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CONNECTING
INDUCTION MOTORS

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CONNECTING
INDUCTION MOTORS

The Practical Application of a Designing Engineer's
Experience to the Problems of Operating Engineers,
Armature Winders and Repair Men. Also the Presentation
to Students of Practical Questions Arising in
Winding and Connecting Alternating Current Motors.

BY

A. M. DUDLEY, B.S. IN E.E. (Michigan)
FELLOW AMERICAN INSTITUTE ELECTRICAL ENGINEERS; MEMBER SOCIETY OF
AUTOMOTIVE ENGINEERS; MANAGER AUTOMOTIVE ENGINEERING
DEPARTMENT, WESTINGHOUSE ELECTRIC AND MANUFACTURING COMPANY

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PREFACE

The material which later developed into this book appeared first in the "Electric Journal" in February, 1916. It was prepared as a general answer to questions which come to the Question Box Editor, regarding Induction Motor Connections and the possibility of making changes to meet varying conditions of voltage, phase, etc. This article came to the attention of Mr. F. A. Annett, Associate Editor of "Power," and at his request was elaborated into a series of articles appearing at intervals from January, 1917, for about 3 years. From the comments on these articles, there appeared to be a justification for a permanent form which is now presented in this book.

Owing to the fact that the articles appeared in this way and without definite plan at the start, the material lacks unity in some details, and also bears evidence of being viewed from a repair standpoint rather than as a book on winding. The author still cherishes the hope that the future may bring time and opportunity for a revision, which will permit a more orderly arrangement. In its present form it is offered for what it may be worth to practical men engaged in operating and repair work. It was these men who were always in mind and for whose use the material was intended.

The author takes this opportunity of expressing his gratitude to the Westinghouse Electric and Manufacturing Company for permission to present the material, and to the "Electric Journal" and "Power" for the use of cuts and material appearing in their columns. He wishes also to express a personal appreciation of the assistance and inspiration afforded by Mr. F. A. Annett, whose interest in the subject made this book possible.

A. M. Dudley.

East Pittsburgh, Pa.,
November, 1920.

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INTRODUCTION

The best text books for students usually are written by those most familiar with the art of teaching; so should the best technical books, for the active workers, be written by those who are in the midst of such work. Otherwise the text is liable to lag behind the actual practice. In the electrical art the growth has been so rapid and the changes in practice so numerous, that only those directly in touch with the many developments are able to tell the up-to-date story. Unfortunately, it is only in rare cases the *doer* is the *teller,* that is, too often he delegates the telling of his work to others, while he continues to *do.* Lack of practice in writing is often back of this. In Mr. Dudley's book we have a very positive exception to the usual practice, for here we have the case of a writer with fourteen years of active practical experience upon which to build his treatment of the subject. Consequently there is a sincerity in the facts presented and a logic in their treatment which appeal strongly to the practical man. The method given for checking phase rotation on a three phase winding, is an example, as is also the table of voltages showing how connections may be changed for any combination of phases and voltages. Since the treatment does represent good engineering practice, it also makes an appeal to the student whose practical experience is still ahead of him.

Like all highly technical subjects, the Induction Motor, in the past, has been treated very completely from the theoretical standpoint, while comparatively little has been published concerning the really practical details, of which the windings are a prominent part. This type of motor, while much later "in the running" than its d.c. rival, has fairly pre-empted the field in general power work. Therefore a practical treatise on the winding characteristics of this apparatus, such as the author has presented, is not only most timely, but is really a practical necessity.

It is with the greatest pleasure that I recommend this work to those who are interested in both the theoretical and practical side of the Induction Motor problem.

(Signed) B. G. Lamme.

CONNECTING INDUCTION MOTORS

CHAPTER I

WHAT THE WINDING ON AN INDUCTION MOTOR ACCOMPLISHES

The simplest conception of any motor either direct or alternating current is that it consists of a magnetic circuit interlinked with an electrical circuit in such a way as to produce a mechanical turning force. A study of the reasons for this force and its results leads naturally to the consideration of the magnetic circuit and the way it is set up and of the electric circuit and the interrelation of the two. It was recognized a long time ago that a magnet could be produced by passing an electric current through a coil wound around magnetic material and the fact was established later that when a current is passed through a conductor or a coil which is situated in a magnetic field there is set up a force tending to produce motion of the coil relative to the field. Since it is equally true that a magnet is most easily produced by an electric current and that an electric current is most easily produced by employing a magnet it is not material which of these elements is considered the more fundamental and the better starting point for study. One thing which becomes apparent is that coils or turns of wire are essential both to the magnetic and the electric circuit and it is the form and combination of these coils in alternating-current motors which is the subject matter of this book.

Functions of the Windings in a D. C. Motor.

In the familiar shunt-wound direct-current motor there are two separate and distinct windings each serving a special purpose. There are the shunt coils on the stator or field member whose function it is to establish the magnetic circuit or "field." There are also the coils on the armature which constitute the electric circuit or the circuit carrying the working current.

In addition to carrying the working current the armature coils are also acting as generator coils and generating a voltage which prevents any more current flowing in the armature than is necessary to produce exactly the required amount of torque. A little consideration shows that this must be the case. The full load current in a 5-hp. 230-volt motor is in the neighborhood of 20 amperes and the resistance of the armature between brushes may be 0.3 of an ohm. Since the armature brushes are put directly across the 230-volt line, if there was no other condition existing except Ohm's law, a current would flow in the armature having a value of $230 \div \frac{3}{10} = 767$ amperes. However, since the full-load current of the motor is only 20 amperes it is evident that only 6 volts are required to circulate this current in the armature and the remaining $230 - 6 = 224$ volts are absorbed or accounted for in some other way. As a matter of fact these 224 volts are taken care of by the armature which actually generates a voltage of 224 volts and opposes it to the line leaving only the difference between 230 and 224 or 6 volts available to force the needed working current through the armature. The name of this voltage generated in the armature is the "back-electromotive force" or "counter-electromotive force" and it is present in the case of all motors of any type whether direct- or alternating-current.

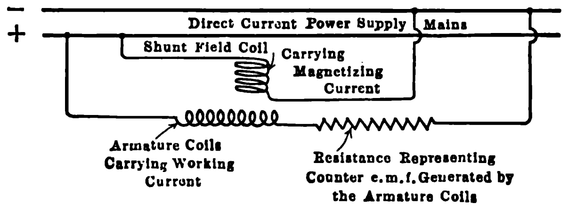

FIG. 1.—Windings of a direct-current motor and their functions.

The foregoing is mentioned to show that on a shunt-wound direct-current motor the windings are exercising three distinct functions, viz., first, the field coils are setting up the magnetic field, second, the armature coils are carrying the working current and, third, the armature coils are generating a voltage which is opposed to the line voltage and which determines how much working current may flow in the armature and hence, directly, how much torque will be produced.

This condition is shown diagrammatically in Fig. 1 where the shunt-field coil is shown setting up the magnetic field and the armature coils carrying the working current. The counter-electromotive force which is generated by the armature coils is represented as a resistance in series with the armature since its action is to cut down the amount of current which would otherwise flow in the armature.

Synchronous Motor.

In an alternating-current motor of the synchronous type there are also two windings exercising these same three functions, viz., first, the direct-current winding serving to set up the magnetic field, second, the alternating-current winding carrying the working current and, third, the alternating-current *winding generating* the counter-electromotive force nearly equal to the applied line voltage.

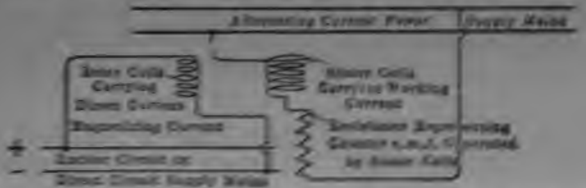

FIG. 2.—Windings of an alternating-current synchronous motor and their functions.

The condition is represented by the diagram, *Fig.* 2, which shows the magnetic-field circuit as separately excited from a direct-current source of supply. The stator winding or alternating-current winding is shown as carrying the working current and in addition generating the counter-electromotive force which is represented as a resistance in series with it.

Induction Motor.

In the case of the alternating-current induction motor there are again two windings, one in the stator and one on the rotor and these two windings are again exercising the same three functions but with a slight difference which is well worth noting. The rotor winding or secondary winding of a polyphase induction motor carries the working current. Since in this type of motor there is no electrical connection between the stator and rotor windings the only manner in which this current can be set up in the rotor is by transforming it from stator to rotor using the transformer action of the primary upon the secondary. This, then, sets up in the primary or stator winding the very interesting condition that in one single winding or set of coils there exist three separate actions. First, the magnetizing current is flowing and setting up the magnetic field just as it does in the shunt direct-current or synchronous alternating-current motor; second, the working current is flowing and being transformed into the rotor and, third, there is a generator action taking place in the coils and generating a back or counter-electromotive force opposite in direction and slightly less in amount than the applied line voltage.

This condition is shown graphically in the diagram of Fig. 3 where the three separate actions are indicated and shown to be similar to the corresponding items in Fig. 1 and Fig. 2.

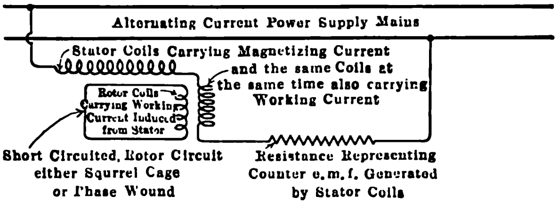

FIG. 3.—Windings of an alternating-current induction-motor and their functions

Since these three conditions do exist in the single winding it becomes evident that when changes in operating conditions occur such as are covered by reconnecting a winding for different phases and different speeds, etc., all three of these conditions must be satisfied if the operation of the motor is to be normal. That is to say, the cross section of the conductor in the windings must be great enough to carry the combined magnetizing and working current; the number of turns must be correct for setting up the required magnetic field and the combination of magnetic field and number of turns in the armature working together must generate the required counter-electromotive force, which in all cases is just slightly less than the applied line voltage. This also shows the reason why one of the simplest methods of figuring how many turns are required in the winding of a given motor is to consider it as an alternating-current generator rather than as a motor. This method is frequently referred to throughout the text and an effort made to have it appear as a physical picture of what is going on inside the motor rather than as a set of mathematical formulæ or an involved vector or circle diagram.

CHAPTER II

THE ROTATING MAGNETIC FIELD

Why a Motor Drives its Load.

An induction motor rotates and drives its load because there exists inside the motor a magnetic field which rotates and pulls the iron of the rotor core and the rotor windings around with it. This magnetic field has a number of north and south poles and in its effect resembles several bar magnets riveted together in the center and spaced radially like the spokes of a wheel. The discovery that such a magnetic field could be established in an iron core and made to rotate by exciting a winding with alternating current is what made possible the development of the induction motor. With the proper conception of how this field is set up and caused to rotate and its effect upon the windings of the motor as it rotates it is easier to understand the working of the motor and also to form an opinion of the possibility of accommodating the motor windings to changes in operating conditions. It is the intent of this chapter to give a physical idea of the rotating magnetic field followed by a graphical explanation of how it is set up by alternating current.

How Torque is Produced.

It is now generally understood that an electric motor produces torque or driving effort by utilizing the effect of a magnetic field upon a wire, or wires, which are carrying electric current. It is also understood that a magnetic field may be produced in an iron circuit by passing an electric current through a coil which surrounds or is interlinked with that iron circuit. The action of producing driving effort in a direct-current motor then becomes very simple. First the magnetic field is set up by passing a direct current through the field coils surrounding the poles. This direct current is drawn from the same source of supply that is to drive the motor. When the magnetic field is set up, another direct current is drawn from the source of supply and caused to flow through the armature coils which lie in the magnetic field just previously set up. The action of the magnetism of the field on the current in the armature wires causes the rotor to develop torque and start to turn.

The foregoing is elementary and exactly the thing that happens in the alternating-current motor, but in a little different way. In the direct-current motor just noted, two sets of coils were used. The first set—the field coils—was used to excite the magnetic field; the second set was the armature coils and was used to carry the working current. In the induction motor there is but one set of coils, which must at the same time exercise the two functions of setting up the magnetic field and carrying the working current. This fact is chiefly responsible for the condition in the motor which is called power factor and which is not present in the case of the direct-current motor.

It is worth while to consider as simply as possible the manner in which the magnetic field is set up in the induction motor and the reason it travels around the machine at a relatively high rate of speed.

Long before the days of Tesla and Feraris, it was known that if a magnet was passed over a sheet of copper close to its surface, a force was produced which tended to cause the copper to move in the same direction as the magnet. Although not then so recognized, this was the fundamental principle on which all modern dynamo-electric machines are based. The contribution that Tesla and Feraris made was the discovery that such a moving magnetic field could be set up by an alternating current and need not rely on a permanent magnet or one excited by direct current.

Setting up a Rotating Magnetic Field by Alternating Current.

The matter of setting up such a field by alternating current and causing it to move can be shown by a few simple figures. Figure 4 is a cross-section through a direct-current machine. It shows an outside field yoke with inwardly projecting field poles with a coil around each polepiece through which a direct current is flowing. The usual convention is adopted to show the direction of the field current by marking the conductors with a dot when the current is flowing toward the observer and with a cross when it is flowing away. The armature is shown by the inside circle carrying the conductors *C* on its periphery; in practice these conductors would be connected to a commutator. The magnetic field itself is represented by the dotted lines passing from one pole into the armature and out through adjacent poles, as indicated by the arrows.

Direct-Current Analogue.

If now, contrary to the usual practice, the machine is suspended by means of the shaft projecting on either side and the armature held from turning by clamping the shaft, it would be possible to take hold of the field frame and rotate it around the armature. Mechanically such a rotation would not interfere with the usual electrical functions of any of the parts of the machine since the brushes would bear on the commutator as usual and move relatively to the polepieces, the only difference being that now the commutator is standing still and the brushes are moving.

Going a step farther, if the field was driven mechanically at a fair rate of speed around the armature, this inverted direct-current machine would give a very fair representation of what is going on inside an induction motor. So far as the rotating magnetism is concerned, it is just as surely present in the one case as in the other and with just as plainly marked north and south poles. The difference is that in the induction motor the magnetic field alone rotates and the iron core with the windings stands still, while in the case of the inverted direct-current machine described, the iron core and the field coils are going around with the magnetism.

The picture that the foregoing is intended to bring out is that in any running induction motor a well-defined magnetic field is actually rotating in the stator exactly the same as would be the case if we excited a field of equal strength by direct current and rotated it mechanically. The manner of setting up this field by alternating current instead of direct current and making it rotate electrically instead of driving it mechanically is explained in Figs. 5 to 8.

Figure 5 shows the same machine as Fig. 4 except that it is developed or rolled out flat the better to illustrate the point. Suppose, for example, that it is desired to set up a magnetic field as shown and cause it to travel from right to left in the direction of the arrow. One method of doing this would be to excite the pole marked No. 1, Fig. 5, with direct current to produce a south pole as shown; a fraction of a second later No. 1 could be cut off and No. 2 made a south pole; after the same interval of time No. 2 could be cut off and No. 3 excited south; followed, in

Fig. 4.—Cross section of a d.c. machine showing the magnetic field.

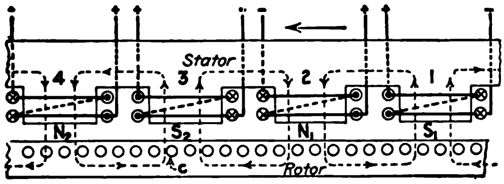

Fig. 5.—Development of Fig. 4.

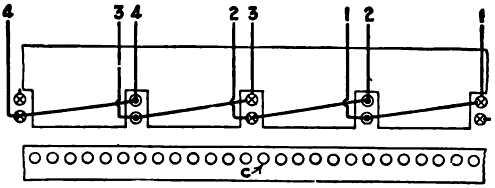

Fig. 6.—Simplest form of four-pole single-phase winding.

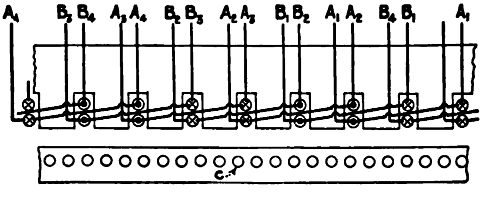

Fig. 7.—Two-phase winding equivalent of Fig. 6.

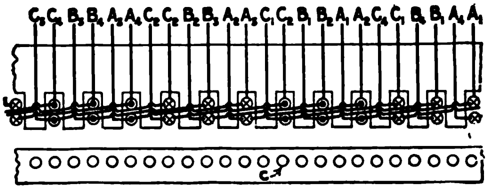

Fig. 8.—Three-phase winding equivalent of Fig. 6.

How the magnetic field rotates in an induction motor.

turn, after the same interval again, by cutting off No. 3 and exciting No. 4. Thus a south pole would have traveled regularly and steadily from right to left as desired. But this is using direct current.

An analysis of what really happened shows that while No. 1 was excited as a south pole, No. 2 might just as well have been excited as a north pole since the magnetism to flow into No. 1 and make it south must flow around and out of No. 2, as shown. This is indicated by the dotted lines, which represent the magnetic field. At this instant, then, coil No. 1 would be excited minus and plus and No. 2 excited plus and minus, as shown. However, the next instant, when No. 2 is to be made a south pole, this excitation would have to be reversed to minus and plus, and an instant later, when No. 3 becomes a south, No. 2 can again be a north and the excitation would again reverse to plus and minus. Consideration of any particular coil in this way shows that each time the field moves forward one pole, the excitation of all the poles changes in direction and consequently each pole might quite as well be excited by alternating current, which in effect is really rapidly reversing direct current.

The Frequency of an Alternating Current.

The rapidity of these reversals or the so-called frequency of the alternating current would depend on how rapidly the field was expected to advance a space represented by the distance from center to center of adjacent poles. And this is exactly what happens: If the motor has four poles the field will have to advance four times to make one complete revolution around the motor, and if it is desired that the field shall make 1,800 r.p.m., there will be required 4 × 1,800 = 7,200 reversals. This is readily recognized as the sixty cycles of the commercial alternating-current circuit. Conversely, since the r.p.m. of the motor roter is nearly that of the magnetic field, if 60-cycle current is available and power is wanted at 1,800 r.p.m. or thereabouts, a four-pole motor is required.

From the foregoing it might appear that single-phase alternating current for excitation is all that is needed, and for this reason Figs. 6, 7 and 8 are shown. Since Fig. 5 is a direct-current structure, the field would progress by jumps and hitches from pole to pole around the machine rather than steadily and evenly; hence, in Fig. 6 the slot between poles is reduced to the size of an armature slot, of which the necessary number are evenly spaced around the machine. Also, for simplicity the field coils are shown gathered into one coil per pole.

In Fig. 6 the step from pole to pole is still rather wide, so that in Fig. 7 coils are introduced halfway in between and these are excited by a second alternating current which is just as much behind the first one in time as it takes the field to travel one-half a pole, and such an arrangement of two alternating currents is called two-phase. Similarly, if desired, three currents could be used, as shown in Fig. 8, and this would represent the well known three-phase arrangement.

From this explanation it must not be gathered that in the case of the two-phase there are two rotating fields and three in the case of three-phase. This would be true if the two currents or three were acting entirely independently, but they are not—they are all trying to excite the same iron circuit and the actual resultant magnetism at any instant is due to the combination. In other words, since one current is ahead or behind the others by a fraction of a pole, the currents in the different phases have different values at any given instant. In the case of three-phase one may be zero, the second be increasing and be equal to one-half its maximum value, and the third be decreasing and be actually at one-half its maximum value. Since these three currents are all acting on the same iron circuit, the magnetic field which actually exists at that instant is due to the resultant of the three currents. Thus the resulting field looks exactly like the field in Fig. 4, which was set up by direct current, and it travels around the stator iron just as did the field in the mechanically rotated direct-current machine.

The Counter-Electromotive Force.

Having considered the manner of setting up the field and causing its rotation, there is another action, easily understood, which is perhaps as useful as any in giving a clear idea of how many turns are required in a motor winding under different conditions. This is what is called the generation of the counter-electromotive force. Since the coils of the motor are standing still and the magnetic field is rotating past them and threading through them, there is of necessity a voltage generated in the coils by the rotating field. This is the voltage which is referred to as counter-electromotive force and is in all cases equal to the voltage of the supply line which is applied to the motor, except for a small loss in the motor caused by producing the necessary torque or driving force.

With this conception and the fundamental formula for the generation of an electromotive force, it is a simple matter to write expressions showing how the turns in a motor should vary with different line voltages and for different speeds, etc. For example, a motor to operate on 440 volts must have twice as many turns in the coils as the same motor when operating on 220 volts, and a motor operating at 900 r.p.m. in general would require twice as many turns as the same motor when operating at 1,800 r.p.m. These are matters with which the designing engineer is chiefly concerned, but they are sufficiently simple to be borne in mind at all times, and in themselves offer the readiest first-hand answer as to the probable result of operating a given motor under changed conditions.

Having in mind this physical conception of the rotating magnetic field the next step is to be able to draw a picture of this field as it would look if it might be arrested in space at any instant and photographed. This can be most easily accomplished by the simple graphical method explained below and sometimes called "stair-step" pictures. By means of this method the rotating magnetic field can be explained and studied and the readiest possible answer given to such questions as, *Why does reversing two leads of a three-phase motor reverse its direction of rotation? Why is a phase-wound rotor always three-phase, whether the stator is for two-phase or three-phase? Also* such questions as the effect of chording the coil and changing the number of poles are readily analyzed.

The confidence that will be gained in the understanding of induction-motor operation and troubles will well repay the amount of study required to master it, and the amount of electrical knowledge required is not so great as to discourage anyone who has even a speaking acquaintance with alternating current and its behavior. No claim is made that this is a new method. This is how it applies, for example, to a three-phase problem:

Method of Building the Magnetic Field from Pictures.

In each of the three wires of a three-phase circuit which is carrying load is an alternating current which several times a an armature slot, of which the necessary number are evenly spaced around the machine. Also, for simplicity the field coils are shown gathered into one coil per pole.

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The confidence that will be gained in the understanding of induction-motor operation and troubles will well repay the amount of study required to master it, and the amount of electrical knowledge required is not so great as to discourage anyone who has even a speaking acquaintance with alternating current and its behavior. No claim is made that this is a new method. This is how it applies, for example, to a three-phase problem:

Method of Building the Magnetic Field from Pictures.

In each of the three wires of a three-phase circuit which is carrying load is an alternating current which several times a second increases from zero to a maximum value in one direction, decreases to zero and increases in the opposite direction to a maximum value and again decreases to zero, thus completing one "round trip," which is called a "cycle." If a pencil could be attached to this current and a piece of paper be drawn under it as the current rose and fell, after the manner that indicator cards are made on a steam engine, its "card," or curve, would have the characteristic shape shown in Fig. 9. Here it will be noticed that the time in fractions of seconds is along the horizontal line *XX* and the value of the current in amperes is along the vertical line *YY*.

All three currents of a three-phase circuit will trace a similar card to that in Fig. 9, but they do not all reach a maximum at the same instant nor pass through zero at the same instant, but are evenly spaced the same distance apart at all times so that if the indicator be connected to all three lines at once, the combined card would be that shown in Fig. 10 where *A* is the card for phase 1, *B* for phase 2 and *C* for phase 3. The values above the *XX* line are considered plus and the values below the line negative. It is the evenly spaced coils in the alternating-current generator winding that keep the current in all three phases of equal value and with a constant spacing with regard to each other.

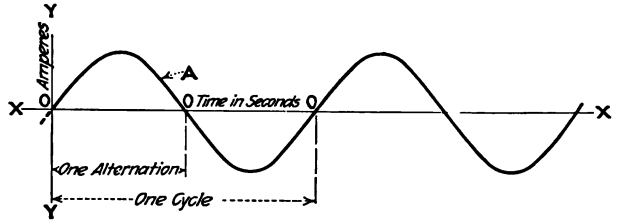


FIG. 9.—The "indicator card" of a single-phase alternating current.

Assume that each one of the three-phase lines is wound an equal number of times around the same iron bar, as in Fig. 12. Whenever a coil is placed around iron and current flows in the coil, it sets up magnetic lines, or flux, and the iron becomes a magnet. It is evident, then, from Fig. 12, that any one of the three coils by itself would make a magnet of the iron bar which would have its north pole at one end at one instant and a south pole at the same end the next instant as the current changed its direction according to the curve in Fig. 9.

However, when all three coils work together on the bar (Fig. 12) there is no magnetism set up, because at any instant the current in one coil is equal in amount and opposite in direction to the currents in the other two coils. This can be seen from Fig. 10. Take, for instance, the time marked by the vertical line 1. At this instant the A and C phases are measured above the horizontal line XX and hence are positive or plus in value and are each equal to $+0.5$, while the B phase is measured below the X line and hence negative or minus value to -1. Therefore, the sum of all three currents is zero because $+(0.5 \times 2) - 1 = 0$.

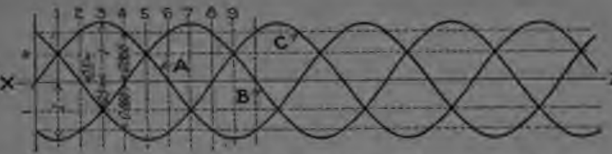


FIG. 10.—Sine wave representation of three-phase alternating current.

At the instant 2, $C = 0$, $A = +0.866$ and $B = -0.866$ and the sum of the three currents is zero. At instant 3, $A = +1, B = -0.5$, and $C = -0.5$, total $= 0$; at the instant 4, $A = +0.866, B = 0$ and $C = -0.866$, total $= 0$; and so on at all points the sum of the three currents is zero. Therefore in Fig. 12 there will be no magnetism in the iron bar, since at all times there is an equal number of ampere turns in the coils trying to force the magnetism in each direction.

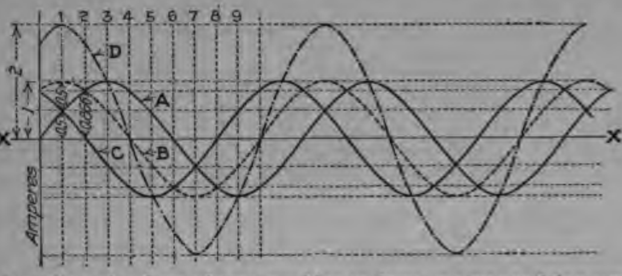


FIG. 11.—How the three phases combine to form one magnetizing current.

The next step is to reverse one coil, as shown at B in Fig. 13, and the bar immediately becomes a strong magnet, reversing its poles from instant to instant according to the change in direction of the curve D in Fig. 11. Reversing one coil in Fig. 13 is the equivalent of reversing the current in one phase of the generator. This is indicated in Fig. 11, in which curve *B* is shown plotted above the line where it is below the line in Fig. 10, and vice versa. The sum of the three curves *A*, *B* and *C*, Fig. 11, gives a resultant curve *D*, which represents the current that will be effective in magnetizing the core, Fig. 13. It will be seen that the *A* and *C* curves in Fig. 11 are the same as in Fig. 10, but the *B* curve is turned over, or reversed, since the *B* coil is reversed in Fig. 13. Curve *D*, Fig. 11, is obtained by adding the values of the three currents at any point. For example, at the time marked by the vertical line, 1, $A = +0.5$, $C = +0.5$ and $B = +1$, hence $D = +2$. At the time marked by the vertical line 3, $A = +1$, $B = +0.5$ and $C = -0.5$, hence $D = +1$. Also at time 4, $A = +0.866$, $B = 0$ and $C = -0.866$, hence $D = 0$. In this manner the curve *D* is obtained, and it serves as an indicator card of the magnetism in the iron bar in Fig. 13.

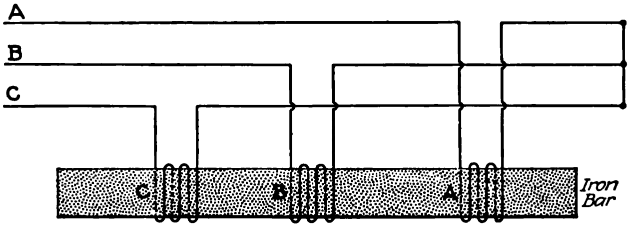


FIG. 12.—Iron bar acted upon by three-phase currents as arranged in Fig. 10. No resultant magnetism.

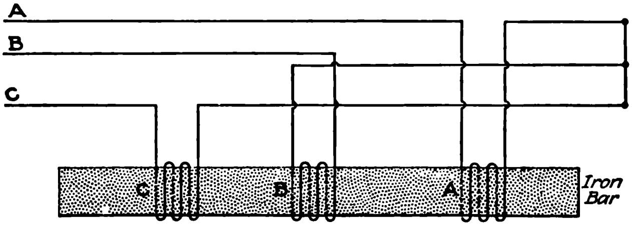


FIG. 13.—Iron bar acted upon by three-phase currents as in Fig. 11. Strong resultant magnetism alternately north and south.

Setting up a Magnetic Field with Three-Phase Currents.

This conception of three-phase coils making a magnet whose flux or field varies in value and direction according to the curve *D* in Fig. 11 can be readily transferred to the stator of an induction motor, as shown in Fig. 14. Here is shown part of a laminated core slotted on the inner periphery, and in two of these slots are shown three coils, *A*, *B* and *C*, to correspond to the coils in Fig. 13. Assume the three coils to be connected in star and to a three-phase circuit. A magnetic field will then flow into the air gap and back through the core, as shown by the curved dotted lines and arrowheads. This magnetic field will flow in the direction of the arrows for a fraction of a second, then fall to zero, and increase to a maximum in the direction opposite to the arrowheads, and so on. In other words, the three coils working together would make first a north pole and then a south pole on the inner periphery, and repeat, and the amount and direction of the magnetism in the iron between the two sides of the coil could be measured by taking the distance from points on the curve *D*, Fig. 11, from the horizontal reference line and calling all points above that line north values and below the line south values.

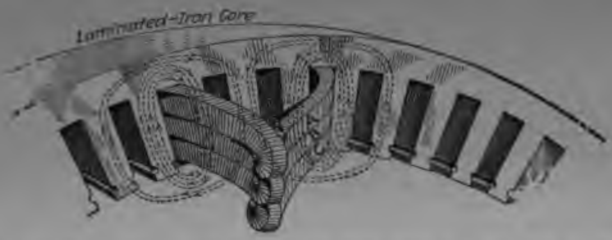


Fig. 14.—Cross-section of stator core with three coils similar to Fig. 13.

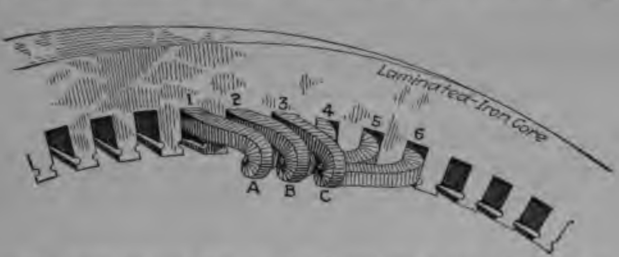


Fig. 15.—The three coils of Fig. 14 distributed as in normal induction motor.

For example, at the position marked 1 the magnetic value would be a maximum north value, at 3 it would be 0.5 north, at 4 zero, at 5 it would be 0.5 south, and at 7 a maximum south value, and so on. There would be no tendency, however, for this magnetic field to rotate or travel around the stator as it does in an induction motor. It would simply stand still in space and alternate backward and forward through the coil as described. In order to get the rotating motion, it will be necessary to separate the three coils and put each one in a separate slot, as shown in Fig. 15, as they would be in any normal induction motor.

A section cut through the core and coils, Fig. 15, is shown in Fig. 16 with one side of each coil in the bottom of slots 1, 2 and 3 and marked *A*, *B*, *C*, respectively, and their other sides in the top of slots 4, 5 and 6 and marked *A′*, *B′*, *C′*, respectively. By means of Figs. 11 and 16 taken together, it is possible to build up small pictures of the magnetic field from instant to instant and show how it moves or rotates around in the stator core and air gap. These small pictures, of which one series is shown in Fig. 17 and another in Fig. 18, can be very well compared to the individual small pictures on a moving-picture film as they appear when the film is at rest, and the rotating magnetic field as it really exists could be compared to the same film when in motion and thrown on the screen. The method of making these small pictures is very simple and is as follows:

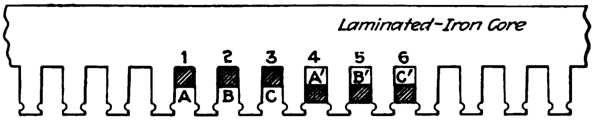


Fig. 16.—Cross-section of core and winding in Fig. 15.

Drawing a Graphical Picture of the Magnetic Field.

