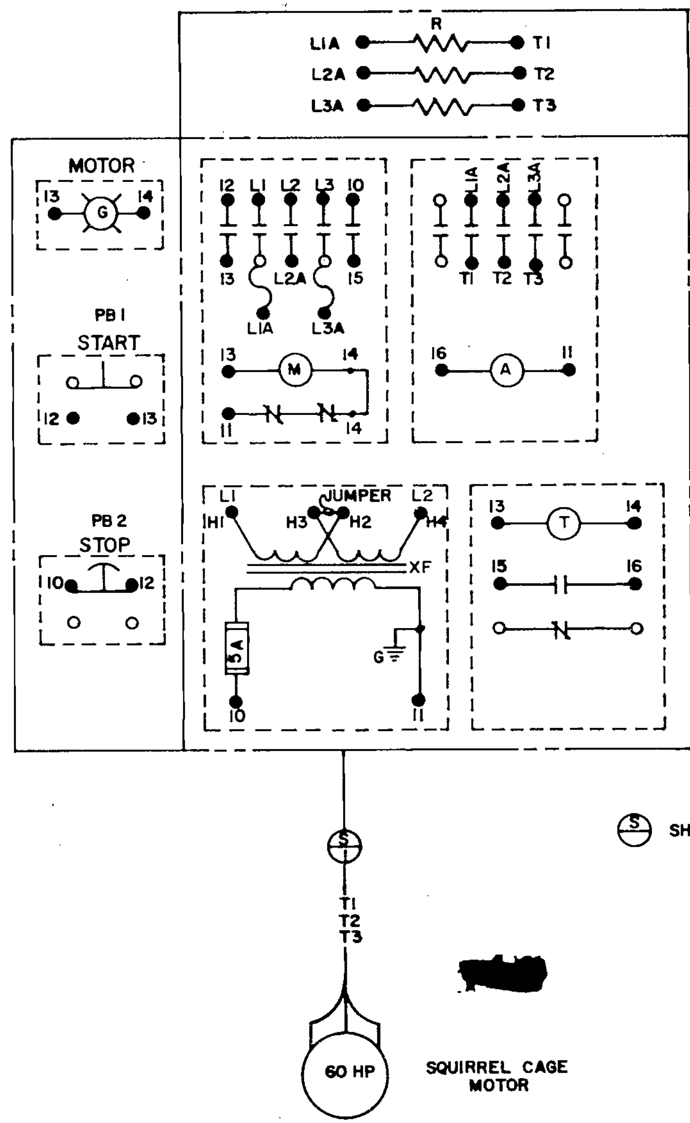


WIRE NO	TABLE	SIZE
L1-L2	XF-M-TB	1
L3	M-TB	1
T1,2,3	M-TB	1
11	XF-RU1-TB	14
12	XF-RU2-M-TB	14
13-14-15	M-TB	14
16	M-TB	14
17	RU-2-TB	14
S1	RU-2-TB	14
A3	RU-2-TB	14
F1 - F2	RU-1-TB	14