At the top of Fig. 17 is a section through the coils and core, Fig. 15, the same as that given in Fig. 16. A current is assumed to be flowing in each coil, and the value of that current is taken from the curve marked with the same letter in Fig. 11. For example, at the time represented by the vertical line 1 in Fig. 11, curve *B* is at its maximum value, which is called +1, because it is above the horizontal reference line, and curves *A* and *C* are each at a value of +0.5, since they are half their maximum value and are also above the reference line *XX*. Similarly, at the time represented by the vertical line 2, which is called position 2, in Fig. 11, the value of the *A* and *B* curves is +0.866 and the *C* curve is zero. The value 0.866 is obtained because these current curves are all what are known as sine curves and the reference points or positions 1, 2, 3, etc., are taken $\frac{1}{12}$ of a complete cycle apart.

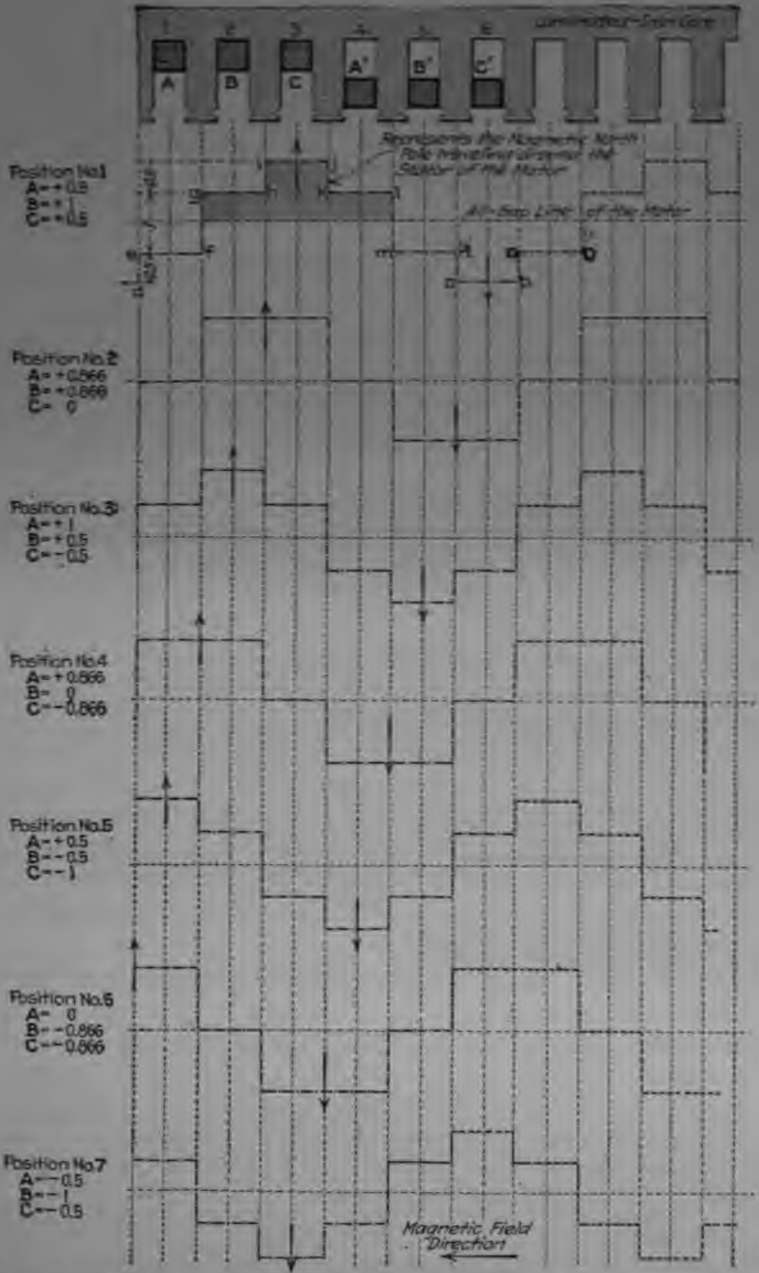


FIG. 17.—Instantaneous values of the magnetic field set up by the coils of Figs. 15 and 16. Note field travelling from right to left.

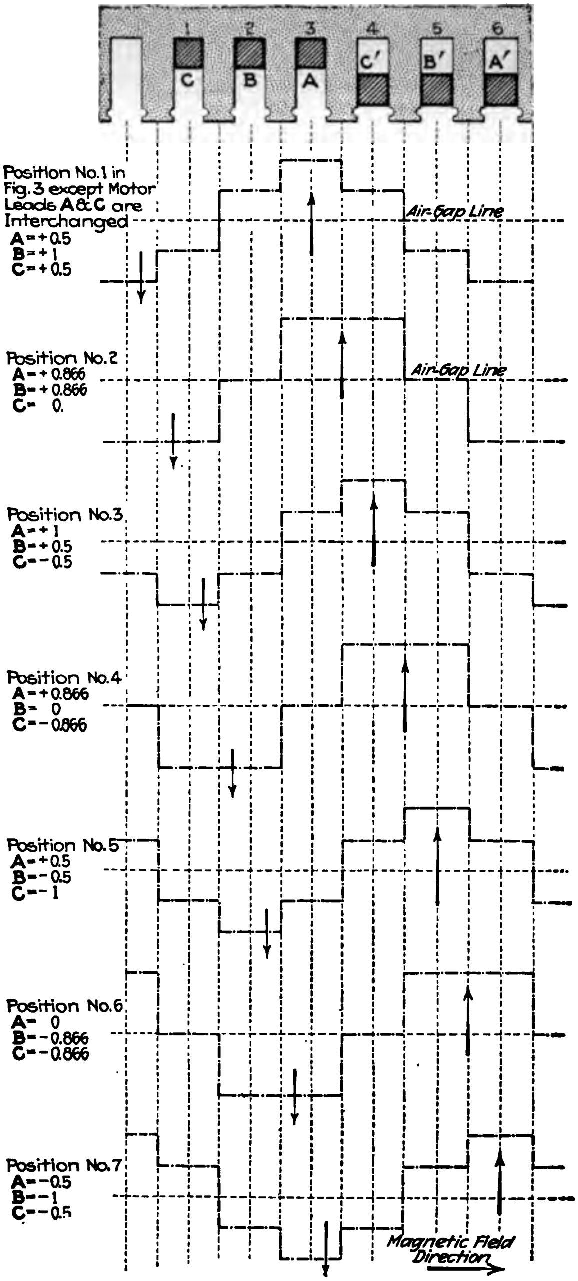


Fig. 18.—Similar conditions to Fig. 17 except two leads reversed causing field to travel from left to right and hence reversing direction of rotation of motor.

A complete cycle is known as 360 electrical degrees similar to the 360 mechanical degrees in a circle, and hence the reference positions 1, 2, 3, etc., are 1/12 of 360 deg. or 30 deg. apart. From a table of natural sines such as is found in any handbook, it will be found that the sine of 30 deg. = 0.5, sine of 60 deg. = 0.866, sine of 90 deg. = 1, sine of 120 deg. = 0.866, sine of 150 deg. = 0.5 and sine of 180 deg. = 0. Continuing from 180 deg. to 360 deg., the same values recur with a minus sign since they are measured below the horizontal reference line. So that it is these values which are used in plotting the pictures in Fig. 17, and the values for different positions are given in the left-hand column in the figure.

From Fig. 15 we have the position of the coils, and from Fig. 11 we have the value of the current in each coil as given in the column on the left of Fig. 17. Then if the values of these currents are plotted or drawn, the resulting curve is a measure of the magnetic field, since such a field depends on the number of turns of wire and the current flowing in the coil. It remains, then, only to draw the small figures or curves in Fig. 17 in the following manner:

Starting from any arbitrary point at as *d*, Fig. 17, the line moves in direction and amount according to the value of the current in slot 1. Slot 1 contains the *A* coil and the value of the current is +0.5 as is shown on the left; since the direction of plus is up, the line is drawn upward from *d* to *e* and *ef* is drawn horizontally, representing by its height above *d* the current in No. 1 slot and the magnetic field at that point. From *f* the line goes up to *g*, making *fg* twice as long as *de* because the *B* coil is in No. 2 slot and the value of the current in the *B* coil is +1, or twice that in *A*, and the line *gh* is drawn horizontally, representing by its height above *d* the current in slot 1 + slot 2 and therefore the magnetic field at that point. From *h* the line goes up to *i* because the *C* coil is in slot 3 and the current in the *C* coil as shown at the left at that instant is +0.5. The line *ij* is drawn horizontally, representing by its height above *d* the combined currents in slots 1 plus 2 plus 3 and therefore the magnetic field at that point. From *j* the line drops down to *k* because the *A′* conductor is in slot 4 and the *A′* conductor is the other side of the *A* coil and hence the current in it is in the opposite direction to that in the *A* side. By referring to the column at the left of the figure, if the current in the *A* side was considered +0.5, the current in the A' side must be -0.5 and hence the curve drops down for a minus value from j to k. Similarly, it drops twice as far from l to m, since $B = +1$ and therefore the other side of the B coil or B' must $= -1$. Following the curve in this manner to n and o, it completes one cycle or one north and south pole. The north pole is considered as that part above the horizontal reference line and under the line g, h, i, j, k, and l, which is shown shaded, and the center of this north pole is indicated by the vertical arrow.

In an actual machine the magnetic field would not have such sharp corners, but would be smoothed out by the rotor winding into a smooth curve practically a sine curve such as the current curves in Fig. 11, but for purposes of illustration the "stair-step," or square-shouldered curves, may be considered as shown. In a similar manner the little stair-step picture may be drawn for each position and the center of the north pole marked by an arrow pointing up as shown. After drawing seven positions, the very interesting fact may be noted that the center of the north pole has traveled three slots to the left, which in this case means 180 electrical degrees, or a half revolution on a two-pole motor or a quarter revolution on a four-pole machine.

Interchanging Two Leads Reverses Direction of Rotation.

Figure 18 is drawn to show the effect of interchanging the leads to the coils A and C, or in other words, the line lead that was connected to A is now connected to C and vice versa. For this reason in the little sketch at the top of Fig. 18, taken from Fig. 15, the C coil is now in slot 1 and the A coil is in slot 3, the B coil remaining in slot 2 unchanged. The numerical values of the currents are again taken from Fig. 11 just as it stands, because it must be remembered that the curves in Fig. 11 represent currents in the line and that they depend on the generator and are not changed by the change in the motor leads. These assumptions give the current values for the different positions, as shown in the left-hand column in Fig. 18, and the small stair-step pictures show the magnetic field in the same manner as in Fig. 17. The interesting thing to note is that the center of the north pole has now traveled from the center of slot 3 to the center of slot 6, or the magnetic field has now traveled three slots to the right, which discloses the well-known fact that interchanging two leads on a three-phase motor will reverse the mechanical direction of its rotation. As a problem the reader might attempt to produce the same result for a two-phase motor and will find, as previously pointed out, that this field plotting becomes a fascinating mental diversion.

A comparison of Figs. 10 and 11 shows at once why the middle leg of a three-phase winding is reversed in all the common diagrams that will be shown in this book. Figs. 17 and 18 show how the magnetic field may be studied and how reversal follows exchange of two leads.

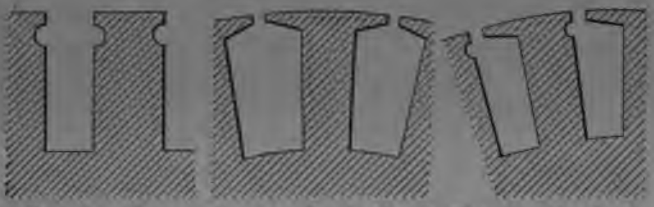


Fig. 19.—Open slots. Fig. 20.—Partly closed slots—center opening. Fig. 21.—Partly closed slots—side opening.

Common forms of induction-motor stator and rotor slots.

After a designing engineer has determined how many turns are required in the winding which he is calculating, the largest single factor which decides the form or type of windings to be used is the mechanical form of the slots; that is, whether they are open, Fig. 19, or semiclosed, as in Figs. 20 and 21, and the width of the opening if they are semiclosed. The factor of next importance is whether the winding is on the rotor or on the stator.

CHAPTER III

TYPES OF WINDINGS

Effect of Form of Slot.

The question of open versus semiclosed slots has out-lasted many controversies and is still open to argument. It is enough to say that, other things being equal, the designing engineer favors semiclosed slots. Slots of this type usually give the highest performance and the maximum efficiency in the use of material. The repair man prefers open slots on account of the greater accessibility of the windings and the consequent ease of repair. These factors will always remain somewhat divergent and must be adjusted to suit the times and the local conditions. The reason why a machine cannot be built with as good a performance or as economically with open slots in both members is that, broadly, its capacity and excellence may be measured by the square inches of laminated-iron surface on the rotor periphery or in the bore of the stator core. Since the slot openings subtract directly from this useful surface, it is desirable to make them as small as possible. If the slot is made wide open, it subtracts the maximum amount from this useful working surface, hence the core must be made longer axially or the rotor increased in diameter to bring back the useful working surface to somewhere near the value it would have if entirely inclosed or if semiclosed slots were used. This problem is of more interest to the designer than to the repair man, but is mentioned to explain the use of a mechanical construction that is apparently undesirable from an operating standpoint.

Windings Used in Partly Closed Slots.

The types of windings adapted to semiclosed slots and most generally employed are:

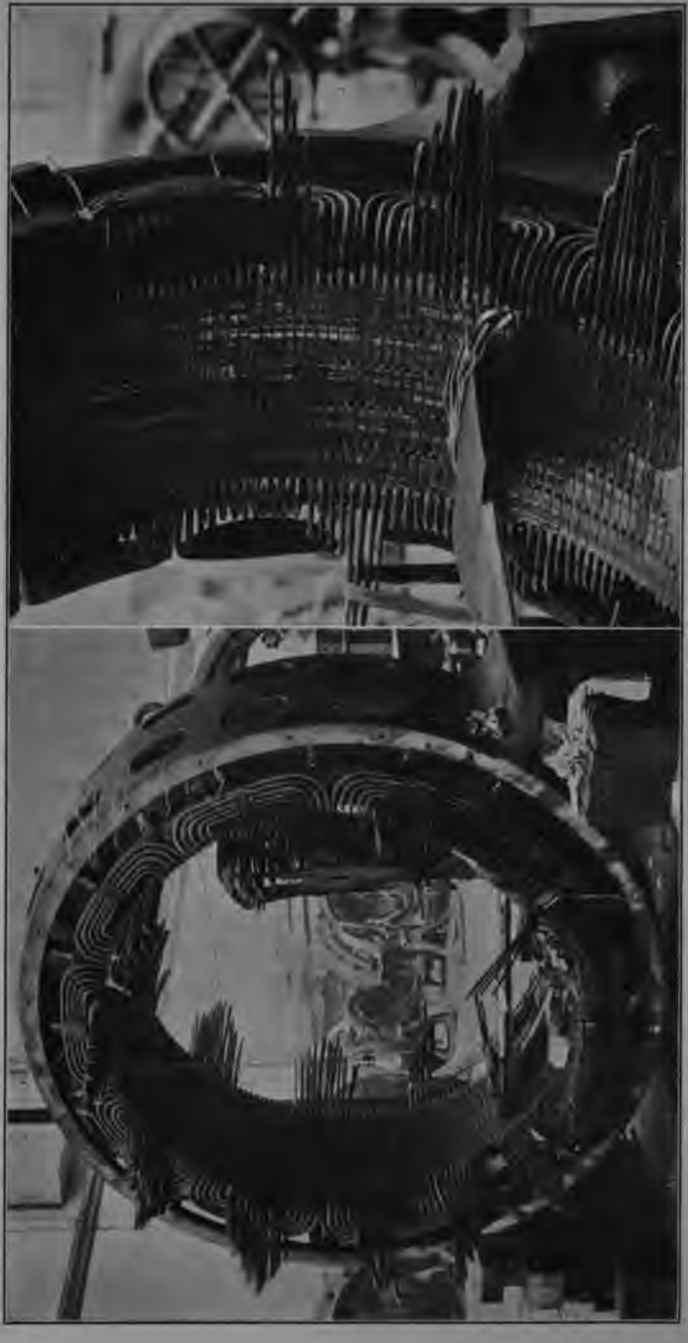
1. Straight bars with involute end connectors.
2. Pushed-through coils. In this type the coils are formed in a U-shape and pushed through two slots at once in a direction parallel to the shaft. After the coil is in place, the separate wires are bent around and connected together at the other side of the core.

3. Hand-wound or threaded coils. In this construction each coil is formed in place in the machine itself, from a single piece of wire, by the process of passing the wire through the length of one slot, bending it around a wooden former to make a suitable end and threading it back through another slot and repeating until the coil is complete with the desired number of turns. When completed, it resembles the pushed-through coil.

4. Fed-in, or dropped-in coils. In this type the coil is formed complete into a so-called diamond shape and then the turns are fed one at a time through the opening at the top of the slot.

FIG. 22.—The bars and connectors. FIG. 24.—Completed winding.
FIG. 23.—Partially completed winding.
Bar and end-connector winding.

The first of these types, bar and end connector, has been widely used for both stators and rotors. The bars and connectors are shown in Fig. 22, and a typical assembled winding in Figs. 23 and 24. This winding gave excellent satisfaction, the only real criticism, from a mechanical standpoint, being that it was difficult to brace the coil ends mechanically owing to their form and relation to other parts. It has been almost abandoned on modern machines for the reason that it limited the winding to one conductor or two conductors per slot, and also because modern practice has demonstrated that the use of



FIGS. 25 and 26.—Partially wound stators showing method of forming and connecting coils. Pushed-through windings.

single very heavy conductors gives rise to additional copper losses which are not present when several smaller conductors in parallel are used to carry the same current. Examples of the different methods of connecting up such windings will be given in a later chapter.

The second type, or pushed-through winding, is illustrated in Figs. 25 and 26. It will be observed that the labor of bending the coil ends and soldering each turn separately was considerable. This construction required somewhat more copper than the hand-wound type, but had the advantage that it could be better insulated. It has practically become obsolete in this country for induction motors, owing to the difficulty of making repairs.

The third type, or hand-wound, is illustrated in Fig. 27. It requires greater skill than any of the other types shown and somewhat more space in the slot than the pushed-through, and great care has to be used to avoid skinning the wire in winding. It has an advantage over the pushed-through winding in having no soldered joint anywhere throughout the entire length of the coil. Both the pushed-through and hand-wound types require considerably more handwork than other types and are consequently better fitted for use abroad, where hand labor is cheaper than in this country. For this reason these types of windings are still very generally used in Europe, but are practically superseded by other forms in the United States.

The fourth type, or fed-in coils, is illustrated in Figs. 28 and 29 and is used almost universally for the stators of motors up to 15 and 20 hp., at voltages of 550 and under. It has been widely employed as a stator winding in larger capacities, but the present-day tendency is to confine its use to smaller ratings and make use of open slots on the stator above this classification. It has still a considerable field as a rotor winding where the mechanical forces acting on the winding make desirable the use of a semi-closed slot with overhanging tooth tips which give greater support to the coils than is possible with open slots with wedges or bands. This type of winding is employed in two forms: First, as shown in Fig. 30, the coil for which is shown at *A*, Fig. 31; and second, as shown in Fig. 32, with the corresponding coil at *B*, Fig. 31. In the first of these forms there is but one coil per slot and the shape of the ends of the coils is controlled largely by the winder as he puts them in place. In the second form there are two coils per slot, which have a definite and final form before being placed in the core and which resemble exactly, when completed, the well-known diamond-shaped coils wound into open slots. The first of these forms is suited to small and the second

Fig. 27.—(A) Hand-wound, threaded type of winding.
Fig. 28.—(B) "Fed-in" type—"mush coil" or one coil per slot.
Fig. 29.—(C) "Fed-in" type—"diamond" or two coils per slot.
Stators with partly closed slots.

to larger machines. A modification of the second form makes use of a slot shaped as in Fig. 21 and is shown in place in Fig. 33. Each coil is completely insulated from ground and inserted in the

FIG. 30.—One coil per slot.

FIG. 31.—Right hand or "A" coil for winding in Fig. 30. Left hand or "B" coil for winding in Fig. 32. Winding "Fed-in" type.

FIG. 32.—Two coils per slot.

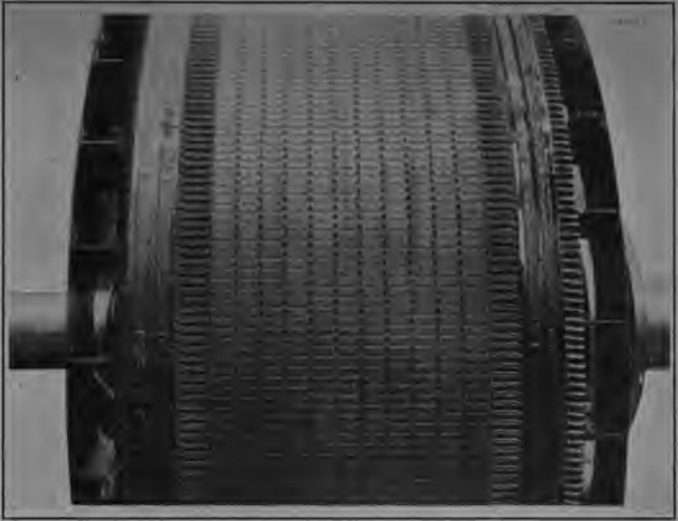
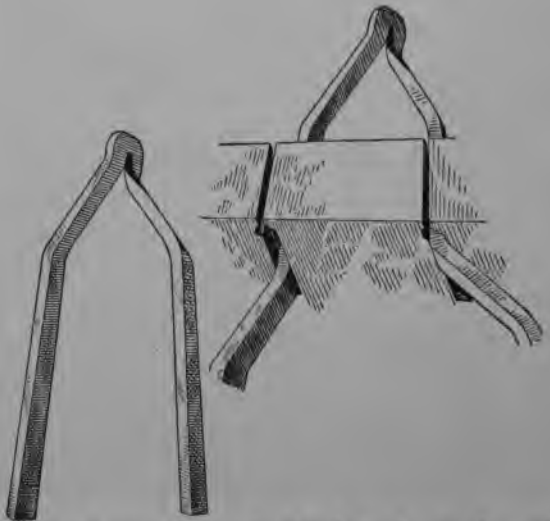


FIG. 33.—Rotor with slots as in Fig. 21 wound with strap coils of the "wave" type.



FIGS. 34 and 35.—Strap coil in partly closed slot bent to form after pushing through slots.

slot as a unit, so that it might be considered as a combination of the coils from two adjacent open slots brought together and securely held by the overhanging tooth tip, which leaves an opening large enough for the passage of one complete coil while winding. It is considered one of the most satisfactory forms for use on the rotating part of machines up to the largest capacity. A similar winding has been made by forming the coil of one or two straps bent on one end only, as shown in Fig. 34, and insulating it. The straight sides of this coil are then pushed through two partly closed slots in an axial direction, and the two ends are bent to the proper form to connect with other coils, as shown in Fig. 35. This makes a good mechanical job, but is rather difficult to repair owing to the fact that several straps must be straightened out to get at the damaged coil.

Windings Used in Open Slots.

With open slots, as illustrated in Fig. 19, the most popular and widely used form of winding is that shown in Figs. 36 and 38, for which the coil is shown in Fig. 37. This is the well-known diamond coil, so-called from its shape, and is entirely formed and insulated before placing in the slots. It is also the simplest and easiest coil to wind and is used by designers wherever the conditions permit. The greater number of typical connection diagrams shown in this book have reference to windings of this general type, since they lend themselves so readily to changes of arrangement and various reconnections.

There have been many other modifications of coils or windings employed with both open and closed slots in making special machines or where unusual conditions justified their use, but the forms described cover the great majority of machines found in use today.

Master Diagrams for Polar Grouped Windings.

In discussing windings, frequent reference is made to the usual forms of connection. For this reason much space in this and the following chapters is devoted to illustrations of the typical forms of diagrams that are employed by all manufacturers in connecting induction motors. A passing consideration will indicate that there would have to be an indefinitely large number of these diagrams to cover all possible combinations. For example, machines are usually connected either two-phase or three-phase. The three-phase machines may be either Y (star) or Δ (delta),

FIG. 36.—Method of placing coils in the core.

FIG. 37.—Typical "diamond" coil extensively used for induction-motor windings.

FIG. 38.—How the last group of coils is put in place.

Open-slot "diamond" coil windings.

any winding may be in series or two groups in parallel, a six-pole machine may be three parallels or six parallels or a ten-pole machine may be five parallels or ten parallels, etc. With these fundamental elements alone, if speeds from two poles to fourteen poles are considered, there are 81 diagrams of connections required. These diagrams are shown in Chapter XIII. Then follows the fact that any one of these 81 diagrams may be used on a core having an indefinite number of different slots such as 24, 36, 60, 72, 90, etc., so it becomes evident that it would require a book of considerable proportions to include even the usual combinations encountered in ordinary commercial machines. Fortunately a simple system has been developed, and will be explained later, by which the number of slots can be eliminated from consideration in the group connections, since it affects only the number of coils that are connected together to form a pole-phase group and does not affect the connection of the ends of this pole-phase group to neighboring groups. As stated earlier in the chapter windings are divided, in general, into two classes with reference to whether they are used in partly closed slots or in open slots. The partly closed slot windings are again divided into four classes: (1) Bar and involute-end connector, (2) pushed-through, (3) hand-wound and (4) fed-in, or dropped-in.

So far as the polar connections are concerned, the bar and involute-end-connector windings may be handled in the same manner as a formed-diamond-coil winding used in open slots, since the bar may be considered as the straight portion of the coil and the involute connector as its diamond-shaped end. This would mean that these windings could be connected up into pole-phase groups and these groups in turn cross-connected according to any of the standard group connections in common use, of which a number will be shown in Chapter XIII.

"Wave" or "Progressive" Diagrams.

In addition to such connections, this type of winding has been often used as a wave or series-circuit winding such as is commonly employed in direct-current armatures. Windings of this type are illustrated in Figs. 39 and 40. It will be seen at once that a desirable feature of such a winding is its simplicity and compactness and comparative freedom from group cross connections. These connections are limited to the connections for the star or the corners of the delta, the leads, and one series connection in

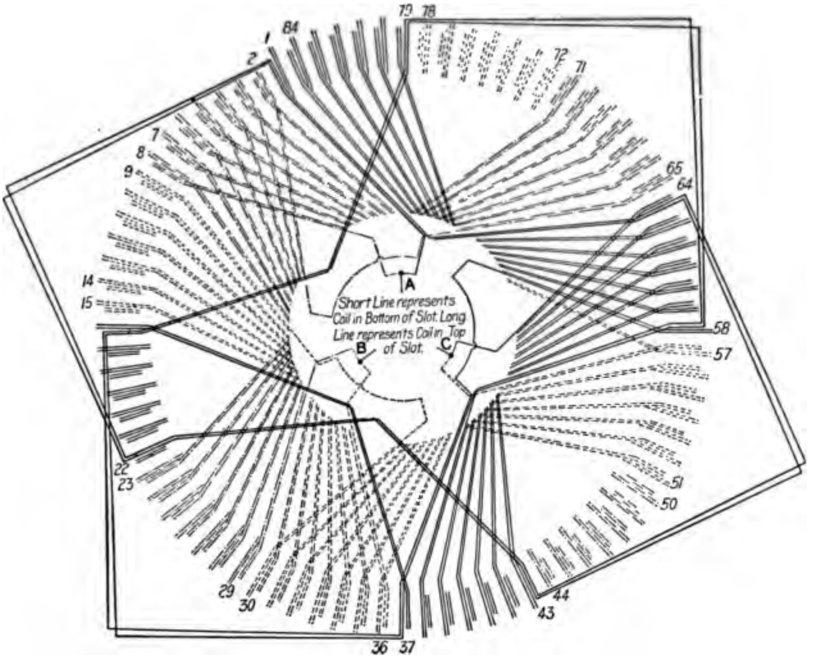


FIG. 39.—Typical "wave" diagram for three-phase, four-pole, series-delta connection.

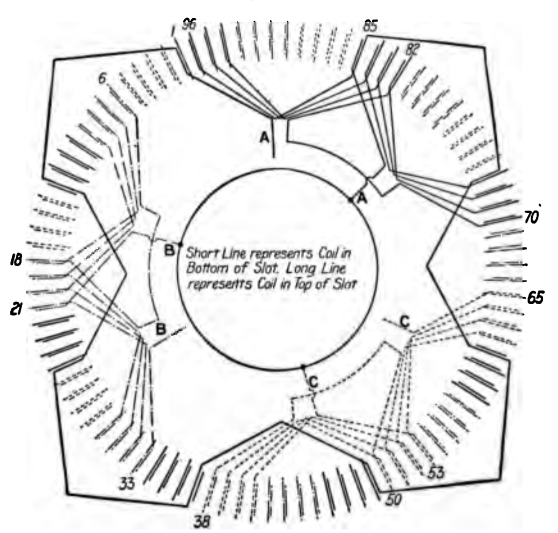


FIG. 40.—Typical "wave" diagram for three-phase, eight-pole, series-star connection.

the middle of each phase. When compared with the mass of cross connections for the simplest form of pole-phase group winding, the advantage is apparent. It will be noticed that the windings shown in Figs. 39 and 40 are perfectly symmetrical and balanced at all points, the number of slots being an exact multiple of the number of phases times the number of poles; this is true in practically all cases for this type of winding.

Standard D. C. Form of Wave Winding Adapted to A. C.

An interesting variation from the foregoing type is illustrated in Fig. 41 and is typical of a method of connection that has been widely employed, particularly on the rotors of motors of the phase-wound type. Here it will be seen that the number of slots, 62, is not an even multiple of 18 (3 × 6, phases times poles), but follows the same law as a direct-current, series or wave, armature winding; namely, the number of slots ±1 divided by the number of pairs of poles must equal an integer, and this

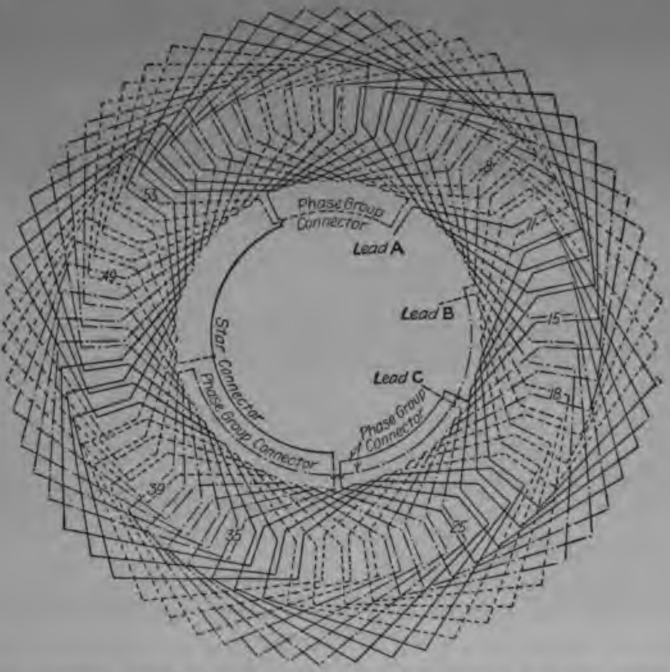


FIG. 41.—Special form of wave diagram for three-phase, six-pole, series-star connection.

integer divided by 2 is equal to the proper pitch, or throw, of the connector. In the case shown in Fig. 41,

$$\frac{\textit{Number of slots} \pm 1}{\textit{Pairs of poles}} = \frac{62 \pm 1}{3} = 21.$$

The proper pitch of the coil is 21 ÷ 2 = 10.5 slots; that is, the throw should be 10.5. Since this is not physically possible, the throw is made 10 slots or 1 to 11 on one end, and 11 slots or 1 to 12 on the other end, giving an average of 10.5.

Assume that a bar in the bottom of the slot 1 is connected by the connector on the back of the core to the bar in the top of slot 12, and that the front end of the bar in slot 12 is in turn connected on the front end of the core to the bar in the bottom of slot 22 and this again on the back end to the bar in the top of slot 33. Tracing the winding through in this manner, after one complete circuit has been made around the core it will be found to connect to the bottom bar in slot 2 and for the second round to the bottom bar in slot 3 and so on, until finally, when all the slots are traced through both top and bottom, the last throw will close the winding on itself by connecting to the front end of the bottom bar of slot 1. This can be proved easily by setting down a table of numbers 1–12, 12–22, 22–33, 33–43, 43–54, 54–2, 2–13, etc., representing the path of the winding around the core as described until each number has appeared two times, or until 2 × 62 = 124 bars have been passed through. This would then give a completely closed winding, and if the middle point of each end connector were attached to a bar on a suitable commutator, it would represent exactly a direct-current series armature winding.

To employ this winding on alternating current, the proper phase leads must be brought out, and this can be accomplished in several ways. One method of doing this would be to leave the winding closed and bring out three-phase taps 120 deg. apart, as shown in Fig. 42, or four taps, as in Fig. 43. The first would give three-phase and the second two-phase. A second method is to open the winding at three proper places and use these three pieces to form the usual star or delta connection. This is indicated in Fig. 44. It must not be assumed that the winding is actually interrupted at the points *A*, *B* and *C* since each portion of the winding between these points actually runs completely around the core several times. This can be readily grasped if the table as set down in the foregoing is separated into three parts, each part having one-third of the total bars in it, or $\frac{62 \times 2}{3} = 41\frac{1}{3}$; say 40 bars in one section and 42 bars in the other two. The slight unbalancing so caused is, in this case, of no consequence.

It is necessary to keep an even number of bars in each section for the reason that the connections are all on one end of the core and an odd number of bars in any section would mean ending that section on the back end of the core. Or, in other words, in tracing through the winding on the odd-numbered bars one is always going from the front to the back and on the even-numbered bars always coming from the back to the front, hence to end on the front an even number of bars must have been passed through.

In the connection shown in Fig. 41 a still different method is adopted by separating the winding into six sections, four of which have 20 bars in them and two have 22 bars each. These six sections are connected in pairs in series and the three pairs connected in series star to form a three-phase winding. The reason for this is a more efficient use of the copper than either of the two preceding methods. This follows from the fundamental idea brought out in the first chapter that every induction motor is at the same time an alternating-current generator, due to the fact that the stationary windings are cut by the rotating field. The output of an alternating-current generator is measured by the product of the volts times the amperes. In Fig. 41 the copper will carry a certain maximum current. It then follows that to get the most out of it as an alternating-current generator, the windings must be made to generate the maximum practicable voltage, and this is the result accomplished by the connection in Fig. 41.

Voltage Relation of Individual Coils in This Winding.

In the complete closed winding, Fig. 41, each coil is generating a small voltage which is slightly out of phase with all its neighbors. The situation can be described as a polygon having 62 equal sides, each side representing the voltage of a single coil. Obviously, the maximum voltage would be obtained if we could roll out this polygon into a straight line and use one-third of its length for each of the three phases. This cannot be done in practice, but it can be approached as shown in Fig. 45. Here the circle represents the 62-sided polygon just mentioned. By dividing the winding into six pieces, the effective voltage of each piece is reduced to the equivalent of one ide of a hexagon. By putting the opposite side of the hexagon in series and then the three pairs in series star, the winding is made to develop almost the maximum voltage. A slight gain could still be made in the same way by dividing the winding in 12 pieces and using these 6 pairs as a six-phase winding, but this is too complicated for ordinary use.

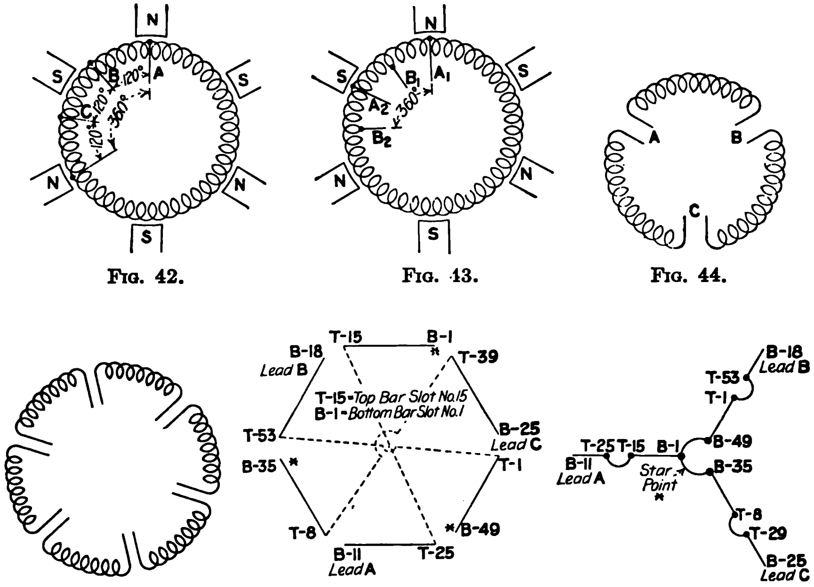


Fig. 42. Fig. 43. Fig. 44.

Fig. 45. Fig. 46. Fig. 47.

Figs. 42, 43, 44, 45, 46 and 47.—Manner of connecting and bringing out leads of the winding in Fig. 41.

The connection shown in Fig. 41 is obtained practically by setting down a table, as previously stated, including all the bars and then dividing it into 6 pieces as nearly equal as possible, keeping an even number of bars in each. In this case sections 1, 2, 3 and 4 have 20 bars and 5 and 6, 22 bars each. Section 1 is then connected with 4 for phase *A*, section 2 with 5 for phase *B*, and section 3 with 6 for phase *C*. The proper ends of these connectors for star and the leads can be determined from Figs.

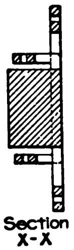
46 and 47, the numbering on which corresponds to that on Fig. 41. A little practice in this way will suggest how different three-phase connections could be made for star or delta or series or parallel to accommodate different voltages and how corresponding two-phase or even six-phase connection, could be obtained.

Concentric-Coil Windings.

In the pushed-through type of winding, previously described, the coil is formed in the shape of a U and the two branches are simultaneously pushed through the proper slots in the core, after which the ends are bent toward each other and the individual conductors connected in series. In the hand-wound type a single long wire is threaded around and back through two slots until the complete coil is formed. The completed coil is practically identical in the two types, and the completed winding takes the form shown in Figs. 48 to 53 inclusive. Figure 49 is typical of a two-phase arrangement. The coils are concentric and there are two shown per group, but in practice on induction motors as high as five or even six have been used. The coils that are inside on one end of the core are outside on the other end, thus insuring symmetry and equal resistance in the two phases. Figure 48 shows a cross-section of the core and coils on the line *XX* and indicates the relative position of the two banks of coil ends.

Figure 51 shows a three-phase winding similar to the two-phase Fig. 49 except that only one coil per group is shown; however, there might be four or more concentric coils per group, as in the two-phase. It will be noticed at once from this figure and Fig. 50 that the winding is not so simple as the two-phase. Owing to the passing of the coils at the ends of the core, three banks, or tiers, are necessary instead of two, and the coil ends are correspondingly longer. It will be noticed that the *A* phase occupies the middle tier all the way through and the *B* and *C* phases are alternately in the inside and outside tiers. In this manner the resistance is kept nearly equal in the three phases.

In order to be able to wind the three-phase with a two-bank winding similar to the two-phase, the scheme shown in Fig. 53 is employed. It can be seen that there are the same number of slots as in Fig. 51 and that both are three-phase, four-pole, series-star windings. However, Fig. 53 has only two tiers at the ends and has two coils per group instead of one, but only two



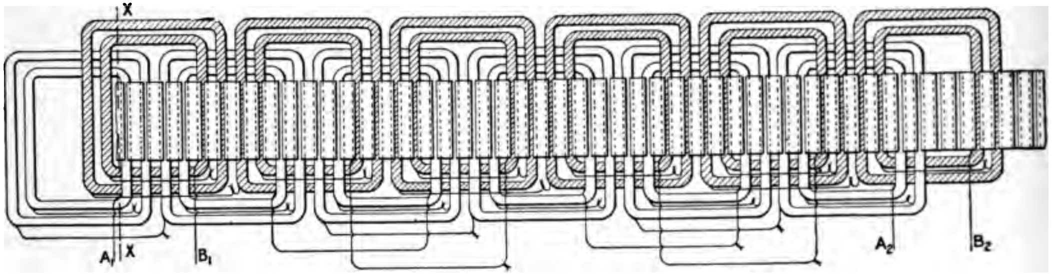
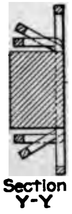
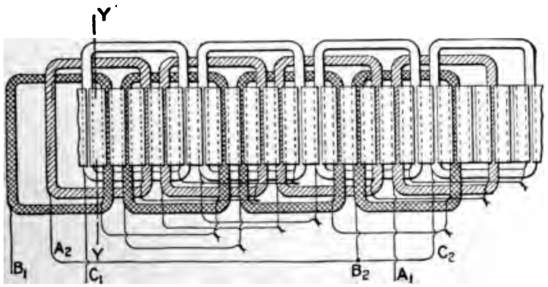
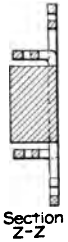


FIG. 48.—Cross-section of winding in Fig. 49.

FIG. 49.—Typical two-phase, two-bank winding.







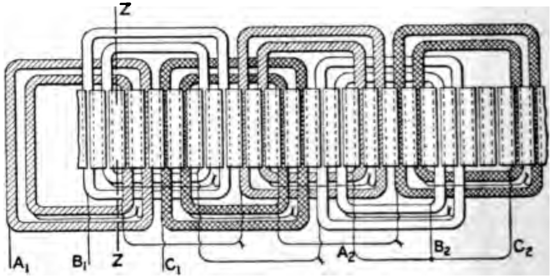


FIG. 50.

FIG. 51.

FIG. 52.

FIG. 53.

FIG. 50.—Cross-section of winding in Fig. 51.

FIG. 51.—Typical three-phase, three-bank winding.

FIG. 52.—Cross-section through winding in Fig. 53.

FIG. 53.—Three-phase winding with only two banks, accomplished by connecting for consequent poles. Pushed through windings.

groups per phase instead of four. This is what is called a "consequent-pole winding," because the current passes in the same direction through all the coils forming, for example, two north poles in each phase. Since there cannot be a north pole without a corresponding south pole, the magnetism returns between the groups in each phase, thus forming the two south poles, or four in all. This winding is simpler to make than Fig. 51, mechanically, but has some slight electrical disadvantages. Figure 52 is a section through the core and winding on the line *ZZ* and indicates the relative positions of the two banks of coils.

Rearrangement of Concentric-Coil Windings.

It will be seen that these concentric-coil windings do not lend themselves readily to rearrangement or reconnection for different poles or phases, and this is one reason why they have gradually fallen into disuse. Two-phase windings such as Fig. 49 can sometimes be connected in "T" and run on three-phase, and mention of this will be made in a later chapter. Also, a comparison of Figs. 49 and 53 indicates that the winding in Fig. 49 might be connected for three-phase 8 poles by a consequent-pole connection similar to Fig. 53, since the total number of groups, being twelve, is half of 3 × 8, and this lines up with Fig. 53, where the total number of groups is 6, or half of 3 × 4.

Where the coils are of the closed type similar to "diamond" coils used in open slots, they may be grouped and connected by the usual diagrams for that type, which will be discussed under open-slot windings. There is, however, a large class using one- or two-turn coils of the open end, or "wave," type which form very interesting windings, two of which are shown in Figs. 39 and 40. This type of winding is believed today to be the form best adapted to the rotating member of phase-wound motors up to the largest sizes. Since they are perfectly symmetrical, they can be equally well employed in the stator, where the design permits a number of conductors not exceeding four per slot. These diagrams are practically self-explanatory, but their great utility and wide employment merits a brief comment. They are typical three-phase diagrams connected both star and delta. Three-phase is chosen as it is suitable for either stator or rotor and is oftenest met with. Figure 39 shows a four-pole series-delta winding, but it may be equally well connected parallel-star. The winding, Fig. 39, has four conductors per slot. In Fig. 40 is an eight-pole series-star connection where the two wires in the top of the slot are connected in parallel, also the two in the bottom of the slot, to form one conductor, or a total of two conductors per slot.

Wave Windings.

In these windings it is of interest to note that the number of cross-connections is a minimum, being reduced to the star or delta connection, the leads and one short connection in the middle of each phase. Such conditions are ideal for a rotor, and when the coils are placed in a slot with the tip overhung from one side, the winding forms one of the best mechanical jobs for a rotor that is known at the present time.

Passing to Open-Slot Windings.

It is the object of the rest of this chapter to explain the method of connecting up these windings with sufficient examples to make it possible to lay out such a diagram when one is not immediately available. It should be borne in mind that such diagrams can also be used with partly closed slot windings when they are of the same form as "diamond coils." Such for example are the so-called "fed-in" or "dropped-in" coils, which are really "diamond" coils except that they are placed in partly closed slots, one wire at a time, through the small opening at the top of the slot. Such also are the strap coils referred to earlier, where the slot is half open and the tooth tip overhangs from one side. While there are four separate coils in such a slot, each coil is insulated from ground and for purposes of connecting up may be considered the equivalent of an open-slot winding laid in twice the number of slots. Such a winding is shown in Figs. 21 and 33. Bar-and-end connector windings when of the "lap" and not the "wave" type are also connected in the same manner.

Standard "Lap" Winding.

A completely developed picture of an open-slot winding is shown in Figs. 54 and 55. The straight radial lines are shown in pairs. These radial lines represent the straight parts of the "diamond" coils. The shorter line of each pair represents the side of the coil lying in the bottom of the slot and the longer line the side of the coil in the top of the slot. Taking Fig. 54, for example, before any cross-connecting was done there were 24 separate coils with the beginning and ending of each coil projecting at the end of the winding as shown in Fig. 56, which is the winding represented in Fig. 54 in place in the stator except laid

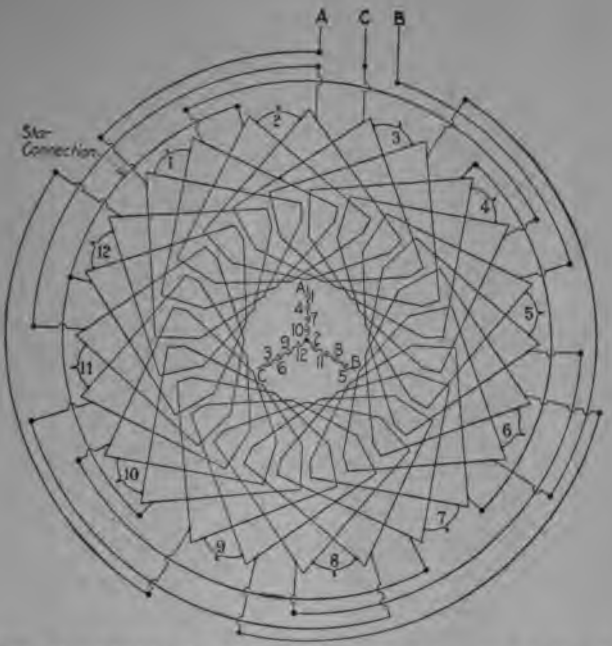


FIG. 54.—Typical three-phase, four-pole, series-star winding for an open-slot stator.

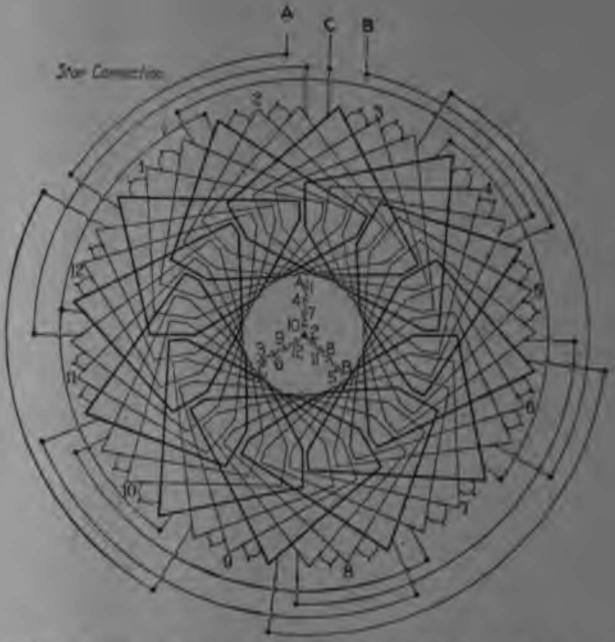


FIG. 55.—Same winding as Fig. 54 except coils with heavier insulation where phase changes are shown in heavy lines.

out flat. Since it is to be connected for three-phase four poles, there is a total of 3 × 4 = 12 pole-phase groups required and this results in 24 ÷ 12 = 2 coils per group. The first step, therefore, is to connect the coils in pairs, each pair forming a pole-phase group, as in Fig. 57. These coil-to-coil connections,

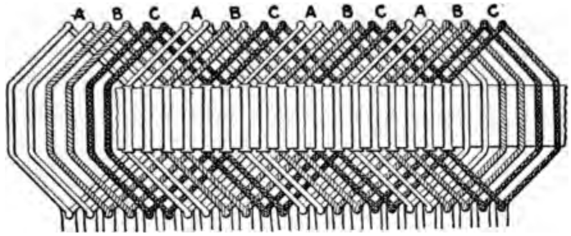


FIG. 56.—Coils for the winding in Figs. 54 and 55 shown in place ready to connect.

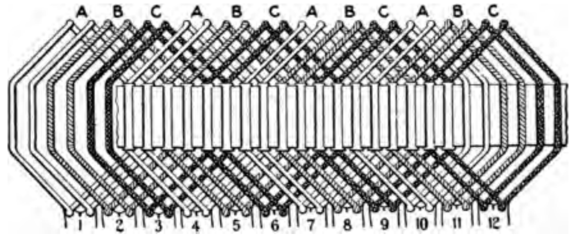


FIG. 57.—Same coils "stubbed up" or connected into pole-phase groups.

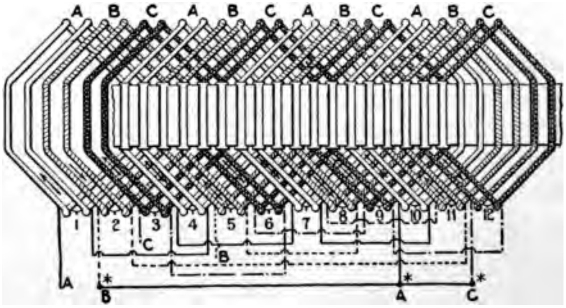


FIG. 58.—Completed winding same as Figs. 54 and 55.

or stubs, are shown at the group numbers. The resulting 12 pole-phase groups are then cross-connected to form the completed winding as in Figs. 54 and 58.

A comparison of Fig. 54 with Fig. 55 shows that the cross-connections or pole-phase-group connections are identical, the only difference between the two being that Fig. 55 has 36 coils total instead of 24 and hence there are three coils in each pole-phase group instead of two. The coils shown in heavy lines, Fig. 55, represent the coils having heavier insulation, where the phases change between adjacent coils and will be referred to in a later chapter. A consideration of these figures leads at once to two conclusions: First, that such a form of diagram as Figs. 54 and 55 is entirely too complicated for use by the average winder and a diagram like that in Fig. 58 requires too much time to make and is therefore too expensive. Second, since the actual cross-connections themselves are not affected by the number of individual coils in the pole-phase group, the entire picture shown in Figs. 54 to 58 may be replaced by the simple diagram shown in Fig. 59. The spiral lines representing the pole-phase groups, which are numbered to correspond with Figs. 54, 57 and 58, can be imagined as being the coils which form the pole-phase groups. It is obvious that there might be any number of coils connected in series to form the groups. If, for example, the complete machine instead of having 24 or 36 slots had 48, 60, 72 or 96 slots, the cross-connections of the groups in any case would be as shown in Fig. 59. A diagram of this type is therefore always used for such windings, since it can be used for any three-phase four-pole machine independently of the number of slots in a particular machine.

Schematic Diagram.

Attention is called to the small "Y" diagram in the center of Figs. 54 and 55 which is also reproduced in Fig. 59. It has no electrical connection with, but is the "schematic equivalent" of, the rest of the diagram. It is the designing engineer's imaginary conception of the cross-connections reduced to their simplest terms. By comparing the numbers of the groups on this small diagram with the corresponding numbers on the larger diagram, it will be seen that each pole-phase group is shown in its proper phase and with the proper direction of its ends toward the lead or toward the star connection. The arrows shown on the larger diagram, Fig. 59, and also on the small schematic equivalent represent a simple and positive check as to whether the connections to the different groups are correct.

Check for Connecting Proper Ends of Phases to Star Point.

There is a danger in a three-phase winding that the three phases may be connected in a 60-deg. relation instead of a 120-

deg. relation, or as it might be expressed on the diagram, Fig. 59, there is danger that the wrong end of the *B* phase, for example, may be connected to the star point. As a check against this each phase is traced through, starting from the lead or terminal and proceeding to the common, or "star," point at the center of the winding. As the successive groups are passed through, an arrow is placed on each as shown, indicating in which direction that group was passed through. When all three phases have been traced through and the arrows on the groups are inspected, the diagram is correct if the arrows on adjacent groups reverse; that is, if they are alternately clockwise and counterclockwise in passing around the winding. This check should be studied over and thoroughly mastered, as it is the one check that the author has found in 15 years of practical experience is always reliable and easily applied. The only exception to this check is the case of consequent-pole machines, to be described in another chapter, but these are so special and so infrequently met with that they may be practically put out of the consideration and the check be regarded as almost universal.

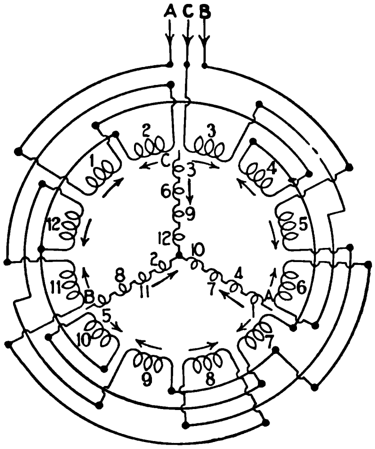


FIG. 59.—Schematic, four-pole, series star diagram exact equivalent of pictured winding in Figs. 54, 55 and 58.

It is the common practice of all manufacturers to send out machines that can readily be connected for either one or two voltages. This is accomplished by a series or parallel arrangement and can be understood by comparing Figs. 59 and 60. By looking at the small "equivalent" diagram in the center, it will be seen that there are twice as many groups in series between the terminal leads in Fig. 59 as there are in Fig. 60. This means that if Fig. 59 is proper for 440 volts, Fig. 60 would be right for 220 volts. The idea was given in an earlier chapter that one function of the winding was to generate the counter-electromotive force. It can be seen at once that if the coils as connected in Fig. 59 are generating 440 volts, they will obviously generate only half as many, or 220 volts, connected as in Fig. 60. As another consideration, it is seen that if the motor has the same horsepower at both voltages, it will have

Fig. 60.—Showing the diagram Fig. 59 reconnected from series to parallel star.

Fig. 61.—Showing the diagrams of Figs. 59 and 60 reconnected to four parallel star.

twice the number of full-load amperes at 220 as it has at 440 volts. This is properly taken care of, as will be seen from Fig. 60, since the winding being doubled has twice the copper cross-section in Fig. 60 that it had in Fig. 59.

If the number of poles in the machine is divisible by 4 as, for example, 4, 8, 12, 16, etc., the winding may be put in 4 parallels as shown in Fig. 61 and by comparison with Figs. 59 and 60 would be good for 110 volts at the same horsepower. The increased current at 110 volts is again taken care of by providing 4 times the copper section, as shown. This same principle can be extended, and when the number of poles for which the machine is wound can be divided by 6, it is possible to have the winding connected for 3 parallels or 6 parallels, as shown in Figs. 62

integer divided by 2 is equal to the proper pitch, or throw, of the connector. In the case shown in Fig. 41,

$$\frac{\textit{Number of slots} \pm 1}{\textit{Pairs of poles}} = \frac{62 \pm 1}{3} = 21.$$

The proper pitch of the coil is 21 ÷ 2 = 10.5 slots; that is, the throw should be 10.5. Since this is not physically possible, the throw is made 10 slots or 1 to 11 on one end, and 11 slots or 1 to 12 on the other end, giving an average of 10.5.

Assume that a bar in the bottom of the slot 1 is connected by the connector on the back of the core to the bar in the top of slot 12, and that the front end of the bar in slot 12 is in turn connected on the front end of the core to the bar in the bottom of slot 22 and this again on the back end to the bar in the top of slot 33. Tracing the winding through in this manner, after one complete circuit has been made around the core it will be found to connect to the bottom bar in slot 2 and for the second round to the bottom bar in slot 3 and so on, until finally, when all the slots are traced through both top and bottom, the last throw will close the winding on itself by connecting to the front end of the bottom bar of slot 1. This can be proved easily by setting down a table of numbers 1–12, 12–22, 22–33, 33–43, 43–54, 54–2, 2–13, etc., representing the path of the winding around the core as described until each number has appeared two times, or until 2 × 62 = 124 bars have been passed through. This would then give a completely closed winding, and if the middle point of each end connector were attached to a bar on a suitable commutator, it would represent exactly a direct-current series armature winding.

To employ this winding on alternating current, the proper phase leads must be brought out, and this can be accomplished in several ways. One method of doing this would be to leave the winding closed and bring out three-phase taps 120 deg. apart, as shown in Fig. 42, or four taps, as in Fig. 43. The first would give three-phase and the second two-phase. A second method is to open the winding at three proper places and use these three pieces to form the usual star or delta connection. This is indicated in Fig. 44. It must not be assumed that the winding is actually interrupted at the points A, B and C since each portion of the winding between these points actually runs completely around the core several times. This can be readily grasped if the table as set down in the foregoing is separated into three parts, each part having one-third of the total bars in it, or $\frac{62 \times 2}{3} = 41\frac{1}{3}$; say 40 bars in one section and 42 bars in the other two. The slight unbalancing so caused is, in this case, of no consequence.

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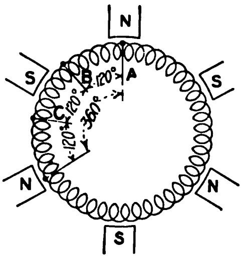


FIG. 42.

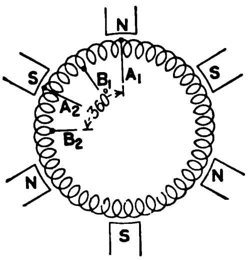


FIG. 43.

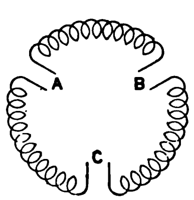


FIG. 44.

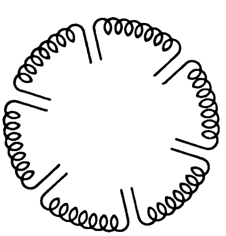


FIG. 45.

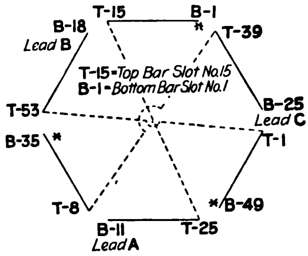


FIG. 46.

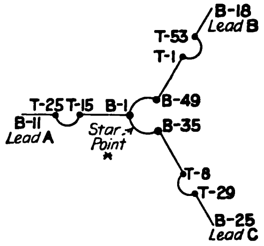


FIG. 47.

FIGS. 42, 43, 44, 45, 46 and 47.—Manner of connecting and bringing out leads of the winding in Fig. 41.

The connection shown in Fig. 41 is obtained practically by setting down a table, as previously stated, including all the bars and then dividing it into 6 pieces as nearly equal as possible, keeping an even number of bars in each. In this case sections 1, 2, 3 and 4 have 20 bars and 5 and 6, 22 bars each. Section 1 is then connected with 4 for phase *A*, section 2 with 5 for phase *B*, and section 3 with 6 for phase *C*. The proper ends of these connectors for star and the leads can be determined from Figs.

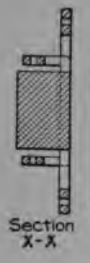
46 and 47, the numbering on which corresponds to that on Fig. 41. A little practice in this way will suggest how different three-phase connections could be made for star or delta or series or parallel to accommodate different voltages and how corresponding two-phase or even six-phase connection, could be obtained.

Concentric-Coil Windings.

In the pushed-through type of winding, previously described, the coil is formed in the shape of a U and the two branches are simultaneously pushed through the proper slots in the core, after which the ends are bent toward each other and the individual conductors connected in series. In the hand-wound type a single long wire is threaded around and back through two slots until the complete coil is formed. The completed coil is practically identical in the two types, and the completed winding takes the form shown in Figs. 48 to 53 inclusive. Figure 49 is typical of a two-phase arrangement. The coils are concentric and there are two shown per group, but in practice on induction motors as high as five or even six have been used. The coils that are inside on one end of the core are outside on the other end, thus insuring symmetry and equal resistance in the two phases. Figure 48 shows a cross-section of the core and coils on the line XX and indicates the relative position of the two banks of coil ends.

Figure 51 shows a three-phase winding similar to the two-phase Fig. 49 except that only one coil per group is shown; however, there might be four or more concentric coils per group, as in the two-phase. It will be noticed at once from this figure and Fig. 50 that the winding is not so simple as the two-phase. Owing to the passing of the coils at the ends of the core, three banks, or tiers, are necessary instead of two, and the coil ends are correspondingly longer. It will be noticed that the A phase occupies the middle tier all the way through and the B and C phases are alternately in the inside and outside tiers. In this manner the resistance is kept nearly equal in the three phases.

In order to be able to wind the three-phase with a two-bank winding similar to the two-phase, the scheme shown in Fig. 53 is employed. It can be seen that there are the same number of slots as in Fig. 51 and that both are three-phase, four-pole, series-star windings. However, Fig. 53 has only two tiers at the ends and has two coils per group instead of one, but only two



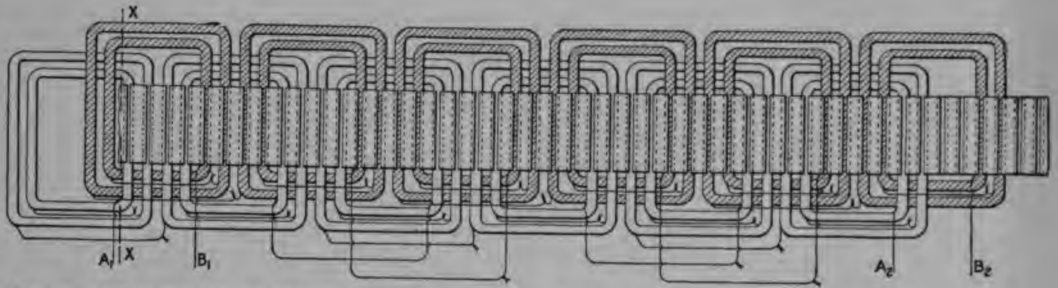


FIG. 48.—Cross-section of winding in Fig. 49.

FIG. 49.—Typical two-phase, two-bank winding.

FIG. 50.

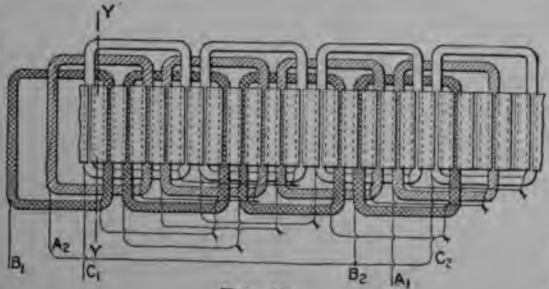


FIG. 51.

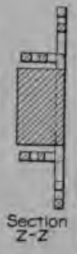


FIG. 52.

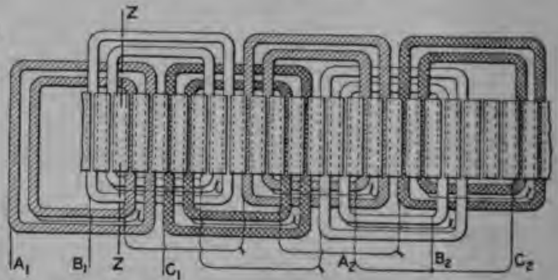


FIG. 53.

FIG. 50.—Cross-section of winding in Fig. 51.
FIG. 52.—Cross-section through winding in Fig. 53.
FIG. 53.—Three-phase winding with only two banks, accomplished by connecting for consequent poles.

FIG. 51.—Typical three-phase, three-bank winding.
Pushed through windings.

groups per phase instead of four. This is what is called a "consequent-pole winding," because the current passes in the same direction through all the coils forming, for example, two north poles in each phase. Since there cannot be a north pole without a corresponding south pole, the magnetism returns between the groups in each phase, thus forming the two south poles, or four in all. This winding is simpler to make than Fig. 51, mechanically, but has some slight electrical disadvantages. Figure 52 is a section through the core and winding on the line *ZZ* and indicates the relative positions of the two banks of coils.

Rearrangement of Concentric-Coil Windings.

It will be seen that these concentric-coil windings do not lend themselves readily to rearrangement or reconnection for different poles or phases, and this is one reason why they have gradually fallen into disuse. Two-phase windings such as Fig. 49 can sometimes be connected in "T" and run on three-phase, and mention of this will be made in a later chapter. Also, a comparison of Figs. 49 and 53 indicates that the winding in Fig. 49 might be connected for three-phase 8 poles by a consequent-pole connection similar to Fig. 53, since the total number of groups, being twelve, is half of 3 × 8, and this lines up with Fig. 53, where the total number of groups is 6, or half of 3 × 4.