THREE-PHASE
SQUIRREL CAGE
MOTOR CONTROLLER
[redacted] WITH D.C. RECIPROCATING DEVICE



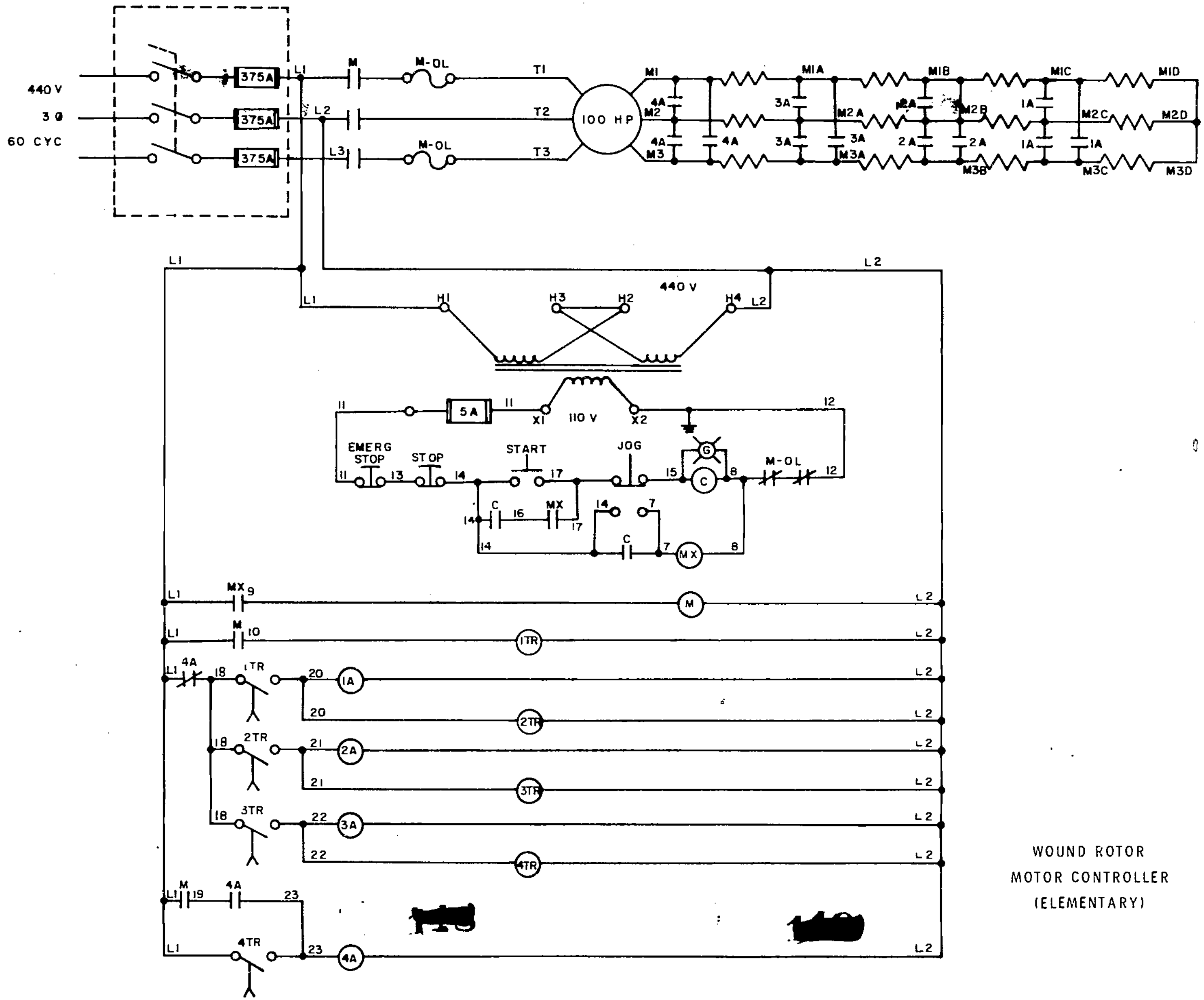
THREE-PHASE
RESISTANCE
CONTROLLER



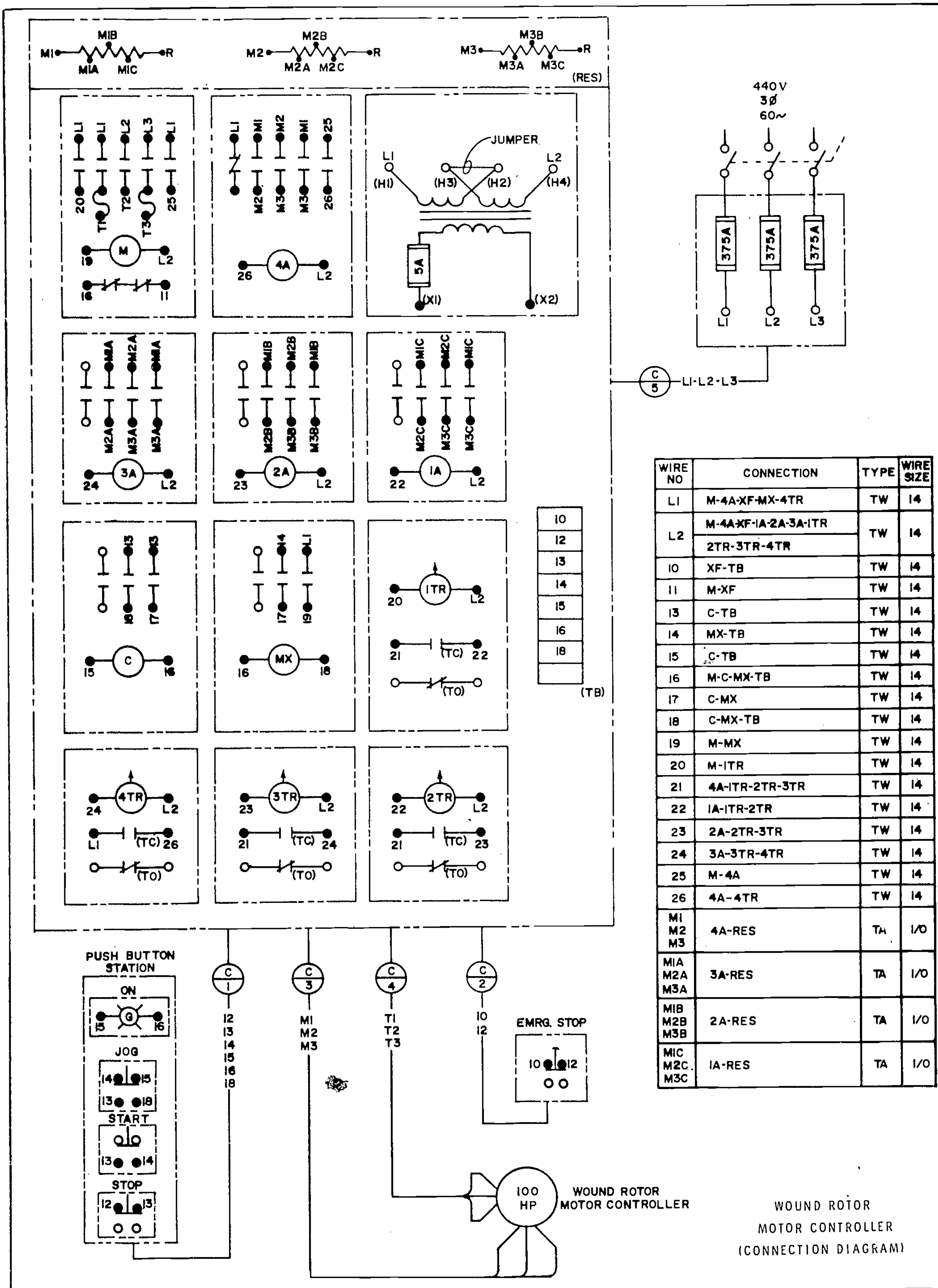
(S) SHOP CONNECTION

SQUIRREL CAGE MOTOR

WIRE NO	CONNECTION	WIRE SIZE
L1A-L2A-L3A	M-A-R	3TA
T1-T2-T3	A-R	3TA
L1-L2	M-XF	3TW
10	M-XF-PB2	14TW
11	M-A-XF	14TW
12	M-PB2	14TW
13-14	M-T-G	14TW
15	M-T	14TW
16	A-T	14TW



WOUND ROTOR
MOTOR CONTROLLER
(ELEMENTARY)



WIRE NO	CONNECTION	TYPE	WIRE SIZE
L1	M-4A-XF-MX-4TR	TW	14
L2	M-4A-XF-1A-2A-3A-1TR 2TR-3TR-4TR	TW	14
10	XF-TB	TW	14
11	M-XF	TW	14
13	C-TB	TW	14
14	MX-TB	TW	14
15	C-TB	TW	14
16	M-C-MX-TB	TW	14
17	C-MX	TW	14
18	C-MX-TB	TW	14
19	M-MX	TW	14
20	M-1TR	TW	14
21	4A-1TR-2TR-3TR	TW	14
22	1A-1TR-2TR	TW	14
23	2A-2TR-3TR	TW	14
24	3A-3TR-4TR	TW	14
25	M-4A	TW	14
26	4A-4TR	TW	14
M1 M2 M3	4A-RES	TA	1/0
M1A M2A M3A	3A-RES	TA	1/0
M1B M2B M3B	2A-RES	TA	1/0
M1C M2C M3C	1A-RES	TA	1/0

WOUND ROTOR
MOTOR CONTROLLER
(CONNECTION DIAGRAM)