Where the coils are of the closed type similar to "diamond" coils used in open slots, they may be grouped and connected by the usual diagrams for that type, which will be discussed under open-slot windings. There is, however, a large class using one- or two-turn coils of the open end, or "wave," type which form very interesting windings, two of which are shown in Figs. 39 and 40. This type of winding is believed today to be the form best adapted to the rotating member of phase-wound motors up to the largest sizes. Since they are perfectly symmetrical, they can be equally well employed in the stator, where the design permits a number of conductors not exceeding four per slot. These diagrams are practically self-explanatory, but their great utility and wide employment merits a brief comment. They are typical three-phase diagrams connected both star and delta. Three-phase is chosen as it is suitable for either stator or rotor and is oftenest met with. Figure 39 shows a four-pole series-delta winding, but it may be equally well connected parallel-star. The winding, Fig. 39, has four conductors per slot. In Fig. 40 is an eight-pole series-star connection where the two wires in the top of the slot are connected in parallel, also the two in the bottom of the slot, to form one conductor, or a total of two conductors per slot.

Wave Windings.

In these windings it is of interest to note that the number of cross-connections is a minimum, being reduced to the star or delta connection, the leads and one short connection in the middle of each phase. Such conditions are ideal for a rotor, and when the coils are placed in a slot with the tip overhung from one side, the winding forms one of the best mechanical jobs for a rotor that is known at the present time.

Passing to Open-Slot Windings.

It is the object of the rest of this chapter to explain the method of connecting up these windings with sufficient examples to make it possible to lay out such a diagram when one is not immediately available. It should be borne in mind that such diagrams can also be used with partly closed slot windings when they are of the same form as "diamond coils." Such for example are the so-called "fed-in" or "dropped-in" coils, which are really "diamond" coils except that they are placed in partly closed slots, one wire at a time, through the small opening at the top of the slot. Such also are the strap coils referred to earlier, where the slot is half open and the tooth tip overhangs from one side. While there are four separate coils in such a slot, each coil is insulated from ground and for purposes of connecting up may be considered the equivalent of an open-slot winding laid in twice the number of slots. Such a winding is shown in Figs. 21 and 33. Bar-and-end connector windings when of the "lap" and not the "wave" type are also connected in the same manner.

Standard "Lap" Winding.

A completely developed picture of an open-slot winding is shown in Figs. 54 and 55. The straight radial lines are shown in pairs. These radial lines represent the straight parts of the "diamond" coils. The shorter line of each pair represents the side of the coil lying in the bottom of the slot and the longer line the side of the coil in the top of the slot. Taking Fig. 54, for example, before any cross-connecting was done there were 24 separate coils with the beginning and ending of each coil projecting at the end of the winding as shown in Fig. 56, which is the winding represented in Fig. 54 in place in the stator except laid

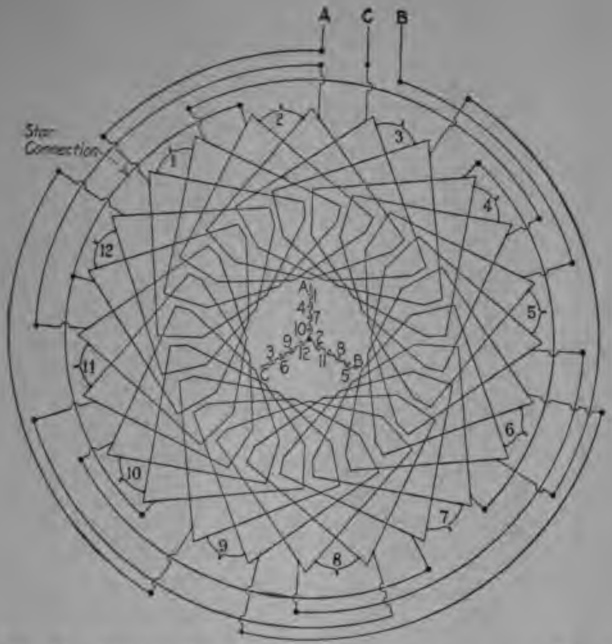


Fig. 54.—Typical three-phase, four-pole, series-star winding for an open-slot stator.

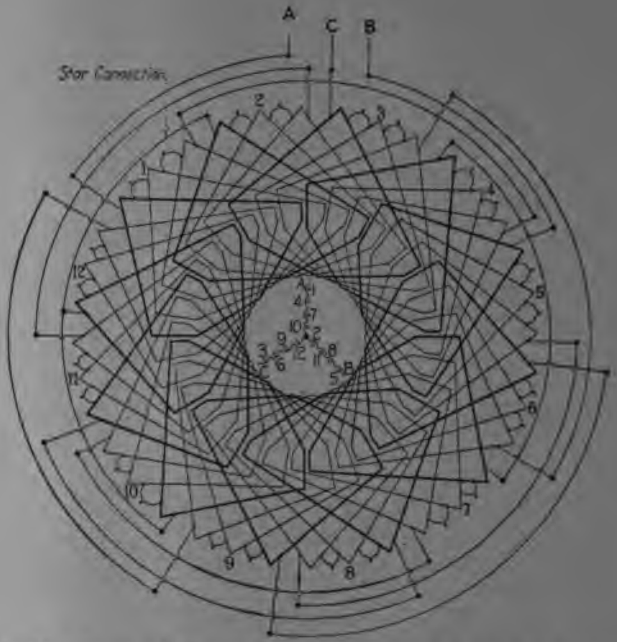


Fig. 55.—Same winding as Fig. 54 except coils with heavier insulation where phase changes are shown in heavy lines.

out flat. Since it is to be connected for three-phase four poles, there is a total of 3 × 4 = 12 pole-phase groups required and this results in 24 ÷ 12 = 2 coils per group. The first step, therefore, is to connect the coils in pairs, each pair forming a pole-phase group, as in Fig. 57. These coil-to-coil connections, or stubs, are shown at the group numbers. The resulting 12 pole-phase groups are then cross-connected to form the completed winding as in Figs. 54 and 58.

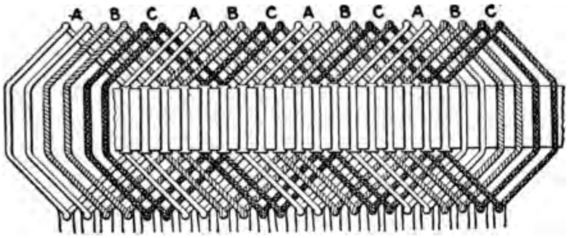


Fig. 56.—Coils for the winding in Figs. 54 and 55 shown in place ready to connect.

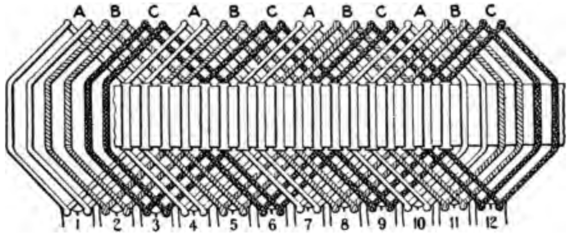


Fig. 57.—Same coils "stubbed up" or connected into pole-phase groups.

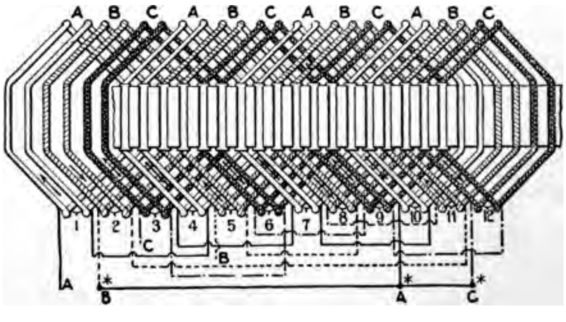


Fig. 58.—Completed winding same as Figs. 54 and 55.

A comparison of Fig. 54 with Fig. 55 shows that the cross-connections or pole-phase-group connections are identical, the only difference between the two being that Fig. 55 has 36 coils total instead of 24 and hence there are three coils in each pole-phase group instead of two. The coils shown in heavy lines, Fig. 55, represent the coils having heavier insulation, where the phases change between adjacent coils and will be referred to in a later chapter. A consideration of these figures leads at once to two conclusions: First, that such a form of diagram as Figs. 54 and 55 is entirely too complicated for use by the average winder and a diagram like that in Fig. 58 requires too much time to make and is therefore too expensive. Second, since the actual cross-connections themselves are not affected by the number of individual coils in the pole-phase group, the entire picture shown in Figs. 54 to 58 may be replaced by the simple diagram shown in Fig. 59. The spiral lines representing the pole-phase groups, which are numbered to correspond with Figs. 54, 57 and 58, can be imagined as being the coils which form the pole-phase groups. It is obvious that there might be any number of coils connected in series to form the groups. If, for example, the complete machine instead of having 24 or 36 slots had 48, 60, 72 or 96 slots, the cross-connections of the groups in any case would be as shown in Fig. 59. A diagram of this type is therefore always used for such windings, since it can be used for any three-phase four-pole machine independently of the number of slots in a particular machine.

Schematic Diagram.

Attention is called to the small "Y" diagram in the center of Figs. 54 and 55 which is also reproduced in Fig. 59. It has no electrical connection with, but is the "schematic equivalent" of, the rest of the diagram. It is the designing engineer's imaginary conception of the cross-connections reduced to their simplest terms. By comparing the numbers of the groups on this small diagram with the corresponding numbers on the larger diagram, it will be seen that each pole-phase group is shown in its proper phase and with the proper direction of its ends toward the lead or toward the star connection. The arrows shown on the larger diagram, Fig. 59, and also on the small schematic equivalent represent a simple and positive check as to whether the connections to the different groups are correct.

Check for Connecting Proper Ends of Phases to Star Point.

There is a danger in a three-phase winding that the three phases may be connected in a 60-deg. relation instead of a 120-

deg. relation, or as it might be expressed on the diagram, Fig. 59, there is danger that the wrong end of the *B* phase, for example, may be connected to the star point. As a check against this each phase is traced through, starting from the lead or terminal and proceeding to the common, or "star," point at the center of the winding. As the successive groups are passed through, an arrow is placed on each as shown, indicating in which direction that group was passed through. When all three phases have been traced through and the arrows on the groups are inspected, the diagram is correct if the arrows on adjacent groups reverse; that is, if they are alternately clockwise and counterclockwise in passing around the winding. This check should be studied over and thoroughly mastered, as it is the one check that the author has found in 15 years of practical experience is always reliable and easily applied. The only exception to this check is the case of consequent-pole machines, to be described in another chapter, but these are so special and so infrequently met with that they may be practically put out of the consideration and the check be regarded as almost universal.

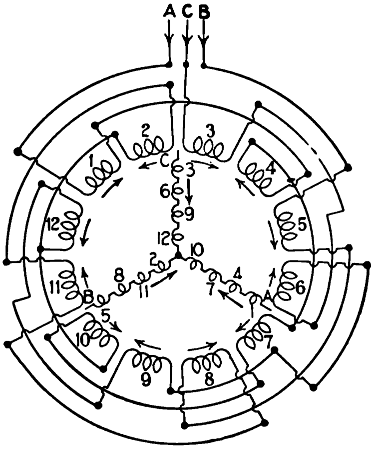


Fig. 59.—Schematic, four-pole, series star diagram exact equivalent of pictured winding in Figs. 54, 55 and 58.

It is the common practice of all manufacturers to send out machines that can readily be connected for either one or two voltages. This is accomplished by a series or parallel arrangement and can be understood by comparing Figs. 59 and 60. By looking at the small "equivalent" diagram in the center, it will be seen that there are twice as many groups in series between the terminal leads in Fig. 59 as there are in Fig. 60. This means that if Fig. 59 is proper for 440 volts, Fig. 60 would be right for 220 volts. The idea was given in an earlier chapter that one function of the winding was to generate the counter-electromotive force. It can be seen at once that if the coils as connected in Fig. 59 are generating 440 volts, they will obviously generate only half as many, or 220 volts, connected as in Fig. 60. As another consideration, it is seen that if the motor has the same horsepower at both voltages, it will have twice the number of full-load amperes at 220 as it has at 440 volts. This is properly taken care of, as will be seen from Fig. 60, since the winding being doubled has twice the copper cross-section in Fig. 60 that it had in Fig. 59.

FIG. 60.—Showing the diagram Fig. 59 reconnected from series to parallel star.

FIG. 61.—Showing the diagrams of Figs. 59 and 60 reconnected to four parallel star.

If the number of poles in the machine is divisible by 4 as, for example, 4, 8, 12, 16, etc., the winding may be put in 4 parallels as shown in Fig. 61 and by comparison with Figs. 59 and 60 would be good for 110 volts at the same horsepower. The increased current at 110 volts is again taken care of by providing 4 times the copper section, as shown. This same principle can be extended, and when the number of poles for which the machine is wound can be divided by 6, it is possible to have the winding connected for 3 parallels or 6 parallels, as shown in Figs. 62

and 63, respectively. If divisible by 8, there could be 2, 4 or 8 parallels, and if divisible by 10, there could be 2, 5, or 10 parallels. It will be explained in a later chapter on "Changes in Voltage" that these possible changes when considered with the possibility of "star" or "delta" allow in many cases the reconnecting of motors for new conditions.

FIG. 62.—Three-phase, six-pole winding connected three parallel star.

FIG. 63.—Three-phase, six-pole winding connected six parallel star.

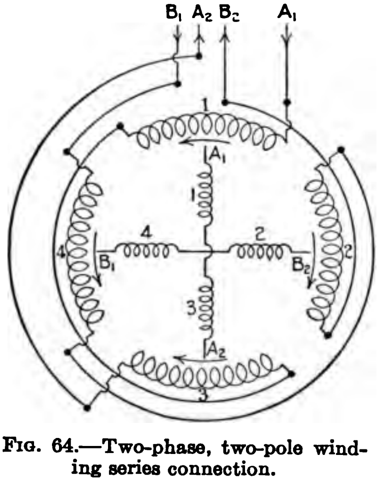


FIG. 64.—Two-phase, two-pole winding series connection.

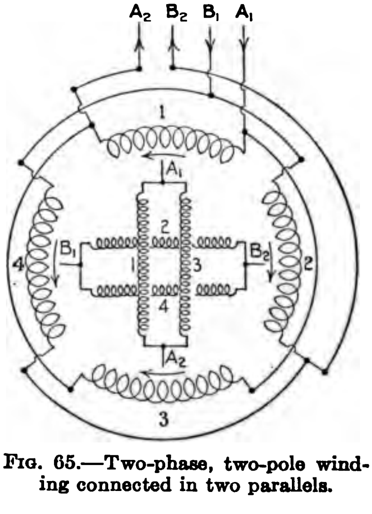


FIG. 65.—Two-phase, two-pole winding connected in two parallels.

How to Draw a Diagram to Suit Any Case.

As regards the number of possible diagrams, these multiply very fast. As an instance are shown the diagrams, Figs. 64, 65, 66, 67, 68 and 69. Here the simplest case is studied—that of two poles—and when two- and three-phase are considered, series and parallel, and star and delta, there are six possible diagrams of connection, as indicated. Considering for the moment a 12-pole winding,

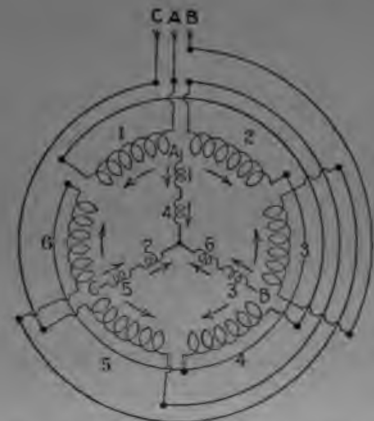


FIG. 66.—Three-phase, two-pole winding connected series star.

FIG. 67.—Three-phase, two-pole winding connected parallel delta.

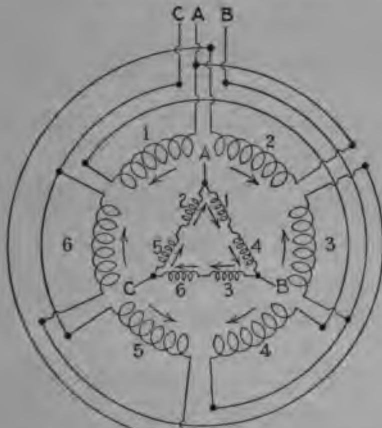


FIG. 68.—Three-phase, two-pole winding connected series delta.

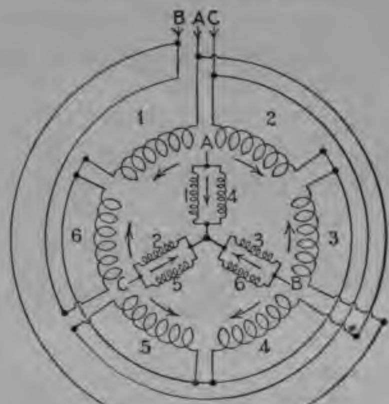


FIG. 69.—Three-phase, two-pole winding connected two parallel star.

there are possibilities for series, 2 parallel, 3 parallel, 4 parallel, 6 parallel and 12 parallel groups, which with two- and three-phase and star and delta give 18 diagrams total, just for 12 poles. It becomes plain that it is desirable to analyze these diagrams and arrive at a simple scheme by which any one can be drawn at need without the necessity of relying on a bulky collection of

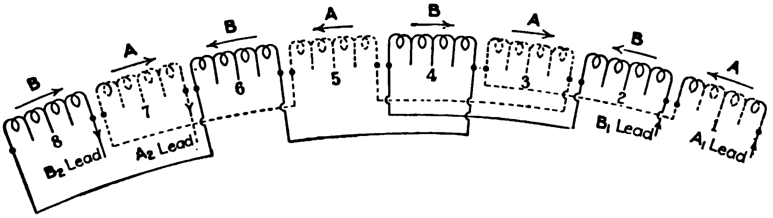


Fig. 70.—Two-phase, four-pole series connection.

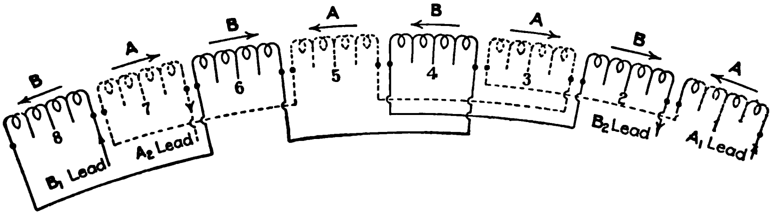


Fig. 71.—Same as 70 except "B" phase reversed.

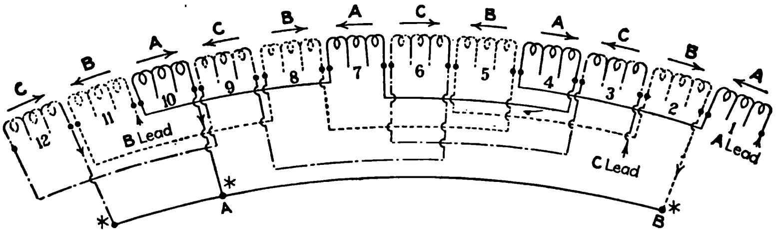


Fig. 72.—Three-phase, four-pole series star connection.

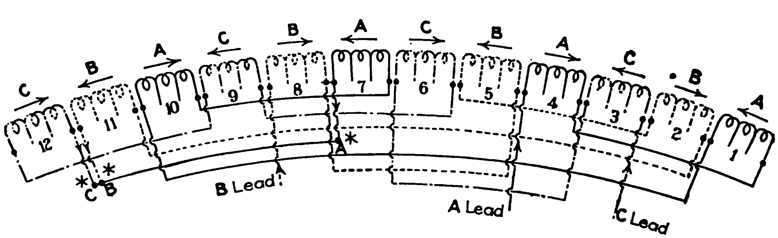


Fig. 73.—Same as Fig. 72 except leads brought out from different groups. General scheme of laying out pole phase group diagrams.

diagrams which may not be available when needed. In Figs. 70, 71, 72 and 73 is shown the method of laying out diagrams of this general nature. The first operation in making the connection is to connect the individual coils into pole-phase groups. There are as many coils in series in each group as the total number of coils in the winding divided by the number of phases times the number of poles. In Figs. 70 and 71 this is assumed to be 4 coils, and hence each pole-phase group is shown as having 4 individual coils in series. The next step, as shown in Figs. 70 and 71, for a two-phase machine is to letter the alternate groups *A*, *B*, *A*, *B*, etc., to designate the groups in the *A* phase from those in the *B* phase. The next step is to put on the arrows, as shown, in groups of two pointing in the same direction on two successive groups of coils. It does not matter what group is used to start with. The only essential is that there shall be first two arrows pointing clockwise and then two arrows pointing counterclockwise. The third step is to show the connections to the different groups so that the current at any given instant will pass through the groups in the same direction as the arrows. If this method is followed in laying out the connections of two-phase windings, the result will always be a diagram that shows the pole-phase groups connected in their proper relation.

Figure 71 is produced to compare with Fig. 70 to verify the statement already made that the arrows may be placed beginning with any group. In Fig. 70, beginning at the right, there are two arrows counterclockwise on groups 1 and 2, whereas in Fig. 71 the first two arrows counterclockwise are on groups 4 and 5. The only effect of this is to reverse the *B* phase, or in other words, the motor in Fig. 71 would have the opposite rotation of the motor in Fig. 70. Since this is at once corrected by reversing the leads of one phase outside the motor, it will be seen that if the internal connections are made according to Fig. 70 or 71, the motor will operate properly in all respects.

Three-Phase Star Diagrams.

The three-phase winding shown in Fig. 72 is even simpler. Here there are 3 coils per pole-phase group, and as in the two-phase winding the individual coils are first connected into pole-phase groups and the groups lettered consecutively *A*, *B*, *C*, *A*, *B*, *C*, to separate the phases. Then the arrows are put on as shown, first clockwise and then counterclockwise, alternately, beginning with any convenient group, it matters not which. The lines are then drawn in for the group connections as shown, following the convention that the arrow enters the lead or terminal of each phase and goes toward the star or common connection at the center of the winding. If this rule is followed, the connection will be correct and it is applicable to any combination of numbers of slots and poles. By keeping in mind either Fig. 70 or Fig. 71 for two-phase and Fig. 72 for three-phase, all diagrams of this type are mastered and can readily be reproduced at a moment's notice.

Delta Diagrams.

In checking a delta diagram, check it first as if it were a star diagram and then form the delta by connecting the star end of the *A* phase to the *B* lead, the *B* star to the *C* lead and the *C* star to the *A* lead. These three connections will be the delta points from which the three external leads are brought out. Another method of checking where it can be handled without confusion is to imagine the current flowing around inside the closed delta. The arrows on adjacent pole-phase groups will then alternate in direction as in the check on a star winding. This latter check may be applied to Figs. 67 and 68 by starting from terminal *A*, or any terminal for that matter, and following around through all the pole-phase groups back to *A*. For example, in Fig. 68, starting from *A* terminal, follow through group 1, then through 4, 3, 6, 5 and 2 back to *A*; thus a closed circuit has been made through all the groups in the direction of the arrows.

A further consideration of the arrows on the pole-phase groups of Fig. 72 shows that there might be a number of different connections, all correct, which check with these arrows and differ only as to the particular group from which the lead or the star connection are taken off. In fact, the lead or the star connection may be taken off from the proper end of any pole-phase group in a given phase so long as the cross-connections, when followed through, give the alternate arrows as shown. Fig. 73 is added to show one of these possible connections just as correct as Fig. 72, but with the leads and stars taken off from different pole-phase groups. Referring to the winding, Fig. 58, and again applying this rule, it will be found to hold good as indicated by the arrows. This demonstrates conclusively the correctness of this method of checking three-phase diagrams of this type.

CHAPTER IV

CHORDED WINDINGS OR THE EFFECT OF COIL THROW ON THE MAGNETIC FIELD

The effect of changes in frequency, phase, voltage or poles upon the performance of an induction motor and the necessary changes in the windings to preserve normal operation may be considered from the viewpoint of a change in voltage only and worked out by that method. By this is meant, for example, that a three-phase motor may be considered as a two-phase machine of a different voltage, in so far as the magnetic flux in the iron is concerned, also the heating, efficiency, torques, power factor, etc. Likewise a 25-cycle motor may be considered as a 60-cycle machine at a different voltage and operated accordingly.

A change in the number of poles can be looked upon as changing the speed of rotation of the magnetic field. With a given number of conductors this would at once affect the generated voltage or counter-electromotive force. It was explained in the second chapter that the counter-e.m.f. was practically almost equal to the applied e.m.f., or line voltage. Hence it may be seen that even a change in the number of poles can be considered as a voltage change and the number of wires in the coils correspondingly changed so as to give the same performance under the new conditions.

Since all these changes can be considered as voltage changes and will be so considered in the chapters to follow, it is necessary to investigate closely all the considerations that directly affect the voltage. The first one of these is the effect of winding the coils less than full pitch, or "chording" the coils, as it is most frequently called. The pitch, or span, is expressed in the number of the slots included between the two sides of the coil.

It is common knowledge that this pitch, or throw, must be somewhere near the quotient of the bore periphery of the core divided by the number of poles. For example, if the stator of a given motor had 72 slots and was wound for four poles, an individual coil would be expected to lie in slots 1 and 19 or there-

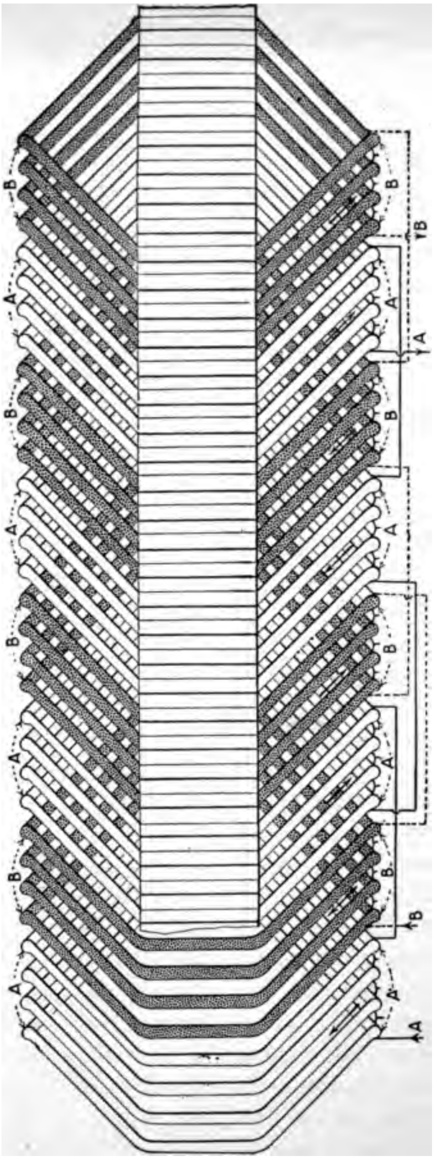


FIG. 74.—Thirty-two slot four-pole stator with coil throw of 1 and 9 or exactly full pitch.

abouts. The reason for this is that if there are four poles, the span of each coil must be somewhere near one-quarter of the bore periphery. In this case 72 ÷ 4 = 18 slots, and 18 + 1 = 19, hence the exact pitch for the coils of this winding would be 1 and 19. Similarly, a six-pole coil for the same core would lie in something like slots 1 and 13 and an eight-pole coil in slots 1 and 10. An examination of any induction motor wound in the usual way discloses the fact that the coils are seldom wound full pitch, as in Fig. 74, but always a few slots less, as in Fig. 75. It is the purpose of this chapter to discuss the reasons for winding the coils less than full pitch and the effect upon the voltage of the machine caused by this practice, which gives a fractional-pitch winding.[1]

One of the immediate results of spreading the coil less than full pitch is to place in the same slot coils carrying currents of different phases. This is illustrated in Figs. 74 and 75, which show a two-phase four-pole winding placed in 32 slots. In Fig. 74 the throw of the coil is 1 and 9, or exact pitch, and it can be seen, that all the slots contain coils entirely of the same phase; that is, all slots contain either *A* or *B* coils. On the other hand, in Fig. 75, the throw of the coil is one less than full pitch, or it is chorded one slot and wound in slots 1 and 8. As a result, it is seen that in slots 1, 5, 9, 13, etc., the coil lying in the top of the slot is of a different phase from the coil in the bottom of the slot. At first thought this appears to be an interference, but it is really not so, since the values of the currents in the two phases at a given instant are different; and since one is increasing and the other decreasing, the effect on the magnetic circuit is due not only to the amount of current in the two coils, but also to their phase relation. Hence the result of chording is not to make the two phases interfere with each other in any way, but simply to have a tendency to reduce the number of turns in the coils, as will be described. That the resulting magnetic field which rotates is due to the interaction of all the phases in this way was mentioned in Chapter II.

Advantages of Chording the Winding.

There are three main reasons for winding the coils less than full pitch: (1) The length of the mean turn is reduced; (2) it has

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[1] A longer theoretical discussion of fractional-pitch windings is found in the "Transactions of the A. I. E. E.," Vol. XXVI, 1907, pp. 1485–1503, Messrs. Adams, Cabot and Irving; and Vol. XXVII, 1908, pp. 1077–85, Jens Bache-Wiig.

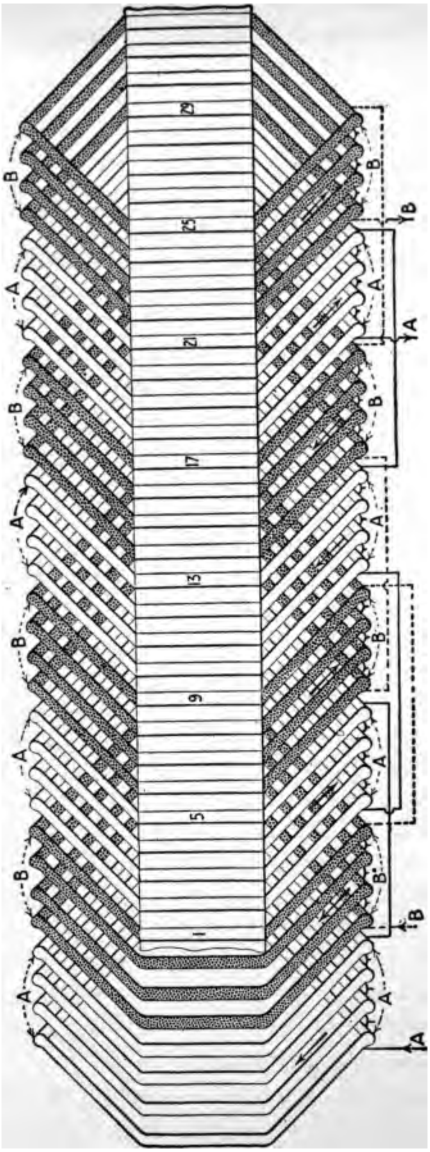

FIG. 75.—Thirty-two slot four-pole stator with coil throw of slots 1 and 8 or "chorded" one slot.

the effect of changing the number of turns in the coil; (3) the over-all length of the winding parallel to the shaft is reduced, thus requiring less space in the end brackets which carry the bearings.

Discussing these effects in order, the reduction in the length of the mean turn accomplishes two results: First, less wire is required to form the coils, which is a slight economy; and second, the total resistance of the winding is reduced. This reduction in resistance, in turn, has two beneficial results—the one a reduction in copper loss with a corresponding gain in efficiency and the other a reduction in heating, since the heating is measured by the total losses that must be dissipated. The reduction in cost and the improvement in performance are both of a relatively small order, but they represent the minor details in which a nicely balanced design has an advantage over one more crude. The reason for the shortening of the mean turn can be seen from Fig. 76. The coil *ABCDEF* is wound in slots 1 and 7 and the coil *AGHIJF* is wound in slots 1 and 6. It will be noted that the gain in length by the shorter coil is due not alone to the fact that the chord *AH* is shorter than *AC*, but also to the fact that the point *G* is considerably nearer the core than the point *B*; or in other words, the angle *AGH* is greater than *ABC*.[1]

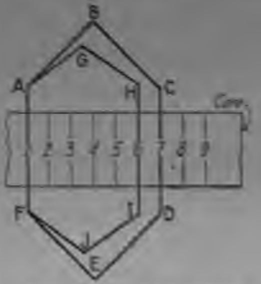

FIG. 76.—"Chording" shortens the length of wire in the coil.

The second effect of chording is that it acts in the same manner as changing the number of turns in series in the coil. Suppose, for example, that a designer of induction motors has made a calculation and finds that if six turns of wire are put in a coil there will be slightly too many turns for the best result, and if five turns are used there will be slightly too few. If there was not the recourse of chording the coil, it would be necessary to decide which was the lesser of the two evils, or else to change the number of slots. The latter might not be possible as it is desirable to have the total number of slots a multiple of the number of phases times the number of poles, and this could not be shifted in fine adjustments. However, it is possible to

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[1] See article in "Electric Journal," Vol. VIII, 94, by Gray E. Miller, on "Determining the Form of a Diamond Coil."

chord the coil and by the simple expedient of winding the coils one or more slots less than full pitch, the effect can be produced of putting 5½ or 5¾ turns in a coil, or in fact a very fine adjustment to give exactly the best possible combination. There would of course be six actual physical turns of wire in the coils, but their magnetic effect would be reduced by the chording to 5½ turns or whatever was desired.

The effect of the turns in the coil varies as the sine of half of the angle in electrical degrees which the coil spans. To illustrate, if there are 72 slots in an eight-pole machine, the coils would spread exactly full pitch if they lay in slots 1 and 10; or in other words, if there were eight slots between the two slots in which the two sides of any coil were located. Such a coil would span 180 electrical degrees. One-half of 180 deg. is 90 deg., and the sine of 90 deg. is 1; therefore the effect of the turns in such a coil is 1, or maximum. Suppose, instead, the coil lies in slots 1 and 8. It would then span 140 deg. electrically, since $72 \div 8 = 9$ slots represents 180 deg.; one slot therefore represents 20 deg. and seven slots 140 deg. The sine of half of 140 deg., or 70 deg., is 0.94. Hence it follows that the effect of the turns in this coil is less than that of the full-pitch coil by the ratio of 0.94 to 1.

Changing Poles with Constant Throw.

The foregoing is of interest in the present problem, because it is often possible in making alterations in the winding to change at the same time the span of the coils by one slot, more or less, by springing the coil mechanically, and so improve the performance of the machine under the new conditions. The point becomes of vital importance immediately when changing the number of poles without changing the throw of the coils. Referring again to the 72-slot motor, assume that the coils are wound in slots 1 and 8. For an eight-pole connection these coils will have an effect of 0.94 as explained. If the connections are changed for six poles, the effect is entirely different; $72 \div 6 = 12$ and $180 \div 12 = 15$, or each slot represents 15 electrical degrees. A throw of 1 and 8 covers seven complete slots, or $7 \times 15 = 105$ deg.; the sine of half of 105, or 52.5 deg. = 0.79, which means that when connected for six poles the coils have an effect of only 0.79, as against 0.94 when connected for eight poles.

It is possible to avoid using the sine of half the angle and secure a factor that is sufficiently accurate for all practical purposes by using the expression,

$$\sqrt{\frac{(\textit{Number of slots per pole})^2 - 2(\textit{Number of slots dropped})^2}{(\textit{Number of slots per pole})^2}}$$

Using the same eight-pole example as above, the number of slots per pole is 72 ÷ 8 = 9, and the pole pitch is 1 and 10. When the coil is wound 1 and 8, it spans 7 slots and there are 9 − 7 = 2 slots dropped. The expression then becomes

$$\sqrt{\frac{(9)^2 - 2(2^2)}{(9)^2}} = \sqrt{\frac{73}{81}} = 0.948$$

and similarly for the six-pole,

$$\sqrt{\frac{(12)^2 - 2(5)^2}{12^2}} = \sqrt{\frac{94}{144}} = 0.807$$

which agrees roughly with the other method.

Explanation of Term "Chord Factor."

A coil should in no case be chorded more than half of the pole pitch, as secondary disturbances of the magnetic field are occasioned by chording which become prohibitive at that point. The expression, "sine of half the angle spanned by the coil," is given the name "chord factor," and it should be considered in the work of reconnecting. For example, if the poles are changed from 8 to 6, as in the example given, and the chord factor changes from 0.94 to 0.79, the new line voltage should be 0.79 ÷ 0.94 times the old, neglecting the effect of other changes that are being made. If nothing else was undergoing change and the normal voltage was 440 in the first place, it should be $440 \times \frac{0.79}{0.94} = 370$ after the change is made; or, expressing it another way, if it was still operated at 440 volts after the change, the motor should be thought of as operating at about 18 per cent. over voltage.

Since the foregoing is one of the important points in induction-motor winding, it is worth while to consider carefully how this effect is produced. It could be stated briefly by saying that the two sides of the coil, which of course are in series, are not strictly in phase with each other. But this can be seen more clearly from diagrams. Suppose, for example, that a two-pole motor is considered and that a cross-section is taken through the core and windings in a plane at right angles to the shaft, as shown in Fig. 77. The dotted parallel lines in the peculiar twin pattern represent the lines of force, or magnetism of the rotating magnetic field, which is rotating in a clockwise direction, as shown by the arrow outside. The small arrows on the lines of flux indicate the magnetism coming from the stator north pole at the top into the rotor core and out again into the stator at the bottom, forming a south pole.

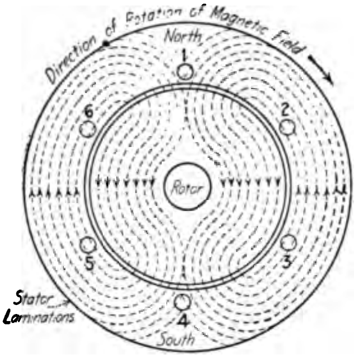


FIG. 77.—Cross-section through a two-pole stator showing magnetic lines of force.

Of course this magnetic field is being set up by polyphase alternating currents, but it need only be thought of as shown in the figure and as if excited by direct current. The six small circles, in the stator and near the bore, numbered 1 to 6, represent the conductors of the stator winding. Consider that these six conductors constitute the complete winding. As the magnetic field swings around in a clockwise direction, it cuts these six conductors because without doing so it cannot get from the stator into the rotor and back and at the same time rotate. As the conductors cut this field, each one generates a voltage which in value and direction may be represented by the arrows or vectors of Fig. 78.

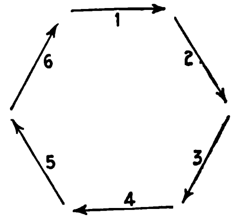


FIG. 78.—Vector diagram showing direction at any instant of voltages generated by conductors in Fig. 77.

The reason these voltages are shown in a hexagon is because they are not all generated at the same time, but in a succession. For example, the north pole sweeps by conductor No. 1 and a fraction of a second later past No. 2 and then past No. 3 and so on around to No. 6, and this can be represented by the sides of a hexagon which finally closes on itself, as shown in Fig. 78. The reason the arrows for conductors No. 1 and No. 4 are shown in the same direction is because the north pole is sweeping past No. 1 to the right at the same instant that the south pole is sweeping past No. 4 to the left, so that the voltages in these two conductors are in the same direction at the same instant. Similarly, Nos. 2 and 5, and Nos. 3 and 6 are alike in pairs. Suppose now that No. 1 and No. 4 had their ends connected together both at the front and the back of the machine so that they formed a short-circuited turn. The voltage then which would be effective in forcing current around this short-circuit would be that generated in No. 1 plus that in No. 4 and may be represented by line No. 1 plus No. 4, or *KL*, shown in Fig. 79. *KL* then would represent the voltage of a coil wound exactly full pitch or from the center of a north pole to the center of a south pole.

Suppose, instead of No. 1 and No. 4, that No. 1 and No. 5 had their ends connected so as to form a short-circuited turn. The voltage which would be effective in forcing current around through this short-circuit would be *MN*, shown in Fig. 80, which it will be seen is somewhat less than *KL* in Fig. 79. The arrow *MN* is made by adding 1 and 5 which in themselves are just as long as 1 and 4, but instead of lying in a straight line they are at an angle to each other. This angle shows what is meant by the two sides of the coil being out of phase with each other, or still another way to say it would be that the magnetic field is not working on No. 1 and No. 5 in exactly the same way at the same instant as it was on No. 1 and No. 4. Therefore, when No. 1 and No. 5 are short-circuited giving the voltage *MN*, they represent a coil chorded to two-thirds of full pitch, or they have the effect instead of being two conductors in series, of being only 2×0.866 conductors, or 1.73 conductors. This is because two-thirds pitch would be $\frac{2}{3} \times 180$ deg. $= 120$ deg. and the sine (0.5 of 120 deg.) = sine 60 deg. = 0.866.

FIG. 79.—Adding voltages generated by conductors 1 and 4, Fig. 77.

FIG. 80.—Adding voltages of conductors 1 and 5, Fig. 77.

FIG. 81.—Adding voltages of conductors 1 and 6, Fig. 77.

In the same way conductors No. 1 and No. 6 could be joined in series to form a short-circuited turn, and the voltage of such a turn would be represented by *OP* in Fig. 81 which is made up of No. 1 and No. 6, which are at an angle of 60 deg. with each other. In this case, instead of having the effect of two conductors in series so far as voltage generation is concerned, the effect will be that of only one, since 1 and 6 represent one-third pitch, and ⅓ of 180 deg. = 60 deg. and the sine (0.5 of 60 deg.) = sine 30 deg. =0.5. Therefore 2×0.5 =1. Of course 6 slots per pole is a small number and it can be seen that with 12 or 15 slots per pole at his disposal the designer can chord to get almost any value required.

Effect of Chording.

It will be noted that in this graphic explanation the conductors were spoken of only as generating counter-e.m.f., as explained in the first chapter and never as setting up the field. However, it should be understood that in the magnetizing function of the winding, also, the chording produces the same effect as explained here by means of the generator idea.

The third effect of chording has been mentioned as shortening the coils axially. This is very useful, especially in the case of two-pole and four-pole machines where the coils, if made full pitch, would protrude so far at each end as to require special end brackets. These long end brackets in turn would spread the bearings farther apart and make necessary a larger shaft to keep down the shaft deflection. Hence it is of prime importance to shorten up on the coil ends in this manner. Also, the end windings are mechanically stiffer. There are other effects of chording known to the designer, which are desirable. These are, for example, a reduction in the leakage reactance, thereby giving better torques and possibly better power factor and efficiency. Also, it is very beneficial in reducing magnetic noise to employ chording, depending on the combinations of slot numbers, so that, taken all in all, chording is one of the prime features in studying the effect of winding changes upon the performance of a machine.

Distribution Factor Less Important.

Another winding factor that acts in a similar manner to the chord factor just discussed is the one known as distribution factor. This is not subject to control as is the chording and is relatively much less important, but should be mentioned in passing, as its neglect might occasion trouble if a combination was employed which otherwise was on the ragged edge of failure. This distribution factor has to do with the fact that the coils in one phase of a two-phase motor are spread over half of the face of a pair of poles and in a three-phase motor are spread over one-third of the face of a pair of poles. This factor varies a trifle with the number of slots per phase and pole, but a fair value for average two-phase windings is 0.905, which is about the ratio of one side of a square inscribed in a circle to one-fourth of the circumference. For a three-phase machine a fair average value is 0.955, which is practically the ratio of one side of a hexagon inscribed in a circle to one-sixth the circumference, or 3 ÷ 3.14.

Ordinarily this factor is not troublesome and if forgotten in changing from two- to three-phase, or vice versa, would not cause any great disturbance. However, in dealing with special machines—as for example, motors wound for two sets of poles—the distribution factor may be more important than the other factors. In such a case the two-phase distribution factor may be as low as 0.707 and the three-phase as 0.866 because the coils for a four-pole motor, for example, are spread over the pole face of an eight-pole. Mention is made of this fact in connection with Fig. 138, Chapter IX.

Phase Insulation Important.

Another general factor is that of "phase insulation." It is the practice of many manufacturers to put heavier insulation on the coils at the ends of the polar groups which are mechanically adjacent to one another and which are also subjected to the voltage between phases, which may be the maximum voltage between supply lines. Such coils are drawn in heavy lines in Fig. 55. By rearranging this diagram for two-phase it appears at once that both the number and location of these so-called "phase-coils" are changed, and in changing the number of poles, the number and location of the phase-coils must also be changed. In fact, whatever reconnection is attempted, the phase coils should be checked and rearranged, since this is comparatively easy and adds considerably to the protection of the machine from breakdowns of insulation.

To illustrate the manner in which the phase coils should be rearranged when changing phases or poles, Figs. 82 to 85 are shown. All four of these figures show the same winding in 48 slots and with a coil throw of 1 and 9. In Fig. 82 the phase coils are arranged for three-phase four-poles, in Fig. 83 for two-phase four-poles, in Fig. 84 for two-phase eight-poles and in Fig. 85 for three-phase eight-poles. It will be noted that since the throw of the coils remains unchanged, it represents a chord factor corresponding to two-thirds pitch, or 120 deg. for the four-pole winding (since 8 slots = $\frac{2}{3}$ of 12) and a chord factor correspond-

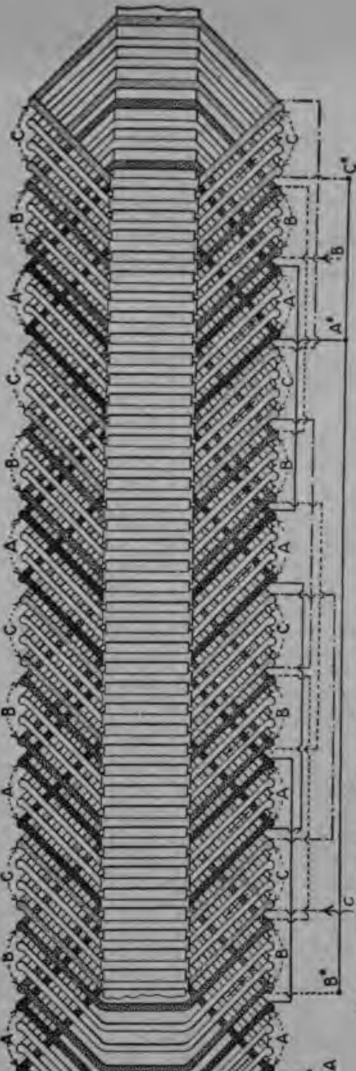


Fig. 82.—Forty-eight slot stator with "phase coils" arranged for three-phase, four poles.

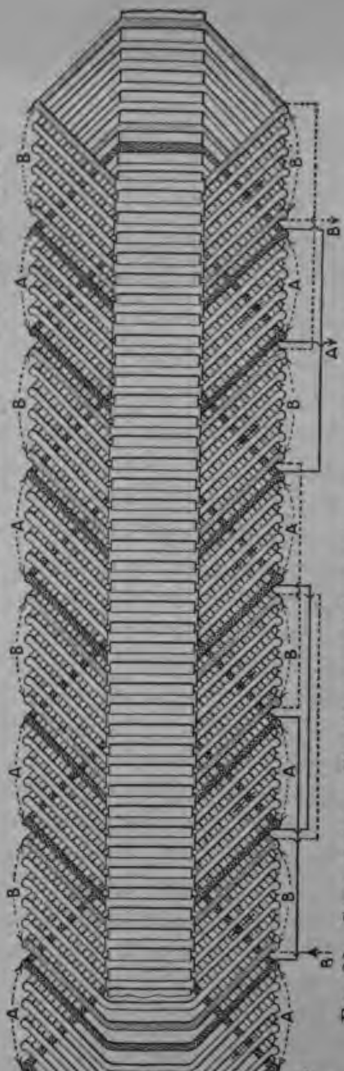


Fig. 83.—Same stator as Fig. 82 except "phase coils" arranged for two-phase, four poles.

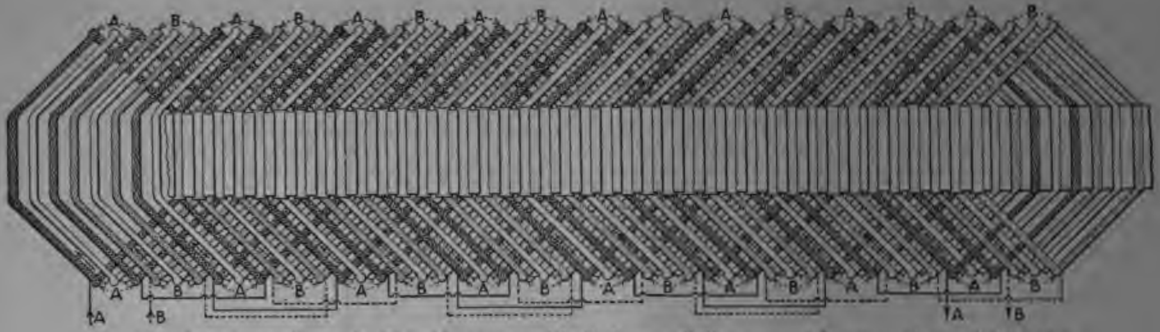


FIG. 84.—Stator as shown in Fig. 82 except with "phase coils" arranged for two-phase, eight poles.

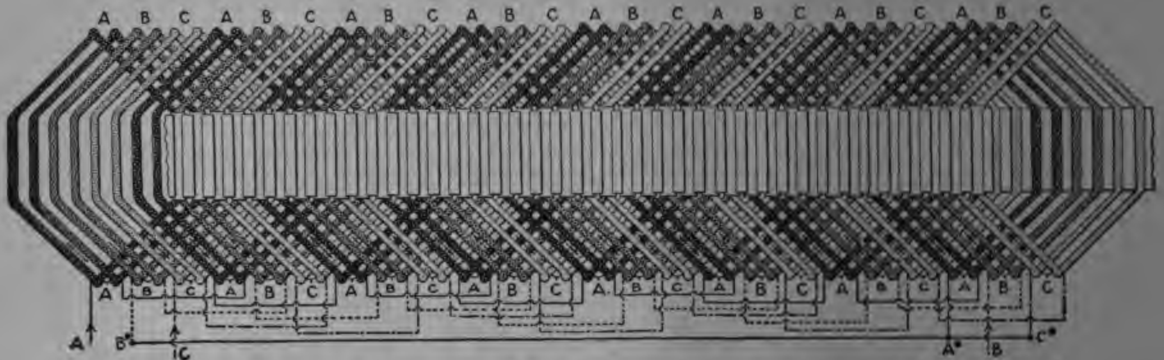


FIG. 85.—Stator as shown in Fig. 82 except with "phase coils" arranged for three-phase, eight poles.

ing to one and one-third or 240 deg. for the eight-pole winding (since 8 slots = 1⅓ of 6). Since the chord factor is equal to the sine of ½ the spread angle and since the sine of 120 deg. = the sine of 60 deg. = 0.866, the effect of the underchording on the four-pole winding is exactly the same as the effect of the overchording on the eight-pole winding.

In all four diagrams the coils having heavier insulation than the others are shown shaded, the different degrees of shading representing the coil having additional insulation in the different phases. In Fig. 82 there are 12 pole-phase groups of four coils each. The two outside coils of each group have heavier insulation, as indicated; this will give 24 phase coils, or one-half the winding is phase coils. The winding Fig. 83 has eight pole-phase groups, with 16 phase coils, or one-third of the total winding is phase coils. In Fig. 84 the winding has 16 pole-phase groups, making it necessary that there be 32 phase coils. The arrangement in Fig. 85 gives 24 pole-phase groups of only two coils per group, hence all the coils must be phase coils with increased insulation.

Plotting Pictures of the Magnetic Field.

In Chapter II there was shown a method of plotting a physical representation of the rotating magnetic field as it varies from point to point around the air gap of an actual machine. The same method may be used to show what effect is produced on its shape by changing the throw of the coil, or chording the winding as it is called. The latter effect is thus investigated for a change of one slot at a time from full pitch to less than half pitch. By full pitch is meant that the span of the coil is exactly the same distance as that from the center of a north pole to the center of an adjoining south pole, and by half pitch that the coil spans or throws only half that distance. Referring to Figs. 17 and 18 of Chapter II the small "stair step" figures represent cross-sections of the magnetic field existing in the motor as the alternating currents in the windings vary in value from instant to instant, and a comparison of the small figures shows that the magnetic field actually travels around the stator bore or "air gap" at a uniform rate. The number of revolutions that it makes in one minute is equal to 120 times the number of cycles per second of the supply circuit divided by the number of poles in the stator. Expressed in symbols this would be $S = 120\frac{f}{p}$; where S is the speed of rotation in r.p.m., f is the frequency in cycles per second, and p is the number of poles.

In order to make clear the field photographs or diagrams of the present chapter and to obviate the possibility of confusion regarding them, attention is called to the fact that they represent the conditions existing in the windings at an instant of time when the current in one of them is at its maximum value. Since we are dealing with three-phase motors, the currents in the windings connected to the other two phases will at that instant both be equal to one-half their maximum values. This may be explained by reference to Figs. 17 and 18 of Chapter II, which represent the values of the currents in the three phases for every 30 deg. of a complete cycle of 360 deg. Suppose these three currents are represented by the three branches, A, B and C of the "Y" illustrated in Fig. 86, each of which is 120 deg. from the other, and that a vertical reference line hk is drawn through the center o. Now assume that the "Y" rotates in a counterclockwise direction about this center while the line hk remains stationary, and that the three branches assume the successive positions represented in the second column of Fig. 87. The values of the currents at any instant of time will be represented by the length of their horizontal projections upon the line hk. If the maximum value of each current is assumed to be one ampere, the instantaneous values of the three for each 30 deg. of a complete cycle would be those given in the last three

FIG. 86.—Normal relation of the currents in a three-phase motor.

columns of Fig. 87. Projections that lie above the center *o* are taken to be positive and those that lie below as being negative.

In Chapter II there was given a picture of the field corresponding to each instantaneous value of the currents, but in the present chapter the figures are given for only one of these values and they have been chosen to be the ones existing when the condition is that shown for 0 deg. in Fig. 87, that is, for the instant when the current in the *B* phase is at its plus maximum value and the currents in the *A* and *C* phases are at minus one-half their maximum values. Of course, any other position could have been chosen for conducting the investigation, but the values for the 0 deg. position are convenient ones to use when plotting the results.

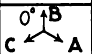
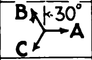
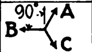
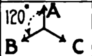
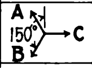
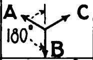
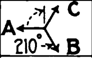
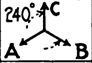
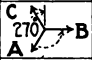
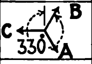
ANGLE. DEG.	POSITION OF BRANCHES OF Y	CURRENT A AMPERES	CURRENT B AMPERES	CURRENT C AMPERES
0		-0.5	+1.0	-0.5
30		0	+0.866	-0.866
60		+0.5	+0.5	-1.0
90		+0.866	0	-0.866
120		+1.0	-0.5	-0.5
150		+0.866	-0.866	0
180		+0.5	-1.0	+0.5
210		0	-0.866	+0.866
240		-0.5	-0.5	+1.0
270		-0.866	0	+0.866
300		-1.0	+0.5	+0.5
330		-0.866	+0.866	0
360	Same as 0 Deg.			

FIG. 87.—Instantaneous values of the currents in a three-phase motor throughout a complete cycle.

Effect of Chording Shown Graphically.

Since one of the effects of reconnecting for a different number of poles is to affect the "chord" or throw of the coil, let us consider first the effect of "chording." Figs. 88 to 93 inclusive show the magnetic field constructed, as explained in Chapter II for a 54-slot three-phase 6-pole winding when the throw of the coil is changed one slot at a time from slots 1 and 10, as in Fig. 94, which is full pitch or 180 deg., down to slots 1 and 5, as in Fig. 95, which is less than half pitch; or to be precise, 80 deg.

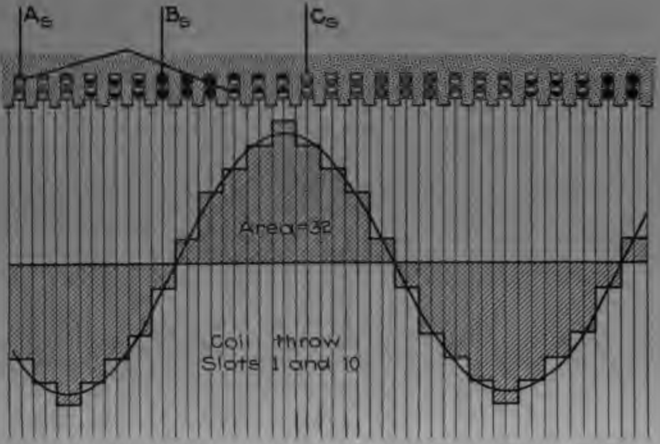


FIG. 88.—Picture of magnetic field set up by winding in Fig. 94.

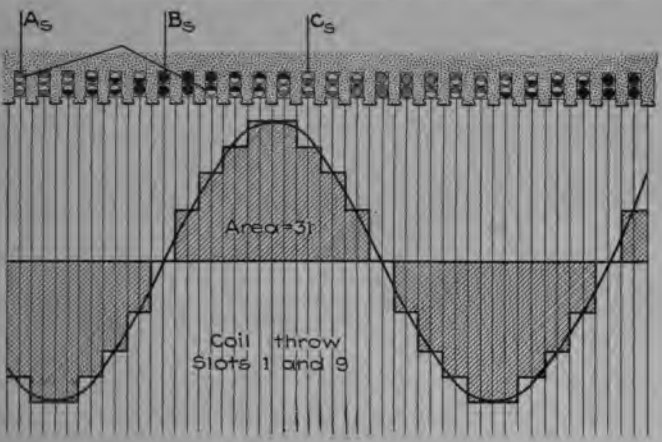


FIG. 89.—Magnetic field if winding in Fig. 94 is chorded to slots 1 and 9.

The same magnetizing current is assumed to flow in the coils in all six cases, although in an actual machine this would not be the case; the magnetizing current would increase with decreased throw of coil due to the attempt of the motor to keep the field at the constant value necessary for the generation of the required back or counter-electromotive force. To facilitate comparison,

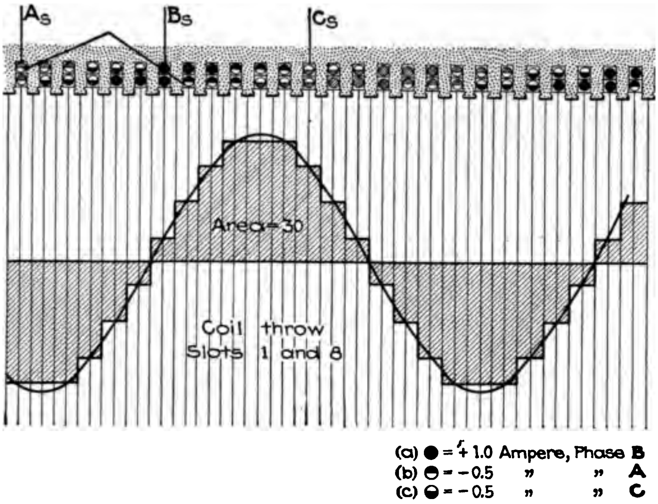


FIG. 90.—Magnetic field if winding in Fig. 94 is chorded to slots 1 and 8.

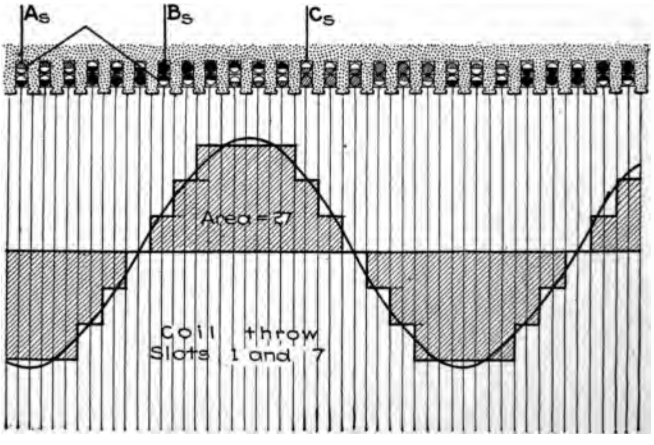


FIG. 91.—Similar to Fig. 90 except chorded to slots 1 and 7.

however, this change in current has been disregarded in the figures. The "stair steps" show the magnetic fields as they would look if there were no winding on the rotor, and the smooth

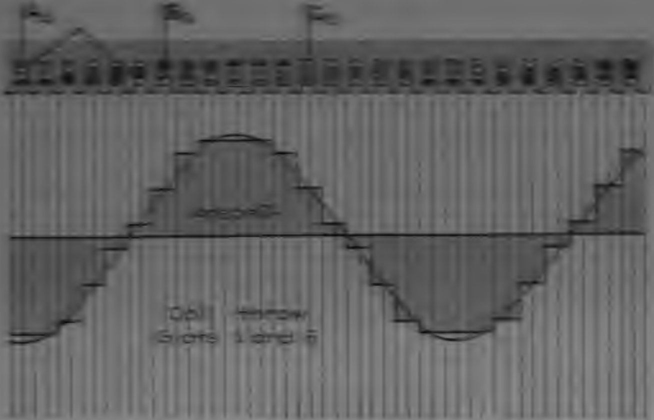


FIG. 92.—Similar to Fig. 91 chorded to 1 and 8.

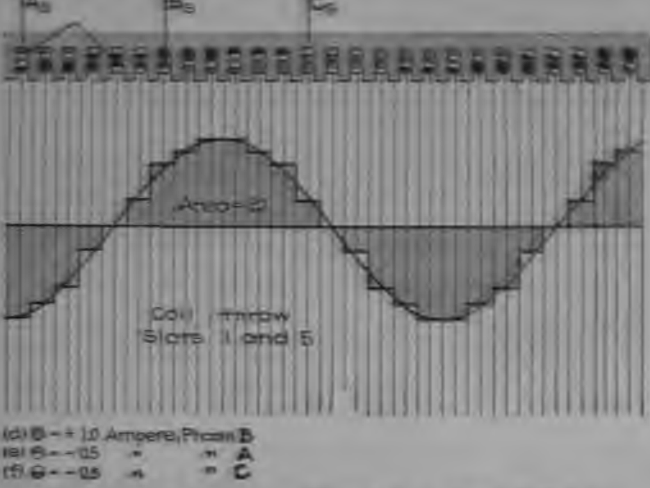


FIG. 93.—Similar to Fig. 92 chorded to 1 and 5 as in Fig. 90.

curves, having the sine shape, show the fields as they look after being smoothed out by the currents in the rotor winding. It will be noticed that the area of the field for one pole is given in each case and that it varies from 32 for full pitch in Fig. 88, down to 20 in Fig. 93. These areas correspond to what is known as the "chord factor" of the winding. In the earlier part of this chapter it was stated that the chord factor for a chorded winding could be expressed in its effect on the magnetizing or no-load current and in its effect on the generated or counter-electromotive force by the mathematical value of the sine of one-half the electrical angle spanned by the coil. This relation is shown in the following table:

Table I.—Chord Factors for Various Angles

Figure	Angle spanned by coil = a deg.	Sine ½a, or chord factor	Area of magnetic pole figured from chord factor	Area of magnetic pole graphically from figure
88	180	1.000	32.0	32
89	160	0.985	31.5	31
90	140	0.940	30.1	30
91	120	0.866	27.7	27
92	100	0.766	24.5	24
93	80	0.642	20.5	20

The slight difference between the last two columns in the table is due to the area under the "stair step" curve not being quite the same as the area under the corresponding smooth sine curve. The chord factor as shown in the third column at once indicates two facts: First, that if the winding is chorded more current will have to flow in the windings to produce the same magnetic field strength; and second, that since the generated or counter-electromotive force in the windings set up by the rotating magnetic field is reduced through chording by the amount indicated by the chord factor, it is necessary to have a stronger magnetic field in the motor if it is to operate at the same voltage when the coil is chorded up. The way this shows up in reconnecting for different numbers of poles, when the reconnection causes chording of the coil, is that the same effect is produced as would be if the motor were connected to a higher voltage. This will be explained fully in a later chapter dealing with the practical application of the principles presented in this chapter to the actual work of reconnecting.

An examination of the shape of the magnetic field indicates that the effect of chording is to flatten the top of the field and make it lower for the same pole span. In Fig. 96 is shown the

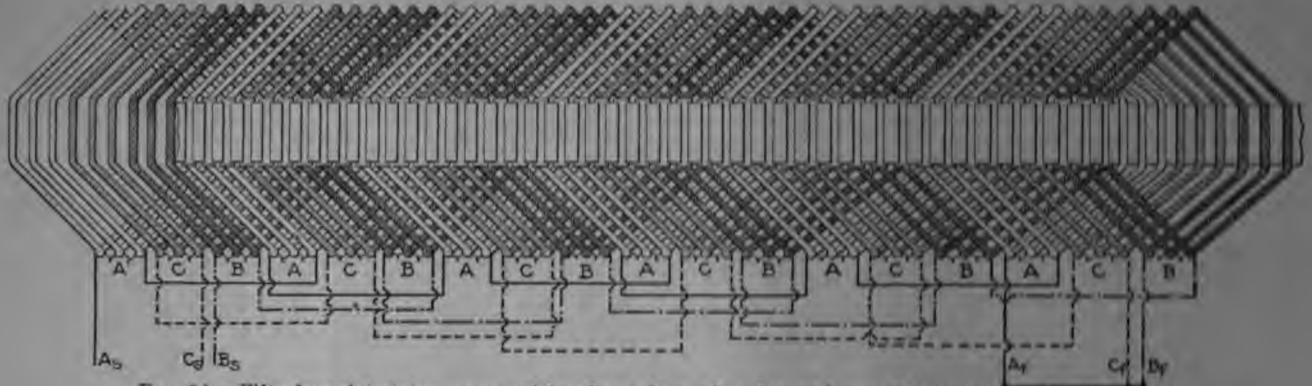


FIG. 94.—Fifty-four slot stator connected for three-phase, six poles, and wound full pitch, in slots 1 and 10.

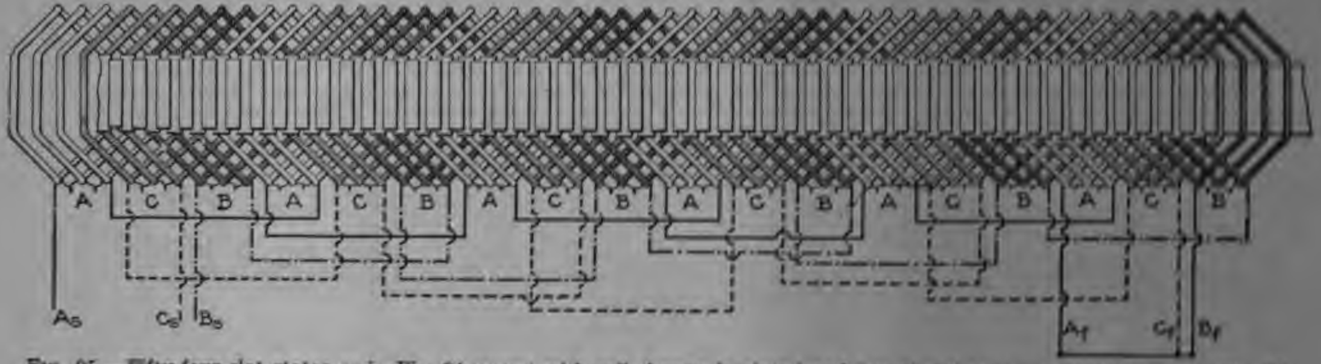


FIG. 95.—Fifty-four slot stator as in Fig. 94 except with coil thrown in slots 1 and 5 to give the magnetic field shown in Fig. 93.

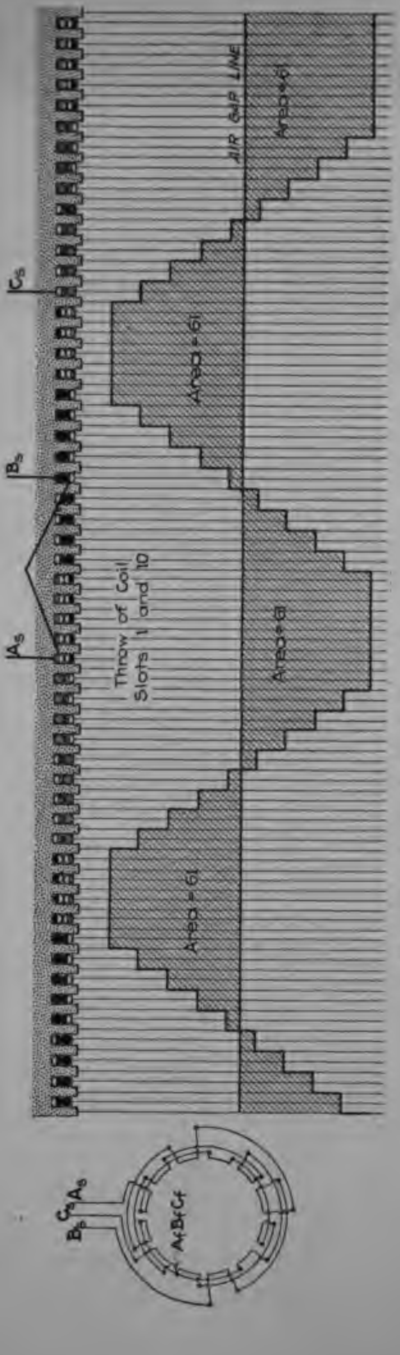


FIG. 96.—Stator shown in Figs. 88 and 94 connected for four poles.

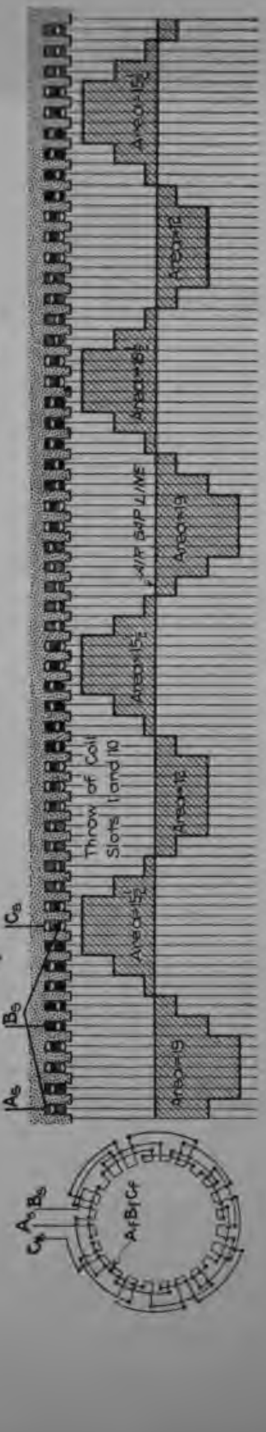


FIG. 97.—Stator shown in Fig. 94 connected for eight poles.

effect of connecting the winding of Figs. 88 and 94 for four poles instead of six. The mechanical throw of the coils is still 1 and 10, but the pole arc is longer for four poles, hence, the coil is actually chorded to 120 electrical degrees for four poles, although it was full pitch, or 180 deg., when connected for six poles. It will be noted that with the 6-pole winding, Fig. 88 the entire area of the poles is $6 \times 32 = 192$, but that for the 4-pole winding, Fig. 96, the area is $4 \times 61 = 244$. In the 4-pole winding, the speed of the rotating field is 1.5 times that of the 6-pole one, and it would therefore seem reasonable that with the same magnetic field density in the air gap and the same currents in the windings, the horsepower when connected as a 4-pole machine should be 1.5 times that of the 6-pole rating. However, since the coil throw on four poles is only 120 deg. the chord factor is sine of 60 deg. = 0.866 and the rating will be reduced by this fact so that only 1.5×0.866, or about 1.3 the 6-pole horsepower can be expected. The total areas of the two fields as previously noted—namely, 244 and 192—have the relation $^{244}/_{192} = 1.27$, which is very close to 1.3, so it follows that a close approximation of the output to be expected from a reconnected motor can be obtained by this simple method of plotting the magnetic fields and comparing the areas. The difference in the saturation of the stator iron would affect this result to some extent, but usually not enough to introduce a serious error.

In Figs. 97, 98 and 99 is shown the effect upon the magnetic field of reconnecting the winding shown in Figs. 88 and 94 for 8, 10 and 12 poles, respectively. The effect of chording becomes more pronounced with each step, and the decreased area of the magnetic field shows that with the decreasing speed the horsepower decreases also until finally in Fig. 99 an impossible condition is reached under which the motor could not run at all, since the throw of the coil is exactly pitch for 6 poles and therefore substantially becomes dead when connected for 12 poles; or putting it another way, the throw of the coil is such that when there are 12 poles both sides of any given coil lie in exactly the same polarity; one side is under a north pole and the other, instead of being under a south pole, reaches clear across and lies under the next north pole, so that the counter-electromotive force, which is generated in one side of the coil, is exactly balanced and neutralized by the voltage generated in the opposite side

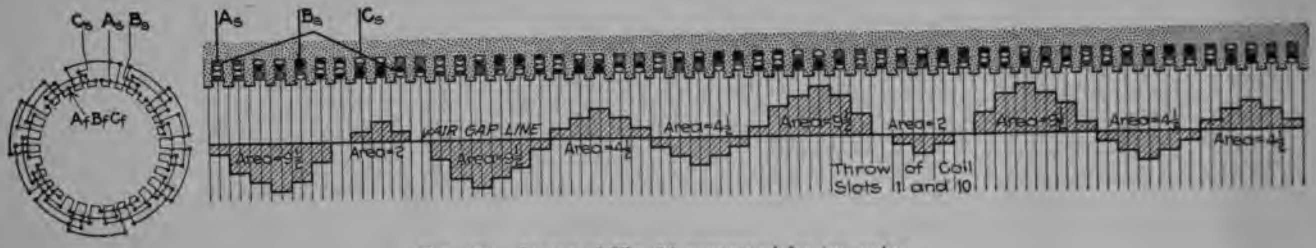


FIG. 98.—Stator of Fig. 94 connected for ten poles.

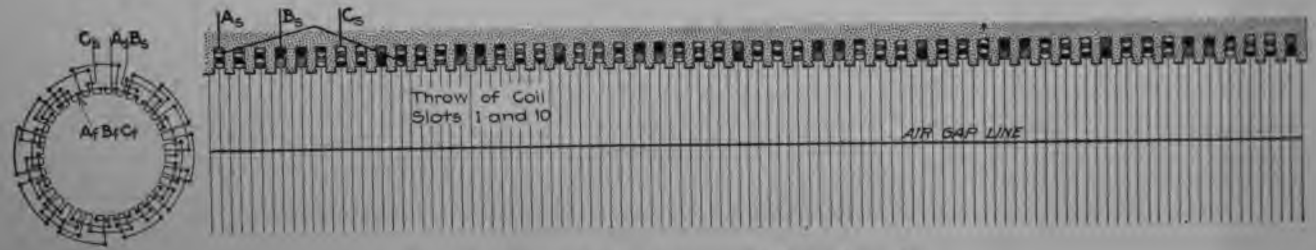
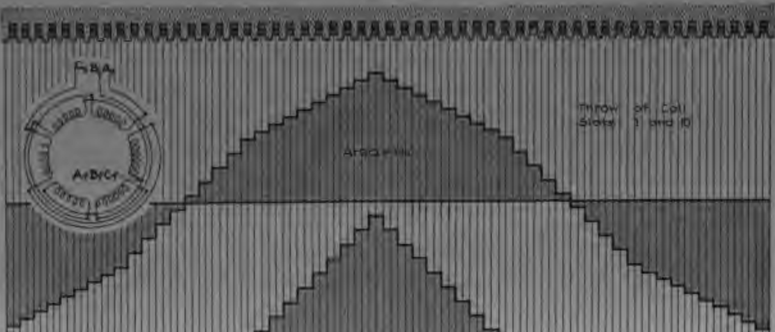


FIG. 99.—Stator of Fig. 94 connected for twelve poles.

and there is no counter-electromotive force left to oppose the applied electromotive force at the stator terminals, consequently, the current in the stator winding is limited only by the ohmic resistance of this winding, and would cause the circuit-breaker to open, or, if the motor was not properly protected, cause the windings to be destroyed in a very short period. Attention was called to this point in an earlier chapter when speaking of the possibility of connecting some windings as they stand for double or half speed; that is, for half as many poles or twice as many poles. The statement was then made that this should not be attempted if the throw of the coils was exactly pitch on the original winding.

Fig. 100.



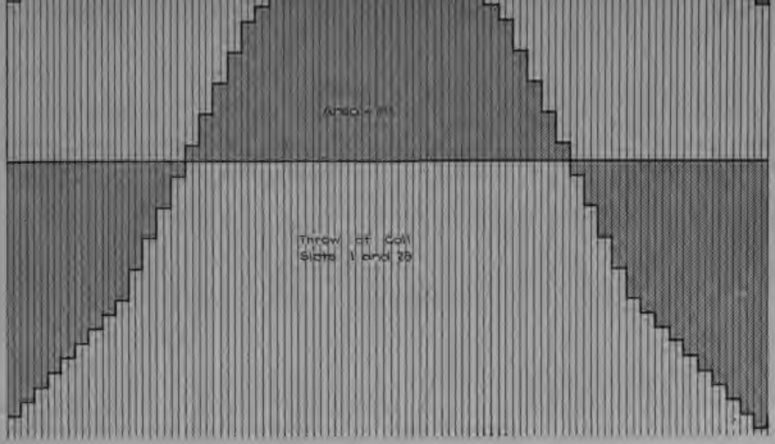


Fig. 101.

Fig. 100.—Stator of Fig. 94 connected for two poles.
Fig. 101.—Stator of Fig. 94 rewound for two poles with coils of correct throw. Note improvement in Fig. 101 over Fig. 100.

Fig. 99 explains why this is true and why such a reconnection is not feasible.

In Figs. 100 and 101 is shown a very interesting comparison. Fig. 100 shows the result of reconnecting the 6-pole winding of Figs. 88 and 94 for two poles. Ordinarily, this would not be possible because a 2-pole motor would require about three times the radial depth of iron behind the slots as is required by a 6-pole one; but assuming for illustration that such a reconnection had been attempted, the field would have the appearance shown, and it will be seen that the area of one magnetic pole would be 142. Suppose, on the other hand, that instead of reconnecting, the motor had been rewound with coils having a throw of 180 deg. for two poles or full pitch, as shown in Fig. 101; then the area of the field would be 284 for one pole or just twice the value for the reconnected motor. Since, as has been shown, the comparative areas of the two poles are some measure of the output to be expected, it can be at once concluded from Figs. 100 and 101 that the use of a new set of coils would double the output of the motor and that it would be poor economy in such a case to reconnect instead of rewinding.

The comparisons made give a good idea of the effect upon any motor of changing the throw of the coil. The main value of the latter idea is that it is often possible when reconnecting a winding to assist in getting normal conditions in the winding by changing the throw of the coils by a slot or two in a certain direction.

CHAPTER V

EFFECT OF VOLTAGE ON WINDINGS AND POSSIBILITY OF CONNECTING A WINDING FOR MORE THAN ONE VOLTAGE

Changing the winding connections of induction motors to accommodate a changed voltage supply is more often considered and accomplished than any other winding change. As was suggested in an earlier chapter, this may arise from the purchase of a used motor, a change in power supply from an isolated plant to central-station power, the remodeling of an old distributing system or in other similar ways. It was stated in Chapter IV that other changes, whether of phase or frequency or speed, could be considered as voltage changes and so worked out. This chapter outlines the considerations involved in the simplest form of voltage changes, thus establishing a basis for the solution of changes in the other characteristics.

In changes of voltage there are two main conditions that have to be met if the operation of the motor is to be kept normal. The first is to determine whether the insulation on the winding is proper for the new voltage that is to be used, and the second is how to adjust the number of turns in series in the winding, so that there will be substantially the same voltage per turn or per coil in the winding as existed under the original voltage. It is assumed that there is to be no change in the frequency of the supply circuit, the throw of the coils, the number of poles in the winding, the horsepower output or the number of phases.

Checking Insulation for New Voltage.

In considering the insulation alone, if the new voltage is to be lower than the old, no further attention need be given this point other than to determine that the insulation is mechanically in good condition and clean and dry. If the new voltage is higher than the old, the amount of insulation must be considered, and if there is any question as to this, it should be settled by the insulation tests described in the following, before proceeding with the actual work of reconnection. This may sometimes save work that would otherwise be lost by discovering too late that the insulation is inadequate for the new conditions.

In many cases suitable facilities are not available for making either of the insulation tests described, and it is well to have some general information on the standard practice followed by good manufacturers with regard to insulation. There is an old saying among insulation engineers that "a winding that will stand any insulation test at all will stand 1000 volts." Like most general statements, this is not strictly true, perhaps, but it brings out the fact that the insulation for all voltages up to 750 volts is practically the same and is determined more by mechanical strength than by strictly electrical considerations. This means that usually a 110- or a 220-volt machine will be all right on 440 or 550 volts provided the number of turns in the winding is suitable for the higher voltage.

Sometimes the insulation for 550 volts is increased over that for 440, but most 440-volt insulation will stand 550 volts if in good condition and the operating temperature of the machine is reasonably cool. Voltages between 550 and 2200 are seldom met with commercially, and the caution which needs to be observed is that machines wound for 550 volts or below should not be operated on 2200 volts even if the number of turns in the coils could be properly arranged. However, there is no reason why machines built for a higher voltage should not be operated on a lower. The only handicap in such a case would be that the temperature would be somewhat higher, owing to the insulation being heavier than would be required for a machine normally wound for the lower voltage. In order to indicate the limits on different classes of insulation, the following shows broadly the classification followed by many manufacturers: Class I, up to and including 500 volts; Class II, from 500 to 1200 volts; Class III, from 1200 to 3500 volts; Class IV, from 3500 to 6000 volts; Class V, from 6600 to 8000 volts. Very few induction motors are built at voltages higher than 6600.

The general statement may be made regarding these classes that any machine of a higher-voltage class may be operated on a lower voltage, but no machine in a lower class should be operated on a higher voltage than its own class.

Insulation Tests.

Where a reference to classification will not settle this matter or there are a number of units involved and the possibility of reconnection is serious, tests should be made. The insulation of electric machines may be tested in two ways—one measures its ability actually to withstand the voltage strains that occur between the parts of the winding and the ground, and the second determines the condition of the insulation as to dryness and cleanliness. The first is called a test for dielectric strength and is performed by applying for one minute, between the winding and the ground, an alternating voltage equal to twice the normal voltage of the circuit to which the apparatus is to be connected, plus 1000 volts.[1]

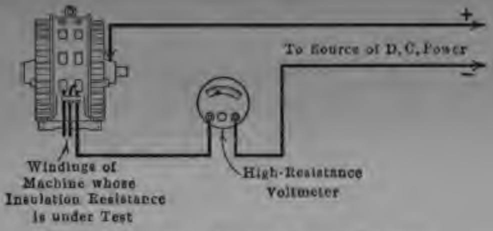


Fig. 102.—Test for insulation resistance.

The second test is called a test for insulation resistance and is usually made by applying a direct-current voltage of 500 volts between the conductors in the winding and the ground, having a direct-current voltmeter of high internal resistance in series with the insulation. Since the insulation is in series with the circuit, there will be practically no current flowing, but the direct-current voltmeter will show a slight deflection and the insulation resistance is measured thereby. The arrangement of this test is shown in Fig. 102.

Then the insulation resistance R of the winding under test is given by the following equation:

$$R = \frac{r\,(E - e)}{e}$$

where

r = internal resistance of the voltmeter, which must be known and is usually given by the maker;

E = direct-current voltage which is used for the test;

e = reading of the voltmeter.

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[1] Standardization Rules of the Amer. Inst. of Elec. Engrs.

For example, suppose the values for the test are, $E = 545$ volts, $e = 5$ volts and $r = 55{,}000$ ohms. Then $R = \frac{(545 - 5)\,55{,}000}{5} = 5{,}940{,}000$ ohms, which would indicate that the insulation was in good condition.

This test is of secondary importance as compared with the test for breakdown under high-voltage alternating current, since the insulation resistance can be considerably increased by baking, but this gives no real increase in the actual ability to withstand voltage strains. Commenting on these two tests, the standardization rules of the American Institute of Electrical Engineers says: "The insulation resistance of a machine at its operating temperature shall be not less than that given by the following formula:

$$\textit{Insulation resistance in megohms} = \frac{\textit{Normal terminal voltage}}{\textit{Rated capacity in kv.-a.} + 1000},$$

a megohm being 1,000,000 ohms and the symbol kv.-a. or kilovolt-amperes being the voltage of the machine times the full-load current, times 1.73 if three-phase, or times 2 if two-phase. A general rule is that machines up to 1000 volts should show somewhere near a megohm. The Institute rules say further: "It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature, humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the foregoing rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test."

These two tests indicate a method of settling any doubt as to whether the insulation on a machine is suitable for a new voltage higher than the old. The method of procedure would be to see that the windings were clean and dry and free from grounds, the latter point to be determined in the usual way with a 110-volt lighting circuit or by "ringing out" with a magneto. If the winding shows clear of grounds the insulation resistance should be measured with any convenient source of direct-current supply, preferably 500 volts. If the insulation resistance is up to or beyond the value specified by the A. I. E. E. formula, the winding may be given the further dielectric or breakdown test for one minute with high-voltage alternating current provided a suitable small testing transformer is available. In making this test great care should be used in handling the high voltage to guard against personal injury and also a suitable circuit-breaker should be in circuit which will open if the insulation breaks down.

Volts per Turn.

Assuming that the question of the adequacy of the insulation is settled, the second main consideration in all voltage changes may be taken up. This is the question of rearranging the coils or coil groups in the windings so that the voltage on each coil under the new conditions may be substantially the same as under the original. In this regard an induction motor is similar to a transformer. It is designed originally for a certain voltage across each coil or group of coils. These coils or groups may be arranged in series or in various parallels to accommodate different line voltages, and so long as the voltage across each coil remains at the figure originally calculated, the operation of the motor will be normal in all respects. This can be shown graphically as in Figs. 103 to 105. In these figures A-B represents one phase of a two-phase, 4-pole winding. It will be seen that the voltage across one pole-phase group, or X-Y, is 110 volts at all times. When the motor is connected for 440 volts, Fig. 103, all four pole-phase groups are in series. When the line is 220 volts, there are two parallels with two pole-phase groups in series in

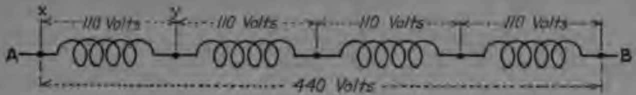

FIG. 103.—Four 110 volt coils connected in series across 440 volts.

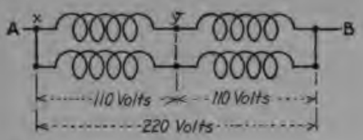

FIG. 104.—Same coils connected two in series in two parallels across 220 volts.

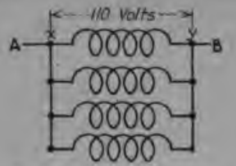

FIG. 105.—Same coils connected four in parallel across 110 volts.

each parallel, Fig. 104. When the line voltage is 110 volts, all four pole-phase groups are in parallel and each group is across the line, Fig. 105, since each group has within itself the proper

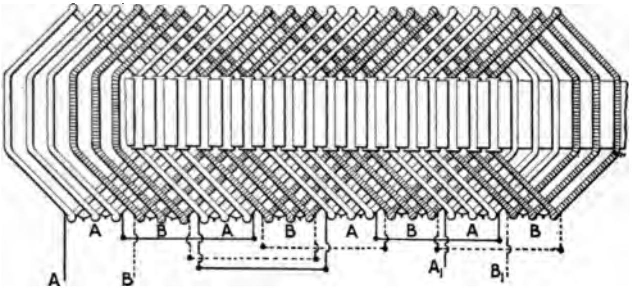

FIG. 106.—Four-pole, series.

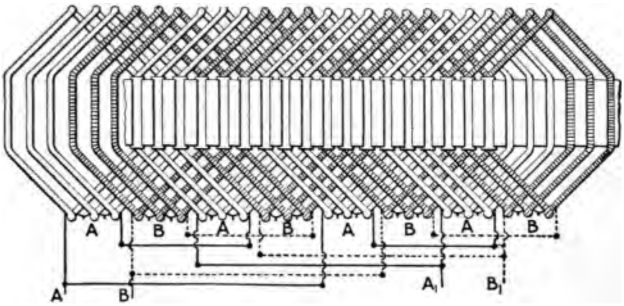

FIG. 107.—Four-pole, two parallels.

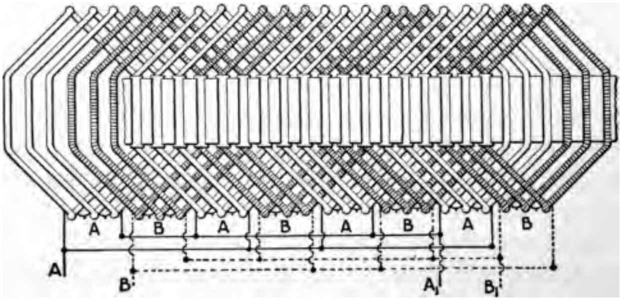

FIG. 108.—Four-pole, four parallels.
FIGS. 106 to 108.—Different groupings of a two-phase, four-pole winding.

number of turns for 110 volts. Figs. 106, 107 and 108 show a 24-coil four-pole two-phase winding connected in series, 2 parallels and 4 parallels respectively, as shown schematically in Figs.

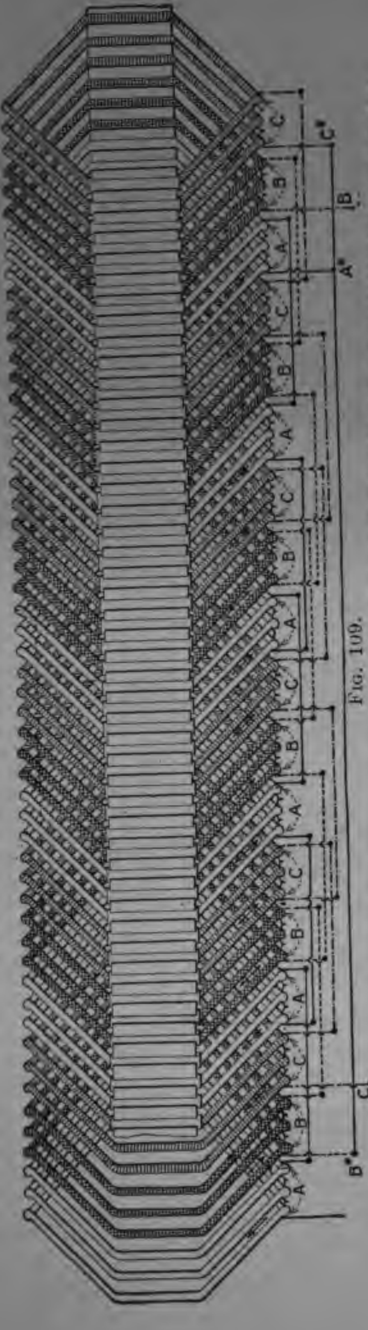

FIG. 109.

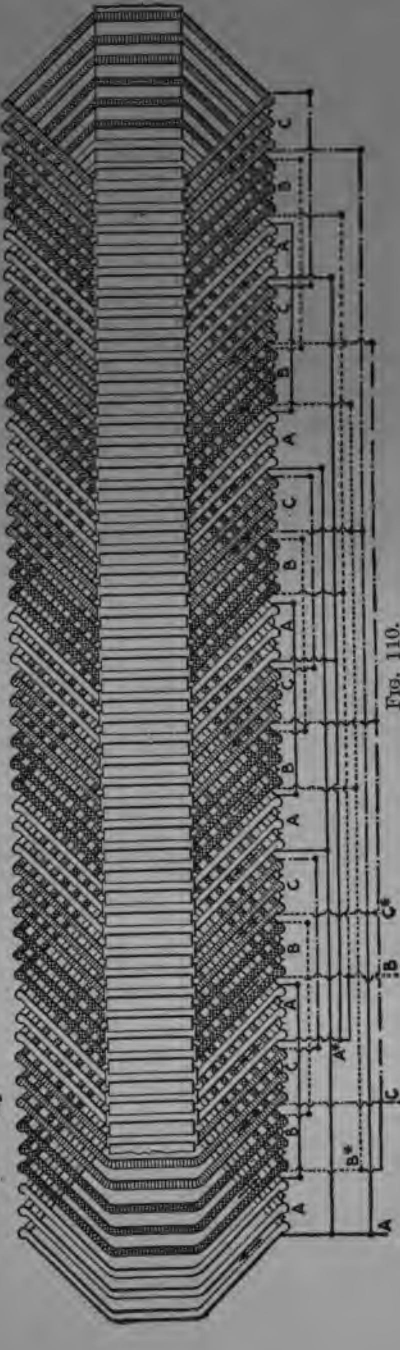

FIG. 110.

103, 104 and 105 respectively. If the connection, Fig. 106, is to operate on 440 volts, for 220 volts the winding will be connected as in Fig. 107 and for 110 volts as in Fig. 108.

The foregoing is very simple and is all that need be borne in mind for changes of this nature. One caution needs to be observed, and that is to handle the pole-phase groups as units and not attempt to split them in the middle again—to make 8 parallels, for example, for a 55-volt connection. Such attempts result in improper connections as will be pointed out in Chapter IX Fig. 140. If the number of poles is divisible by 3 or 5 or 7 corresponding numbers of parallels may be made, which is often convenient.

For example, if a three-phase six-pole 2200-volt motor is to be reconnected for 440 volts, it may be connected 3 parallel delta, Fig. 110, and would give 423 volts, if it had been connected series star, as in Fig. 109, on 2200 volts. The quotient of $\frac{2200}{3 \times 1.73} =$ 423; the 3 comes from the 3 parallels and the 1.73 is due to changing from star to delta. The latter change is one of the advantages or points of greater flexibility of three-phase over two-phase. This is illustrated in Figs. 111 and 112. The "star" diagram shows the winding connected for a line voltage of 440. The voltage which then exists between any lead and the star point is 254 volts, as shown on the *B* phase. Since this is true, the winding can be connected in delta as shown in Fig. 112, and operated on a line voltage of 254. This change is sometimes made to operate a 440-volt motor on 220 volts, but since 254 volts is

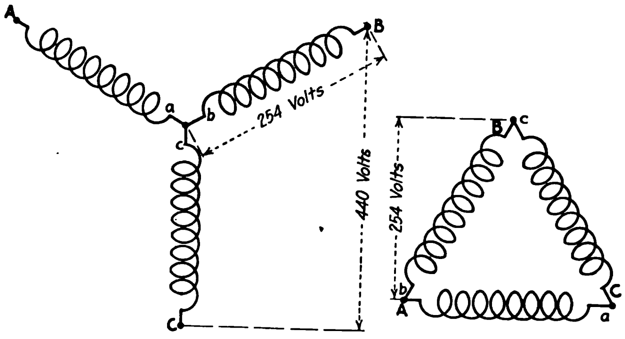

Fig. 111. Fig. 112.

Figs. 111 and 112.—Equivalent voltage for star and delta connection.

normal, the delta-connected winding will compare with the star winding as though operated on $\frac{220}{254}$ of normal voltage, or 87 per cent. Many motors have sufficient margin to stand this reduction, but the copper heating will be $\frac{4}{3}$ as great and the starting and maximum torques only $\frac{3}{4}$ as great as on the winding connected in star and run on 440 volts.

Changes of this nature can be summed up in convenient form as in Tables II and III for three-phase and two-phase motors respectively. *If a motor connected originally as shown in any horizontal column has a voltage of 100, its voltage when reconnected, as indicated in any vertical column is shown at the intersection of the two columns.*

TABLE II.—COMPARISON OF MOTOR VOLTAGES WITH VARIOUS THREE-PHASE CONNECTIONS

	Series star	2 parallel star	3 parallel star	4 parallel star	5 parallel star	6 parallel star	series delta	2 parallel delta	3 parallel delta	4 parallel delta	5 parallel delta	6 parallel delta
Series star	100	50	33	25	20	17	58	29	19	15	12	10
2 parallel star	200	100	67	50	40	33	116	58	39	29	23	19
3 parallel star	300	150	100	75	60	50	173	87	58	43	35	29
4 parallel star	400	200	133	100	80	67	232	116	77	58	46	39
5 parallel star	500	250	167	125	100	83	289	144	96	72	58	48
6 parallel star	600	300	200	150	120	100	346	173	115	87	69	58
Series delta	173	86	58	43	35	29	100	50	33	25	20	17
2 parallel delta	346	173	115	87	69	58	200	100	67	50	40	33
3 parallel delta	519	259	173	130	104	87	300	150	100	75	60	50
4 parallel delta	692	346	231	173	138	115	400	200	133	100	80	67
5 parallel delta	865	433	288	216	173	144	500	250	167	125	100	83
6 parallel delta	1038	519	346	260	208	173	600	300	200	150	120	100

TABLE III.—COMPARISON OF MOTOR VOLTAGES WITH VARIOUS TWO-PHASE CONNECTIONS

	Series	2 parallel	3 parallel	4 parallel	5 parallel	6 parallel
Series	100	50	33	25	20	17
2 parallel	200	100	67	50	40	33
3 parallel	300	150	100	75	60	50
4 parallel	400	200	133	100	80	67
5 parallel	500	250	167	125	100	83
6 parallel	600	300	200	150	120	100

General Tables Covering All Voltage Connections.

The figures in the tables should be considered as percentages or comparative values rather than actual voltages. For example, in the case just cited, of the 2200-volt motor to be reconnected for 440 volts, assume that an inspection of the existing winding connection shows it to be series star. Since 440 is 20 per cent. of 2200, the problem resolves itself into how a series-star connection may be changed so that the resulting voltage will be 20 per cent. of its value. Looking at Table II, locate the horizontal line reading "series star," or the existing connection. Since 20 per cent. is required, read along the same horizontal line till the figure 20 is reached. This is found under the vertical heading "5 parallel star." In other words, if the number of poles is divisible by 5, the winding can be put in 5 parallels and operated on 440 volts, since 2200 ÷ 5 = 440. Since six poles were assumed, the number of poles is not divisible by 5 and a 5-parallel connection is not possible. A further search across the table shows the figure 19 under the vertical heading "3 parallel delta"; 19 per cent. of 2200 is 418, which is 95 per cent. of 440. This varies from the figure 423 previously mentioned, for the reason that the table is made to the nearest whole number and $\frac{100}{3 \times 1.73} = 19.2$ per cent. It will be near enough right to reconnect in 3 parallel delta and operate on 440 volts. Similar problems can thus be solved by inspection, making such a table a very convenient reference. In Chapter VI this table will be elaborated and combined with changes in phase also, thus covering a large percentage of the possible changes in windings at a glance.

CHAPTER VI

HOW THE NUMBER OF PHASES AFFECTS THE WINDINGS AND THE RESULT OF CHANGING VOLTAGE AND PHASE AT THE SAME TIME

It was shown in Chapter V that changes in voltage of the supply circuit can be taken care of with comparative ease and simplicity by the proper changes in connection of the motor windings, provided that the maximum number of turns which can be placed in series in the coils is equal to or greater than the number required under the new conditions. For example, a 220-volt motor may be reconnected for 440 volts, provided the windings can be so arranged that there will be twice as many turns in series between the terminals of each phase as there were with the original connection. These changes, when possible, offer no particular difficulty.

On the other hand, changes in the number of phases of the supply circuit are usually difficult to accommodate by changes in the motor connections and many times when they can be accomplished are attended with a loss in capacity of the motor or a serious reduction in the excellence of the motor's performance as regards torque, heating, power factor and efficiency.

Changes in Phase.

By far the commonest change of this nature is changing from two-phase to three-phase and *vice versa*. Of the two changes, that from two-phase to three-phase can more often be taken care of for the reason that a normal two-phase motor has approximately 25 per cent. more turns in series in its windings than a three-phase motor of the same characteristics. Thus it is usually possible to cut out 20 per cent. of the turns in a two-phase winding, leaving them dead, and have left the proper number of turns for the corresponding three-phase winding. However, in going from three-phase to two-phase a corresponding increase of 25 per cent. of the total number of turns in series is required; and if the three-phase winding as it stood had all the turns in series, any further increase is not possible and a set of new two-phase coils will be required.

There are three methods of reconnecting from two-phase to three-phase, which are here given in the order of their desirability: (1) Twenty per cent. of the coils are cut out and left dead and the motor operated on 80 per cent. of the two-phase turns; (2) the number of coils is not changed, and the coils are reconnected according to the proper diagram; (3) a "T" or Scott two-phase to three-phase connection is used.

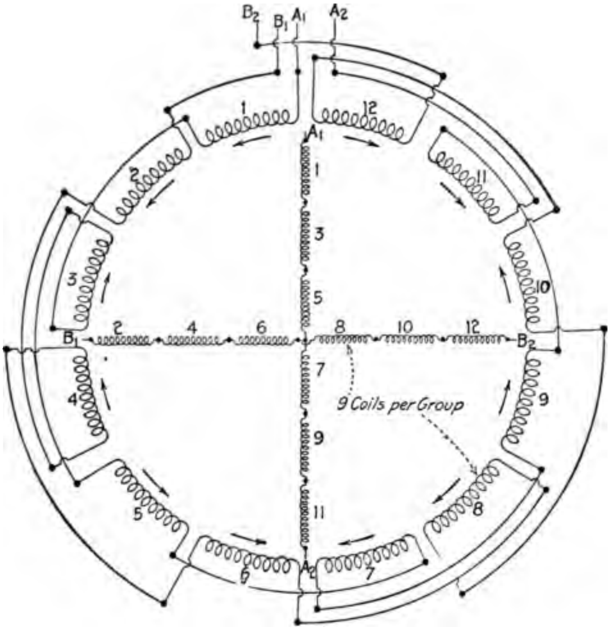

FIG. 113.—Normal two-phase, six-pole series connection, nine coils per group.

None of these is ideal, and in general it is a good investment to rewind the motor with proper three-phase coils. In the first method it must be borne in mind that the full-load current of a three-phase motor is $\frac{2}{1.73}$ or about 115 per cent. of the current in a two-phase motor. This means that for the same heating the horsepower output when reconnected for three-phase can only be in the neighborhood of 87 per cent. of what it was on two-phase. This loss of 13 per cent. of the horsepower when capitalized in the proper manner will be found to pay a high rate of interest on the money that would be invested in a new set of coils for normal three-phase operation which would give the same horsepower output as the original two-phase winding.

Another way of arriving at the foregoing conclusion is as follows: If one-sixth of the two-phase coils are to be cut out of circuit and left dead, as shown in Fig. 114, the amount of active copper is reduced by the same percentage; and it might be expected that the horsepower output would be similarly reduced, which is the case. This method of reconnecting from two-phase to three-phase is shown in Figs. 113 and 114. Fig. 113 shows a winding with 108 coils connected in series for two-phase and six poles. There are $2 \times 6 = 12$ pole-phase groups and $\frac{108}{12} = 9$ coils in each group. As already stated, if this winding is to be reconnected for three-phase, six poles, there should be only 80 per cent. as many coils in series in the winding, or $0.80 \times 108 = 86.4$ coils.

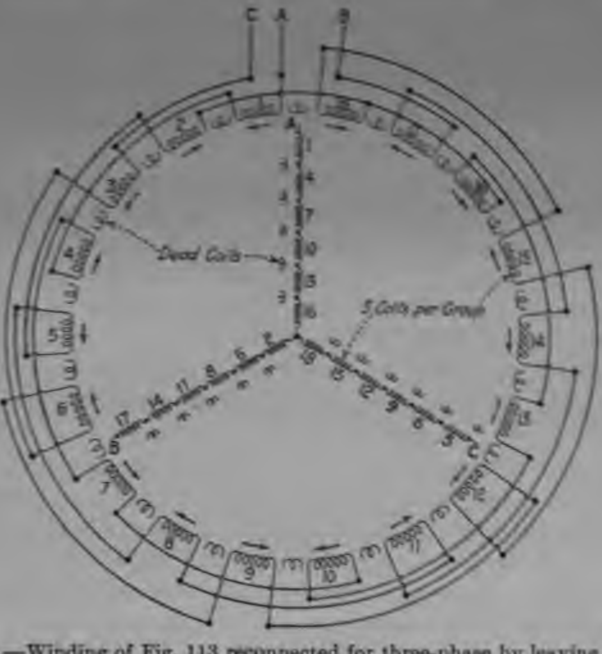

FIG. 114.—Winding of Fig. 113 reconnected for three-phase by leaving "dead" coils.

Since there are to be $3 \times 6 = 18$ pole-phase groups in the new connection, there should be the same number of coils in each group; the nearest integer is 5, and $5 \times 18 = 90$ coils, which will be used instead of 86.4, which is theoretically correct. This leaves $108 - 90 = 18$ coils dead, or 1 dead coil in each group, as shown in Fig. 114. Since $\frac{90}{108} = 0.833$, then 83.3 per cent. of the coils are active instead of 80 per cent., and this will have the effect of operating a three-phase motor on $\frac{80}{83.3}$, or 96 per cent. of normal voltage, as compared with the two-phase motor. The starting and maximum torques of the three-phase motor will be about $\left(\frac{80}{83.3}\right)^2 = 92$ per cent. of their value on a two-phase connection; but this is sufficiently close for all practical purposes, especially as the horsepower rating will have to be reduced 13 per cent., as stated above, if the original maximum heating in the stator coils is not to be exceeded. A comparison of Figs. 113 and 114 indicates that the position of the coils, which are specially insulated to stand the voltage between phases, will have to be changed. This was mentioned in the Chapter IV under "phase insulation."

A consideration of the fact that there are 18 dead coils in the three-phase winding which are active on the two-phase connection suggests at once that if the reconnection was attempted from three-phase to two-phase there might in many cases be insufficient coils to put in series for the two-phase connection. If the coils are regrouped for two-phase and run on the same voltage, the motor shows all the signs of a machine operating on 25 per cent. overvoltage and may even overheat when running light and not connected to any load whatever. On the other hand, if a two-phase winding is regrouped and operated three-phase on the same voltage without cutting out any coils, as explained in connection with Fig. 114, the three-phase motor shows all the effects of a motor operating on 80 per cent. of normal voltage; that is, the starting and maximum torques will be considerably reduced and the heating increased. These two latter conditions are covered by the second method of reconnecting listed in the foregoing—namely, changing the grouping and connections properly, but neglecting the change in the total number of coils in series.

The third method occasionally employed is that of making a

"T" connection of the two-phase windings or a Scott connection inside the motor and operating the resulting winding on a three-phase circuit. This should not be confused with the use of Scott connected transformers for changing from two-phase to three-phase or vice versa. The latter may be an excellent solution in many cases where there are several motors affected by the change in phase. Let us assume, for example, that a user of motors has 15 machines of various sizes from 1 to 50 hp., which have been operating from his own steam-driven plant at two-phase, 220 volts. He decides to purchase power from a neighboring distribution system at three-phase, 220 volts. It is a matter of considerable expense to rewind all the motors for three-phase, and if simply reconnected the losses on the rated capacity are as previously suggested. In addition, it is desired to hold the old generating plant as a stand-by, in case of interruption to the purchased service. All these results can be secured by putting in transformers equivalent to 50 or 60 per cent. of the capacity of motors installed and by means of a Scott connection on the transformers operate the two-phase motors from the three-phase supply in a perfectly normal manner. This is one very neat solution for a problem in reconnecting induction motors which does not involve any reconnection whatever.

On the other hand, assume that in the same plant the generating system has broken down and, in the emergency, power can be purchased from the same neighboring power line at three-phase. There is no time to secure transformers, and there is no time to secure three-phase coils for the motors—it then becomes essential to make some kind of reconnection so that the two-phase motors will operate on three-phases. One of the possibilities in such a case is a Scott connection inside the motor winding itself. This is shown in Chapter IX and Fig. 115.

Table IV shows comparative performances of a two-phase motor reconnected for operation on three-phase by a "T" connection and the performance of the same motor when supplied with new three-phase coils and connected in a normal three-phase manner.

In order to make this connection clear, Fig. 116 shows the windings on the motor connected for two-phase, and Fig. 117 the motor as reconnected with a "T" connection, corresponding to the schematic diagram, Fig. 115.

TABLE IV.—COMPARISON OF A TWO-PHASE MOTOR CONNECTED "T" TO OPERATE ON THREE-PHASE WITH NORMAL THREE-PHASE WINDING

	Normal two-phase winding	Three-phase "T" connection	Normal three-phase winding
Full-load efficiency........	88.0	86.9	88.5
Full-load power factor.....	89.0	84.8	90.0
Starting torque...........	1.75	1.20	1.94
Maximum torque.........	3.3	3.17	3.3
Deg. C. Rise at Full Load:			
Stator copper............	22.5	32.0	21.0
Stator iron...............	20.0	32.5	19.0
Rotor copper.............	22.0	30.0	22.0

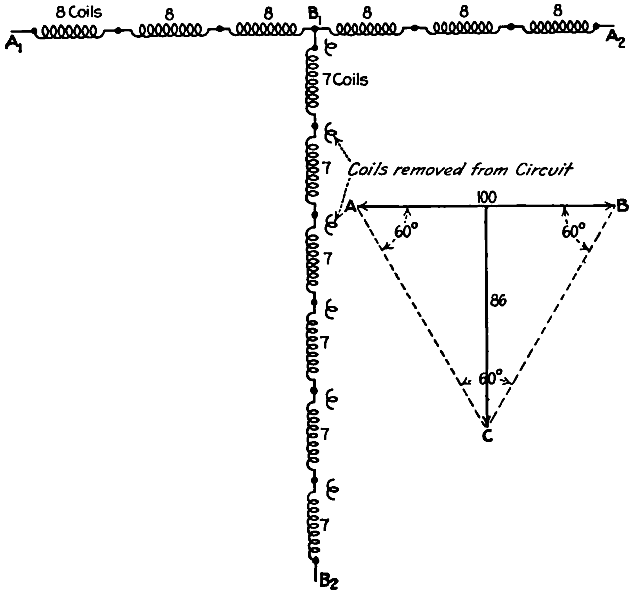

FIG. 115.—Schematic diagram of "Tee" connection.

The principle of the Scott connection is well understood and explains the reason for omitting the coils in one leg, as indicated. It may be of interest, however, to consider what would happen if these coils were not omitted. This is indicated in the voltage diagram, Fig. 118; *BD* represents the voltage generated in the phase B_1B_2 of Fig. 115, by the rotation of the magnetic field and *AC* the voltage generated in the phase A_1A_2. The result is three perfectly balanced voltages, AB, BC and CA, which correspond to the voltage of the line in the three phases and allow normal operation. If the coils had not been *cut out* of the B phase, as shown in Fig. 115, the voltage generated in that phase by the rotating magnetic field would have been the same in value as that in the A phase and would be represented by DK in Fig. 118. The voltages AE and EC would then be represented by

FIG. 116.—Normal two-phase, six-pole, series connection, eight coils per group.

111, while CA would be 100. This would be equivalent to having one alternating-current generator representing the lines with balanced voltages of 100 each, or AB, BC and CA connected in parallel with another, alternating-current generator representing the motor windings and having unbalanced voltages, AE, EC and CA of 111, 111 and 100 respectively. The result of this would be a component BE equal to 14, which would spend itself driving useless wattless currents through the motor windings in an effort to balance properly the voltages and make them equal to AB, BC and CA. The immediate result of this useless current would be to increase the heating of the machine and decrease its torque and efficiency and power factor.

It is characteristic of an induction motor that it always makes this attempt to balance by circulation of wattless current any eccentricities either existing in its own windings or in the circuit to which it is connected. At times when such eccentricities exist in the stator winding, there will be wattless currents flowing in the rotor winding trying to correct them through the medium, always, of the rotating magnetic field. At other times when a power circuit of relatively large power is somewhat unbalanced and is connected to an induction motor, the motor will take upon itself the burden of correcting the dissymmetry of the entire line with disastrous results to the motor from overheat due to excessive corrective currents, although the motor may have been running idle at the time and developing no actual power. This explains why the coils are cut out of one phase, as shown in Fig. 115.

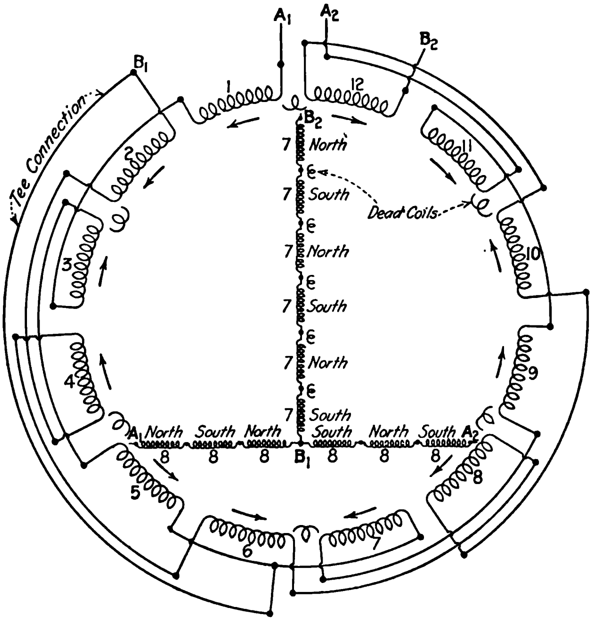

FIG. 117.—Winding of Fig. 116 reconnected "Tee" for three-phase, so-called "top to bottom" connection.

Poor Results of the "T" Connection.

The reason for the comparatively poor results on the "T" connection, as shown in Table IV is that the motor was connected as shown in Fig. 117. The result of this connection, if the air gap was not absolutely the same all around the rotor, would be to make AD and DC in Fig. 118 unequal; and a voltage diagram, as shown in Fig. 119, might result. When the voltage triangle $A'B'C'$ of Fig. 119 is connected in parallel with the symmetrical line triangle represented by ABC in Fig. 118, the result is that corrective current will flow and these corrective currents pull down the performance, as shown in the table. A much better connection is the one shown in Fig. 120, since this will have a tendency to keep the point D in Fig. 118 in the middle of the side AC and not let it be moved to one side, as in Fig. 119.

A comparison of Figs. 117 and 120 shows that in Fig. 117 the half legs A_1B_1 and B_1A_2 of the A-phase, represented by AD and DC, Fig. 118, each contain both north and south polar groups, while in Fig. 120 the half leg A_1B_1, represented by AD, Fig. 118, contains only north poles and B_1A_2 only south poles. The result of this is that if the rotor is displaced slightly in the stator bore from any cause, when the motor is connected as in Fig. 117, it may narrow the air gap opposite to B_1A_2 and widen it opposite to A_1B_1, which means the field will be stronger opposite B_1A_2. Consequently, the voltage generated in this section will be greater, as represented by $D'C'$ in Fig. 119. However, when connected as in Fig. 120, no matter if the rotor is near the stator at some point, it cannot affect any north pole without affecting the corresponding south pole, since all the lines of force that start out from a north pole must return through a south pole. Since

FIG. 118.—Voltage diagram for Fig. 117.

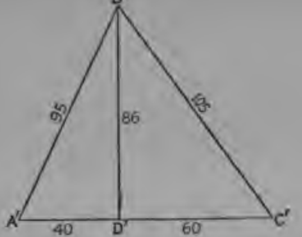

FIG. 119.—Effect on voltages of uneven air gap.

the legs A_1B_1 and B_1A_2 are so arranged that one has all the north poles and the other all the south poles, this means that they will be affected exactly alike by any displacement of the rotor, and the voltage in the two sections will be maintained equal as represented by the lines *AD* and *DC* in Fig. 118. Therefore, in connecting a two-phase motor in "T" for operation on three-phase a diagram similar to Fig. 120 should be used, in which case the three-phase results will be much more favorable than shown in the table.

The statement has been made above that the winding of a normal two-phase motor has approximately 25 per cent. more turns in series than the corresponding three-phase motor. This is, of course, true only if the turns are all in series in either case and the three-phase motor is arranged for connection in series star. If the three-phase motor under consideration is connected delta instead of star, it should be thought of as a star-connected motor at a corresponding voltage before reducing it to terms of a two-phase winding. For example, if a motor is connected series delta for operation on 220 volts, it could be reconnected series star and operated on 1.73 × 220 = 381 volts; or connected for

FIG. 120.—Preferable connection to Fig. 117 so-called "top to top" connection.

two-phase, it would be suitable for approximately 80 per cent. of 381 volts, or 305 volts. It will thus be seen that a delta-connected three-phase motor when reconnected for two-phase has about 38 per cent. more turns in series than are actually required, and this condition will have to be balanced up by some one of the various schemes suggested.

In general, manufacturers prefer a star to a delta connection, for the reason that the delta connection requires 1.73 times as many turns for the same operating voltage and these turns are of a correspondingly smaller-sized wire. The greater number of turns of smaller wire is an objectionable condition for several reasons, among which may be mentioned that more space is occupied in the slots by insulation, leaving less for copper; the coils mechanically are less rigid and self-supporting; the smaller-sized wire costs more per pound and the same number of pounds are required; and it is more expensive to wind a coil with a greater number of turns. For these reasons, if there is no other good reason to the contrary, a three-phase winding is apt to be arranged for star connection.

It often happens that in changing the winding of a motor to accommodate a change in the number of phases, it is necessary to arrange for a change in the operating voltage at the same time; as for example, changing a three-phase 440-volt winding to operate on two-phase 220 volts. Reference was made above to the fact that on a given winding the normal three-phase voltage would be 125 per cent. of the normal two-phase voltage. Expressing the same condition in another way, if two motors that are otherwise identical are made to operate on the same voltage except that one is two-phase and the other is three-phase, the three-phase winding will have only about 80 per cent. of the number of turns in series that are necessary in the two-phase winding. The foregoing is on the assumption that the three-phase winding is star-connected, which is usually the case. This fact permits one very convenient reconnection of this nature; namely, the one where a two-phase 440-volt winding is to be reconnected for three-phase 550 volts or vice versa.

Since 440 is 80 per cent. of 550, the number of turns in series is exactly right for either the two-phase or the three-phase combination, and the only thing that has to be done is to regroup the coils for the proper number of pole-phase groups, which in a three-phase motor is 50 per cent. greater than in a two-phase, and to shift the so-called "phase coils" or coils with heavier insulation to their proper positions at the beginning and end of each pole-phase group. Other combinations of change of phase and voltage are met with, and it is useful to make up a table such as Table V, which indicates at a glance the possible changes between two- and three-phase, star and delta, series, 2, 3, 4, 5 and 6 parallels.

Phase Changes and Voltage Changes Combined.

This table is a combination of the two given in Chapter V under voltage changes and shows the combination of phases as well. The manner of using this table has been explained under voltage changes, but further examples will be given here showing the way to apply it, since it gives a ready answer to practically any questions that may be asked regarding the possibility of changing windings when a change of voltage or phase or a combination of the two is involved. It will be noticed that the table as arranged is really given in percentages. That is to say, the original connection on the motor is called 100 or assumed to be good for a normal voltage of 100, and then if the winding is assumed as reconnected in some other way, the normal voltage on which the reconnected motor should be operated is shown at the intersection of the horizontal and vertical columns.

Take, for example, a motor which was originally connected three-phase 2 parallel delta. Following across this horizontal line, the number 100 is found under the vertical heading that also reads "three-phase 2 parallel delta," or, in other words, when a motor is normally connected for three-phase 2 parallel delta and is operated as three-phase 2 parallel delta, it is being operated at 100 per cent., or exactly as the designer intended it should be operated. Suppose, however, that the winding is reconnected two-phase series, the question at once arises upon what voltage the motor should be operated to give normal operation. Following the same horizontal column, "three-phase 2 parallel delta" (since that is the original connection) across until it intersects the vertical column marked "two-phase series," the number 280 appears at the intersection of the two columns. In other words, if the three-phase 2 parallel delta-connected winding is regrouped and reconnected two-phase series it must be operated on a voltage 280 per cent. of the original voltage for which it was designed.

TABLE V.—COMPARISON OF MOTOR VOLTAGES WITH VARIOUS CONNECTIONS AND PHASES

If a motor connected originally as shown in any horizontal column had a normal voltage of 100, its voltage when reconnected, as indicated in any vertical column is shown at the intersection of these two columns.

Form of connection	Three-phase series star	Three-phase 2 parallel star	Three-phase 3 parallel star	Three-phase 4 parallel star	Three-phase 5 parallel star	Three-phase 6 parallel star	Three-phase series delta	Three-phase 2 parallel delta	Three-phase 3 parallel delta	Three-phase 4 parallel delta	Three-phase 5 parallel delta	Three-phase 6 parallel delta	Two-phase series	Two-phase 2 parallels	Two-phase 3 parallels	Two-phase 4 parallels	Two-phase 5 parallels	Two-phase 6 parallels
Three-phase series star........	100	50	33	25	20	17	58	29	19	15	12	10	81	41	27	20	16	14
Three-phase 2 parallel star.....	200	100	67	50	40	33	116	58	39	29	23	19	162	81	54	40	32	27
Three-phase 3 parallel star	300	150	100	75	60	50	173	87	58	43	35	29	243	122	81	60	48	41
Three-phase 4 parallel star.....	400	200	133	100	80	67	232	116	77	58	46	39	324	163	108	80	64	54
Three-phase 5 parallel star.....	500	250	167	125	100	83	289	144	96	72	58	48	405	203	135	100	80	68
Three-phase 6 parallel star.....	600	300	200	150	120	100	346	173	115	87	69	58	486	243	162	120	96	81
Three-phase series delta.......	173	86	58	43	35	29	100	50	33	25	20	17	140	70	47	35	28	23
Three-phase 2 parallel delta....	346	173	115	87	69	58	200	100	67	50	40	33	280	140	94	70	56	47
Three-phase 3 parallel delta....	519	259	173	130	104	87	300	150	100	75	60	50	420	210	141	105	84	70
Three-phase 4 parallel delta...	692	346	231	173	138	115	400	200	133	100	80	67	560	280	188	140	1 1	93
Three-phase 5 parallel delta....	865	433	288	216	173	144	500	250	167	125	100	83	700	350	233	175	140	117
Three-phase 6 parallel delta...	1,038	519	346	260	208	173	600	300	200	150	120	100	840	420	280	210	168	140
Two-phase series.............	125	63	42	31	25	21	72	37	24	18	15	12	100	50	33	25	20	17
Two-phase 2 parallels.........	250	125	84	63	50	42	144	73	49	37	29	24	200	100	67	50	40	33
Two-phase 3 parallels.........	375	188	125	94	75	63	216	111	73	55	44	37	300	150	100	75	60	50
Two-phase 4 parallels.........	500	250	167	125	100	84	288	148	97	73	58	49	400	200	133	100	80	67
Two-phase 5 parallels........	625	313	208	156	125	105	360	165	122	91	73	61	500	250	167	125	100	84
Two-phase 6 parallels........	750	375	250	188	150	125	433	217	144	108	87	72	600	300	200	150	120	100

The reason these values are given in percentages instead of actual voltages is to make the table more flexible and of wider application. The percentages, however, can be very simply changed to voltages by using them as a multiplier. Applying this to the case just used as an example, assume that the voltage on which the original motor operated was 220. This then represents the 100 per cent. which was called "three-phase 2 parallel delta." When changed to two-phase series, it has been shown that a voltage of 280 per cent. would be required. From this it follows at once that the new operating voltage for the motor when reconnected two-phase series must be 280 per cent. of 220 volts, or $2.8 \times 220 = 616$ volts.

As another example of applying the table take a case where a four-pole motor connected two-phase 2 parallels, as in Fig. 121, and operated on 220 volts is to be changed, if possible, for operation on a three-phase 550-volt circuit and it is desired to know what particular kind of a three-phase connection on the winding will give normal operation when the motor is run on 550 volts. In this case the horizontal line two-phase 2 parallels represents 100 per cent. If the original voltage was 220 and that was 100 per cent., the new voltage 550 must be 250 per cent., since it is 2.5 times 220. To find the proper form of three-phase connection, follow the horizontal column "two-phase 2 parallels" (since that was the original connection) across until it shows the value 250 under some vertical column which is headed "three-phase." This is seen to be the first vertical column, marked "three-phase series star." From this the conclusion is at once correctly drawn that if a motor is connected two-phase 2 parallels and run on 220 volts and it is reconnected to three-phase series star, it will be suitable for operating normally on a three-phase 550-volt circuit. It is assumed, of course, in this problem that the number of poles and the frequency and horsepower remain the same on the new circuit as on the old, the only difference being that the old circuit was two-phase 220 volts and the new circuit three-phase 550 volts. The changed connection is shown in Fig. 122.

To illustrate further the use of the table, assume that an eight-pole motor is connected series star, as in Fig. 123, and operated on a three-phase 2200-volt circuit, what form of reconnection would make it suitable for operation on a two-phase 440-volt circuit? In this case "series star" is 100 per cent. in the horizontal column and 100 per cent. equals 2200 volts. The desired

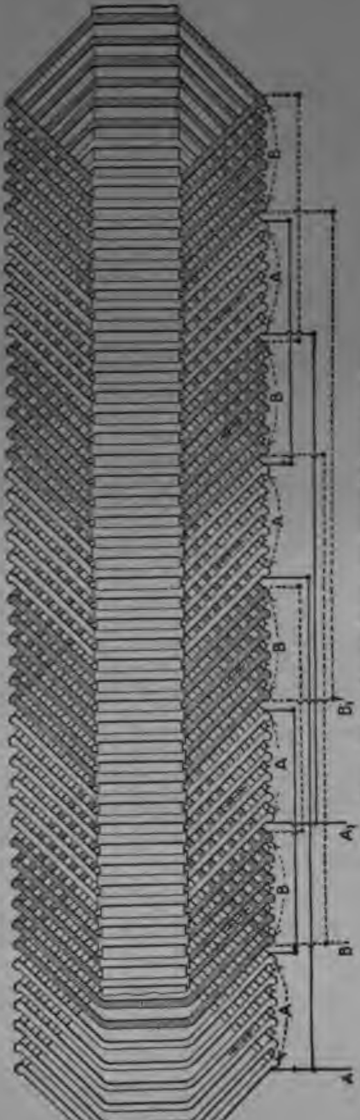

FIG. 121.—Two phase, two parallel connection.

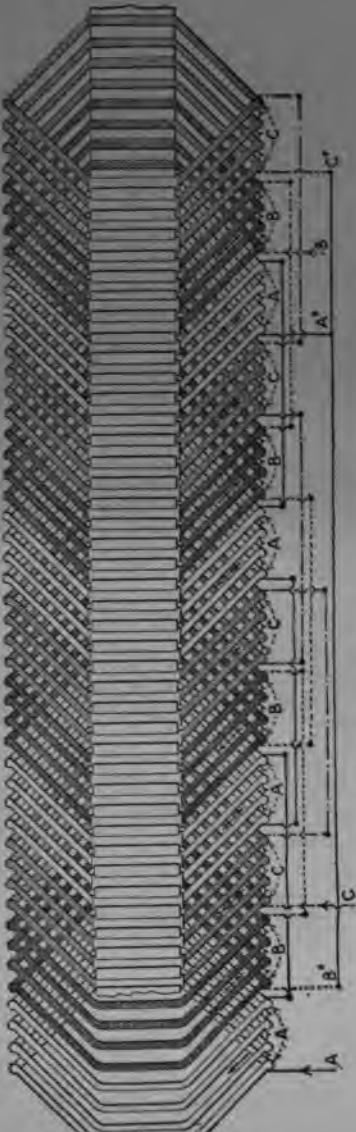

FIG. 122.—Same winding as Fig. 121 connected three-phase series star.

voltage is 440, which equals $\frac{1}{5}$ or 20 per cent. of 2200. Following the "three-phase series star" horizontal column across to the value 20, it is found first under "three-phase 5 parallels," but this is discarded since a two-phase connection is wanted; furthermore, an eight-pole winding cannot be connected in 5 parallels. The value 20 is seen the second time under the vertical column marked "two phase, 4 parallels." If the number of poles is divisible by 4, as in this case, the winding can be put in 4 parallels, therefore the conclusion is reached that this is the desired connection, or in other words, if a three-phase motor is connected series-star and operated on 2200 volts and is reconnected to two-phase 4 parallels, it will be suitable for operation on 440 volts. This connection is shown in Fig. 124. Again, assume that the motor has only six poles, as in Fig. 109, and it is to be changed from three-phase 2200 volts to three-phase 440 volts. In this case 2200 volts is again 100 per cent. and 440 volts is 20 per cent. Following the horizontal column marked "three-phase series star" the value 20 is found under "three-phase 5 parallel star," meaning that if the winding could be put in 5 parallels it would be good for 440 volts, since $\frac{2200}{5} = 440$. However, a six-pole winding cannot be connected in 5 parallels and the horizontal column is followed farther. There is not another 20 under the three-phase vertical columns, but there is a 19, which is nearly right, under "three-phase 3 parallel delta." Since a six-pole winding can be arranged in 3 parallel delta, as in Fig. 110, this is the connection desired, and the normal operating voltage will be 19 per cent. of 2200 = 418, which is near enough to operate satisfactorily on a 440-volt circuit.

From these scattered examples it can be seen that the table is of wide application and answers two types of questions. The first of these is what will be the new operating normal voltage if a winding is reconnected in a certain way, and the second is, what will be the form of the connection to get a new operating voltage which is desired. Indirectly, the table answers the question of whether it is at all possible to get the desired combination of changes without new coils, and if not exactly possible, what degree of approximation may be obtained by means of the working combination utilized.

In the case of wound-rotor machines it may be noted that changing either the phase or voltage of the stator has no effect

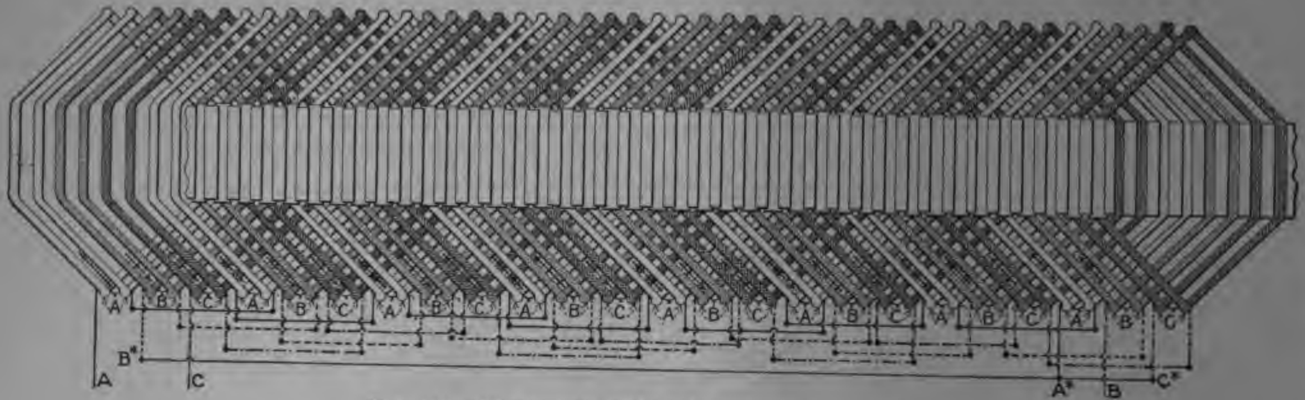

Fig. 123.—Three-phase, eight-pole, series star connection.

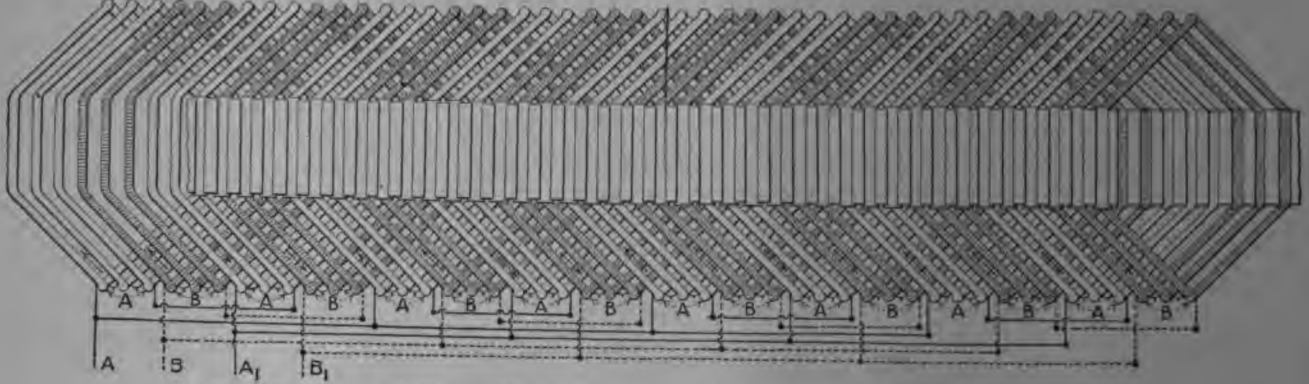

Fig. 124.—Same winding as Fig. 123 reconnected for two-phase, eight-pole, four parallels.

on the rotor winding as long as the table shows that the reconnection gives exactly the right conditions. The reason for this is that the real magnetic rotating field is neither two-phase nor three-phase, but is just the same as if set up by direct current. This was described in Chapter II. Since this rotating field remains at the same value before and after the reconnection, it will clearly have the same effect on the rotor winding in generating counter-electromotive force. Hence there will be the same voltage between collector rings as existed with the original connection, and there need be no change in the controller or the external resistance used in starting and running the motor.

CHAPTER VII

HOW THE FREQUENCY AFFECTS THE WINDINGS

The necessity for operating motors on a frequency differing from that for which they were originally designed may be the result of actually changing the frequency of the power supply and thereby affecting a number of motors in one installation, or it may result from applying used or repurchased motors on new circuits. At times such as those at the outbreak of the European War, when numbers of concerns were undertaking the manufacture of explosives and all sorts of munitions, the sudden demand for motors for the operation of machine tools and other purposes greatly overtaxed the available stocks and created a brisk demand for second-hand motors wherever they could be found. The installation of these machines on new circuits necessitated a change in frequency in many cases as well as changes in phase and voltage. Another instance of a wholesale change of frequency is the retiring of an existing isolated plant for the purchase of central-station power which may differ in frequency. This may result sometimes in changing the motors in a single plant, or it may involve a plant serving a town, in which case the motors in the entire district served must be arranged for the new frequency.

The commonest changes of this kind are from 25 cycles to 60 cycles and vice versa. There is also some changing from 60 cycles to 50 and infrequently 40-cycle motors are changed to 60 or the reverse.

Checking the Speed when Operating at Higher Frequency.

The most important and immediately noticeable change in the motor when the frequency is changed, is that the motor operates at a different speed. This change in speed is directly proportional to the change in frequency. It was explained in Chapter II that the so-called synchronous speed, or the number of revolutions per minute made by the magnetic field of the stator is equal to the alternations per minute of the supply circuit divided by the number of poles, or it is equal to the expression $\frac{\text{cycles} \times 120}{\text{number of poles}}$. From this it follows at once that if the cycles are changed and the poles remain the same, the revolutions per minute will change exactly as the frequency.

As an example, a 4-pole motor operated on 25 cycles will have a synchronous speed (practically the no-load speed) equal to $\frac{25 \times 120}{4} = 750$ revolutions per minute. The full-load speed is usually about 3 per cent. to 5 per cent. less than the synchronous speed. If now this same motor is operated on 60 cycles, the speed will be $\frac{60 \times 120}{4} = 1800$ revolutions per minute. This immediately brings up two serious mechanical questions: First is the mechanical design of the rotor such that it will stand this increase in speed, 240 per cent. of the original value? The peripheral speed of the rotor (that is, diameter in feet × 3.14 × revolutions per minute) should not be permitted to go beyond 7500 ft. per minute without consulting the manufacturer of the machine. Second, can the belting or gearing be suitably adjusted so that the speed of the driven machine or apparatus will remain practically unchanged? If these two questions cannot be satisfactorily taken care of, it will be necessary to change the number of poles in the motor winding also, so that the speed on the new frequency and with the new number of poles will be nearly the same as the speed on the old frequency and with the original number of poles.

For example, in the case just cited, a 4-pole motor operated on a 25-cycle circuit runs at about 750 revolutions per minute. The nearest combination to give this speed on 60 cycles would be to wind the motor for ten poles, and the resulting revolutions per minute would be $\frac{60 \times 120}{10} = 720$. There are, therefore, two conditions in case of a change in frequency—the first, when the number of poles remains the same and the speed changes with the cycles, and the second, when the number of poles is changed so as to keep the original speed or as nearly so as possible.

Consider first the case where the frequency is changed and the number of poles remains the same. The resulting change in the speed in this case is assumed to be proper for the motor in question, and the gears or pulleys are changed so that the driven load will operate at the same speed.

Relation between Voltage and Frequency.

The next thing that is affected by the change in frequency is the operating voltage. That is to say, if the frequency is raised, the voltage should be raised also and vice versa, if the conditions in the magnetic and electric circuits are to be kept normal. Assuming that the rotating magnetic field is to be kept at the same value and the frequency raised, this field will rotate at a faster rate and cut more conductors in a given time, which will immediately result in the generation of more voltage, or counter-electromotive force as it is called in a motor. It will be remembered that in the first chapter attention was called to the fact that one of the easiest ways of thinking of an induction motor is as an alternating-current generator generating a counter-electromotive force almost exactly equal to the line voltage on which it is operated. In the present instance, then, if raising the frequency causes the motor to generate more of this back voltage, it will be necessary to oppose it by a higher applied voltage; or, speaking simply, if the frequency is to be raised the line voltage should be raised by the same amount to keep the same magnetic conditions as existed in the original motor.

Relation between Torque, R.P.M., and Horsepower.

Suppose that the frequency is raised and the voltage is not raised. If the same magnetic field existed and rotated faster, it has been shown that an increased back voltage would be generated. However, if the line voltage is not raised, the motor does not require any increased back voltage and hence it does the only other thing it can to keep the generated voltage equal to the line voltage, and that is automatically to decrease its own magnetic field to such a point that the new field rotating at the new speed will generate the same back voltage as the old field rotating at the old speed, and this electromotive force will be nearly the same as the applied line voltage, which has been assumed to be the same on both frequencies. The result of a decrease in the magnetic field would be a decrease in torque or turning effort, and this might result in a reduced horsepower output were it not for the fact that the speed increases and tries to make up for the decrease in torque

$$Horsepower = \frac{Torque\ at\ one\ foot\ radius \times r.p.m.}{5252}$$

From this it follows that if the frequency was raised and the voltage left the same, the magnetic field might decrease and the torque decrease without lowering the horsepower by the same amount, since the speed increases and partly makes up for it. On most of the loads that are driven by motors, the driving effort, or pull, or torque is practically the same at all speeds. This is not true of centrifugal pumps or fans or similar apparatus, but is generally true of a great deal of industrial machinery. Since this is the case, it may be seen from the horsepower formula just given that if the torque is constant the horsepower will vary directly as the speed; that is, a higher speed will call for more horsepower and a lower speed for less horsepower. Going back to the frequency, a higher frequency means a higher speed and hence, directly, a higher horsepower, and a lower frequency means a lower speed and a lower horsepower. All these things work out automatically if the voltage and frequency are varied on the motor at the same time and by the same amount. This is for the reason that torque is the product of the magnetic field acting on the currents in the windings. To keep the heating reasonably the same, the magnetic field and the currents in the coils should be kept as nearly the same as possible.

It was shown in the foregoing that if the field is kept constant and the speed increased, the generated voltage would increase, and hence the applied voltage should be increased also. This brings about a rule which may be most easily remembered in this form: *If the frequency on a motor is changed, the voltage should be changed in the same direction and by the same amount.* If this is done and the torque against which the motor is working is constant, the magnetic field in the iron will remain constant, the currents in the windings will remain constant, the speed and the horsepower will vary directly with the change in voltage and frequency, and the heating will vary somewhat due to the variation of the iron loss with the frequency and the variation of the ventilating effect with the speed.

A concrete instance of the foregoing would be to take a 50-hp. 440-volt 60-cycle motor and operate it on 25 cycles and $\frac{25 \times 440}{60} = 183$ volts, in which case it would develop $\frac{25 \times 50}{60} = 20.8$ hp. If 183 volts was not available, a connection of the windings should be selected which would have been equivalent to 880 volts on

60 cycles and this would be suitable for $\frac{25 \times 880}{60} = 366.6$ volts on 25 cycles, which in many cases would operate satisfactorily on a commercial 440-volt circuit. In the case which is most commonly met with, which is changing from 25 to 60 cycles, this condition can often be taken care of by impressing twice the voltage on the motor on 60 cycles that was used on 25 cycles, such as operating a 220-volt 25-cycle motor on a 440-volt 60-cycle circuit, at about double the horsepower.

Theoretically, to follow the rule already given, the voltage on 60 cycles should be 2.4 times the value on 25 cycles, since $^{60}/_{25} = 2.4$. This would result in 2.4 times the speed and 2.4 times the horsepower. Practically, it is easier to get twice the voltage than 2.4, so the voltage is doubled and the horsepower considered as double also. In case it is not possible to get double the voltage on 60 cycles, the same result can be secured in another way. Suppose the original motor is operating on a 220-volt 25-cycle circuit and is connected series star as in Fig. 109. Suppose, also, that the available 60-cycle voltage upon which it is to run is 220. To get the effect of doubling the voltage, the motor can have its pole-phase groups connected in two parallel star, Fig. 125, for 60 cycles and it will then be affected in the same way as it would if the windings had not been reconnected but had been operated on 440 volts 60 cycles. On 60 cycles the motor would then run 2.4 times as fast and develop about twice the horsepower.[1]

In some cases it would happen that the same horsepower was required on the new frequency and at the increased speed as on the original frequency. Hence, it would be undesirable to reconnect the motor so as to raise the voltage with the frequency, since this would result in twice the required horsepower and would mean operating the motor at all times at half-load and consequently somewhat lower efficiency and power factor than if it were fully loaded.

Considering again the horsepower formula, it can be noted that if the horsepower is to remain constant, the torque must decrease as the speed increases and *vice versa*. Since the torque varies as the square of the applied voltage, it is evident that approximately the same horsepower can be kept with a changing fre-

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[1] See articles in the "Electric Journal," Vol. III, p. 400, by G. B. Werner, and Vol. VII, p. 680, by R. E. Hellmund.

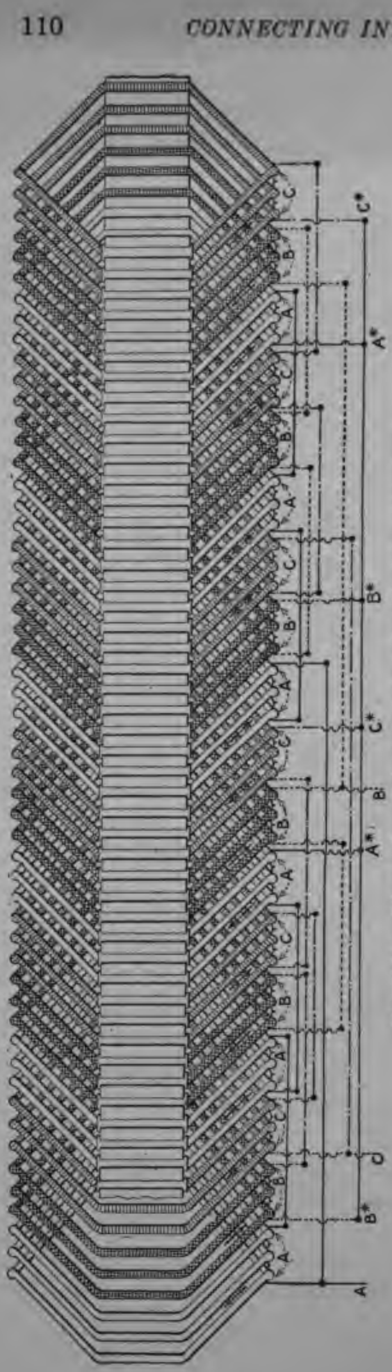

FIG. 125.—Three-phase, six-pole, two parallel star connection.

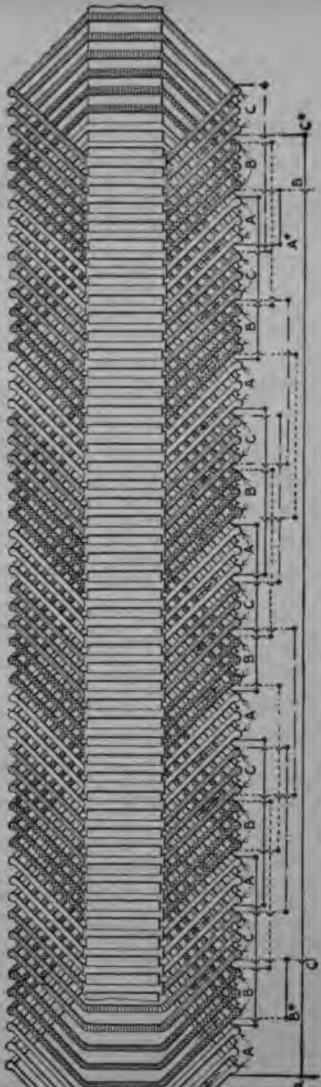

FIG. 126.—Three-phase, six-pole, series delta connection.

quency by varying the voltage applied to the motor as the square root of the change in frequency instead of directly as the first power. An example of this would be operating a 440-volt 25-cycle motor on a 550-volt 40-cycle circuit. The square root of $^{40}/_{25} = 1.26$. Then if $1.26 \times 440 = 554$ volts be used on 40 cycles, the magnetic density in the iron will be about 80 per cent. of its 25-cycle value and the torque will be $\frac{80^2}{100} = 64$ per cent of the 25-cycle value. Since the speed will be $^{40}/_{25}$ of that on 25 cycles, the resulting horsepower will be $^{40}/_{25} \times {}^{64}/_{100} = 1.02$ times its 25-cycle value or practically the same.

A similar instance would be operating a 50-cycle motor on 60 cycles and at 110 per cent. voltage to keep the same horsepower. Suppose in the latter instance it was not possible to juggle the generator or the transformers so as to get a 10 per cent. increase in voltage. It would then be necessary to reconnect the motor so that there would be $^{100}/_{110} = 91$ per cent. as many turns in series. One way of accomplishing this if the 50-cycle motor was originally connected series delta, as in Fig. 126, would be to reconnect it two parallel star (Fig. 125) for 60 cycles and the same horsepower. This would have the effect of increasing the applied voltage $\left(\frac{200}{1.73}\right) - 100 = 15$ per cent. However, since the frequency has increased 20 per cent. (50 to 60 cycles) and the speed also has increased the same amount, if the voltage is increased only 15 per cent. the magnetic density in the iron will be only $^{115}/_{120}$ of its 50-cycle value and the torque will be only $(^{115}/_{120})^2 \times 100 = 92$ per cent. of its 50-cycle value. The resulting 60-cycle horsepower rating as compared with the 50-cycle will be $^{92}/_{100} \times {}^{120}/_{100} = 110$ per cent. (since the torque is 0.92 and the speed 1.2 of its 60-cycle value). Instances could be multiplied of this, and some further examples will be given in a later chapter giving practical applications of the principles laid down here.

The fact that raising the frequency, and hence the speed also sometimes results in a horsepower rating greater than that actually required, leads at once to a word of caution regarding the converse proposition; namely, that in reducing the frequency on a motor and keeping the same number of poles, it should be figured that the horsepower will decrease exactly in proportion to the decrease in frequency and the consequent decrease in speed. The physical conception of this is that if the frequency and voltage are varied together and the motor is working against the same torque, the magnetic density in the iron will remain the same and the current in the copper of the stator and rotor will remain substantially the same, but the horsepower will rise and fall with the voltage and frequency, since it is the product of the torque and the speed divided by a constant. If it be imagined that the voltage and the frequency be carried down to zero and the motor just came to a standstill, it could be seen that the motor was developing full-load torque at standstill with no more than full-load current flowing in its windings.

The foregoing at once suggests a method that is sometimes used for starting a large squirrel-cage motor or a group of small motors where such motors constitute practically the only load on the generating unit from which they are operated. While the motors and the generator are at standstill, the motors are connected electrically to the generator by closing all line switches. The generator field is next excited to its normal value. The steam engine or the waterwheel is then started slowly from rest, and as the generator builds up in speed the motors come right up along with it and no more current is required in the motor windings than is represented by the torque against which they are starting. This gives the best physical picture of the voltage and frequency building up together from zero to normal value and yet the motors exerting a constant torque from standstill to normal full-load speed under these varying conditions.

The example just cited brings out the fact, also, which will be mentioned in Chapter X, that practically all changes in operating conditions can be considered equivalent to changes in voltage and so calculated and used. So it is with the change in frequency—if the torque is to be kept constant with the same number of poles and the horsepower is to vary with the speed, the voltage should be varied with the frequency or the winding connections changed to produce the equivalent. However, if the horsepower is to be kept constant at any and all speeds with the varying frequency, then the voltage should be varied as the square root of the change in cycles.

CHAPTER VIII

THE NUMBER OF POLES AND THE R.P.M. AND THE POSSIBILITY OF VARYING THEM WITH THE SAME WINDING

The speed of an induction motor expressed in revolutions per minute = (cycles × 120) ÷ number of poles. The speed so determined is called synchronous speed and is very nearly the same as the no-load speed. When operating under full load the speed will be a few revolutions less than this—for ordinary motors, on an average of about 95 to 97 per cent. of the synchronous speed. The synchronous speed is the speed at which the rotating magnetic field is traveling around in the stator, and the difference between this and the full-load speed of the rotor (3 to 5 per cent.) is called the "slip" of the motor.

From the equation for revolutions per minute it can be seen at once that if the speed of the motor is to be changed, it is necessary to change either the cycles or the number of poles. Or, assuming that the cycles have been changed and that it is necessary to keep the same speed as before, it will be necessary to change the number of poles. So far as the cross-connections themselves are concerned, and admitting windings where all the pole-phase groups do not have the same number of coils, as discussed in Chapter IX, it is evident that any winding might be connected for several different numbers of poles and for either two-phase or three-phase, by the simple expedient of changing the number of coils in each pole-phase group.

For example, a winding having 54 slots and 54 coils if arranged for three-phase 6 poles would have 3 coils per group and 18 pole-phase groups. If the same winding is rearranged for three-phase 4 poles there will be 12 pole-phase groups having alternately 4 and 5 coils per group. Or, if the same winding is arranged for two-phase 4 poles there will be 8 pole-phase groups, 6 of which would have 7 coils and 2 of which would have 6 coils, or 54 total. There are practical limits beyond which this form of reconnection cannot properly be carried and which are discussed farther on

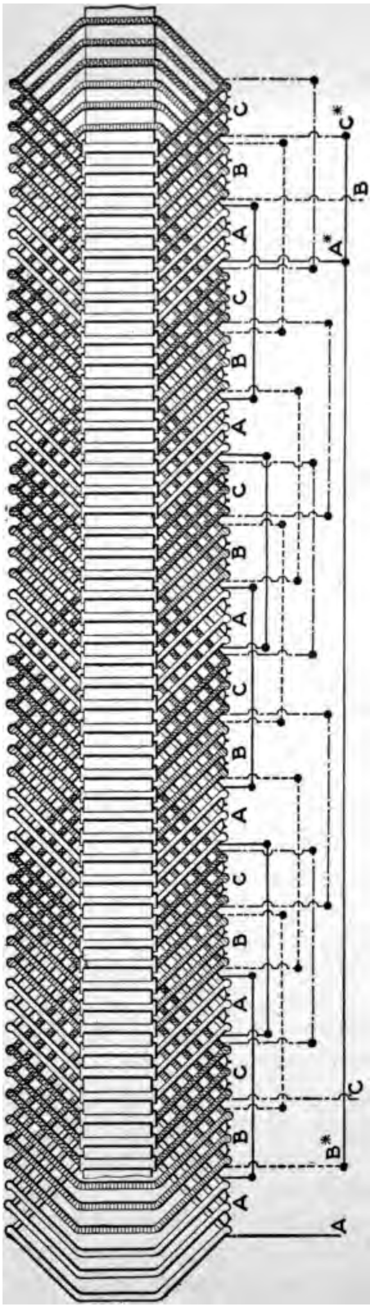

FIG. 127.—Three-phase, six-pole series star connection.

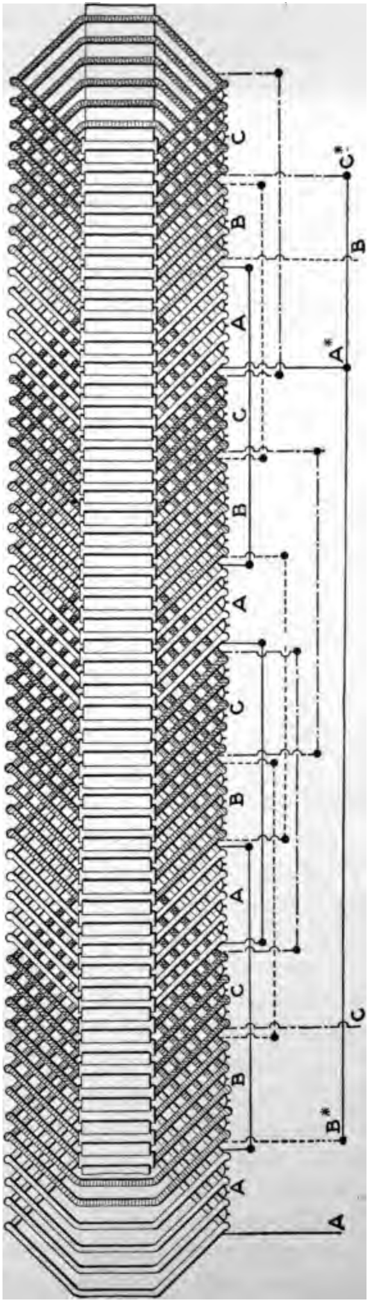

FIG. 128.—Same winding as Fig. 127 reconnected for three-phase, four-pole series star with uneven grouping.

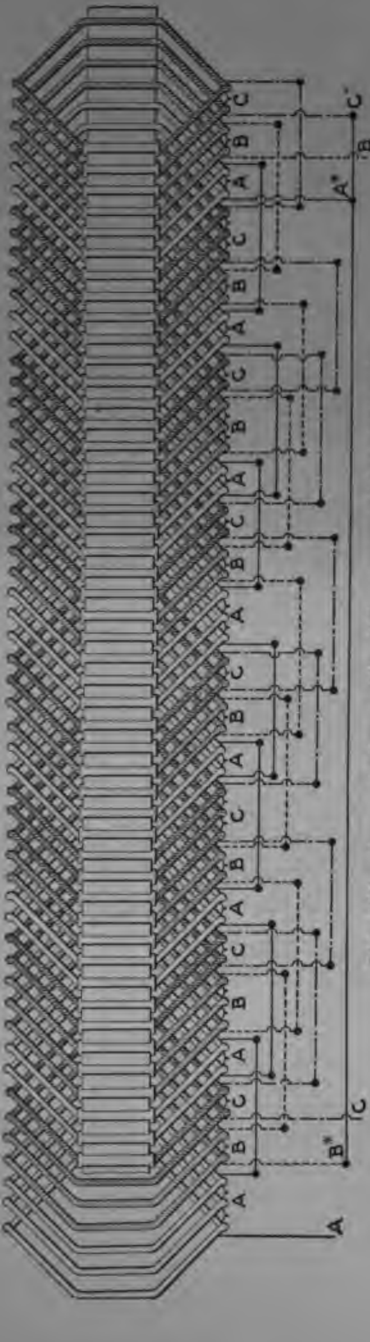

FIG. 129.—Same winding as Fig. 127 reconnected for eight poles.

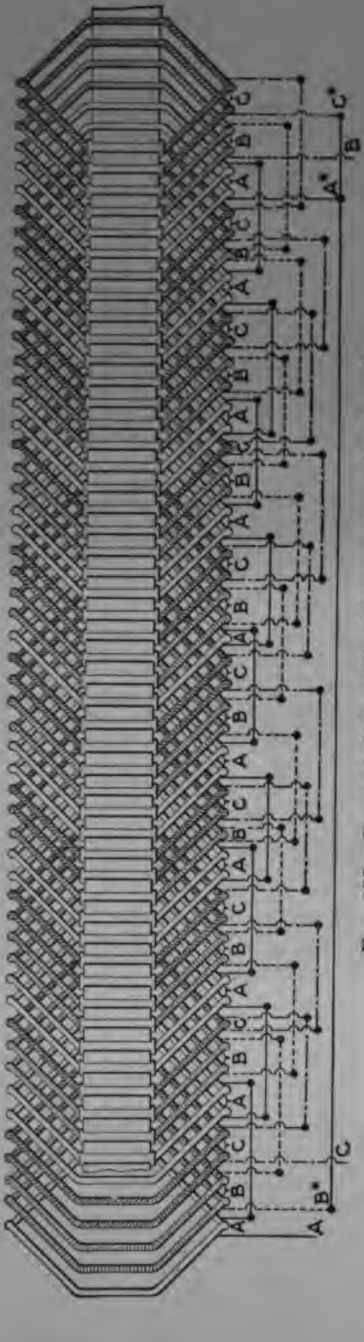

FIG. 130.—Same winding as Fig. 127 reconnected for ten poles.

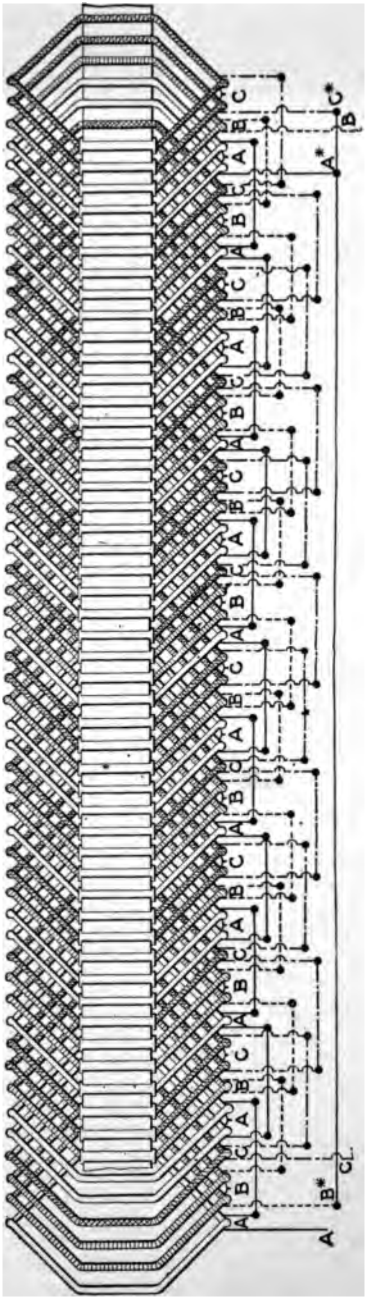

FIG. 131.—Same winding as Fig. 127 reconnected for twelve poles.

in this chapter, but before proceeding to a discussion of them attention is called to some typical cases of reconnection of this nature.

Fig. 127 shows a 54-slot winding having a coil pitch of 1 and 7 as arranged for 6 poles and connected series star. There are 3 coils in every group. Fig. 128 shows the same winding as Fig. 127 except grouped and connected for 4 poles. It will be noted that there are now 3 × 4 = 12 pole-phase groups containing alternately 4 and 5 coils per group. Fig. 129 shows the same winding as in Fig. 127 arranged and connected for 8 poles; there are 18 pole-phase groups with 2 coils and 6 with 3, making total of 24 groups and 54 coils. Fig. 130 is the same winding as Fig. 127 connected for 10 poles. There are 24 groups having 2 coils each and 6 groups with 1 coil, making a total of 30 pole-phase groups and 54 coils. Fig. 131 shows the winding, Fig. 127, connected for 12 poles. There are 18 groups of 2 coils each and 18 groups of 1 coil each, making a total of 36 groups and 54 coils.

Of course all these connections would not normally operate at the same voltage, nor would the horsepower developed be the same, and the speed would vary inversely as the number of poles. Assuming, for example, that the motor was 100-hp. 60-cycle three-phase 440-volts and run at 1160 r.p.m. on the 6-pole connection, the characteristics for the other connections are shown in Table VI. Three-phase is assumed throughout.

TABLE VI.—CHARACTERISTICS OF A THREE-PHASE MOTOR CONNECTED AS IN FIGS. 127 TO 131

Poles	Hp.	Voltage	R.P.M.	Connection
6	100	440	1,160	Fig. 127
4	110	484	1,750	Fig. 128
8	86	375	860	Fig. 129
10	68	300	690	Fig. 130
12	50	220	580	Fig. 131

The only commercial voltages in Table VI are the first and last, 440 and 220. To operate the motor on the other connections would require special taps from the transformer, unless some other change could be made in the motor's winding at the same time that the number of poles was changed. For example, the 8-pole connection requires 375 volts. If it so happened that the

6-pole motor was connected in parallel star, then the 8-pole motor could be connected series delta, which would be the same thing as operating the motor on a voltage in the ratio of 1.73 to 2 or $\frac{375 \times 2}{173} = 434$, which is approximately the voltage required.

Table VI of horsepowers and normal voltages is figured by taking account of the speed and of the chord factor in the following way:

One of the functions of the winding is to be acted upon by the rotating magnetic field and to actually generate a counter-electromotive force which is opposed to and almost equal to the applied line voltage. If, then, in reconnecting for a different number of poles, the assumption is made that the magnetic field in the teeth and air gap remains at a constant value irrespective of the connections, it is at once evident that the generated electromotive force, and consequently the applied line voltage, should vary directly as the speed of the rotating magnetic field, which is practically the same as the revolutions per minute of the motor at no load. For example, in the case cited in the foregoing, if the normal voltage on the 6-pole connection is 440, everything else being equal, the normal voltage on the 12-pole connection should be 220, since the revolutions per minute of a 12-pole motor are just one-half those of a 6-pole machine.

Practically, the only condition which enters to change the voltage from varying directly as the speed is the "chord factor," which is due to the throw or pitch of the coil. This is described under "Fractional Pitch Windings" in Chapter IV. It will be recalled that this is a factor which reduces the voltage generated in a coil because one side of a coil is not exactly under the center of a north pole when the other side is exactly under the center of a south pole. The numerical value of this factor is expressed as the sine of one-half the electrical angle which is spanned by the coil. It may appear in the example given in Figs. 127 to 131 that the chord factor should remain constant since the physical throw of the coils is unchanged. It should be carried in mind, however, that while the coil spread remains unchanged, the number of poles is changed, consequently the pole arc is changed; hence, the relation of the throw of the coil to the pole arc is different in each case. The foregoing can be best shown by Table VII, remembering that the throw of the coils is slots 1 and 7 in all cases.

Table VII.—Effects of Changing the Number of Poles in an Induction-motor Winding

Number of poles	4	6	8	10	12
Throw of coil	1–7	1–7	1–7	1–7	1–7
Slots spanned by coil	6	6	6	6	6
Number of slots equivalent to 180 electrical degrees = $\frac{54}{\text{No. of poles}}$	13.5	9	6.75	5.4	4.5
Electrical degrees represented by six slots	80	120	160	200	240
Sine of half the electrical angle covered by the coil throw or pitch = chord factor	0.64	0.866	0.99	0.99	0.866

Table VII indicates that the normal 6-pole voltage of 440 must be modified by two factors to find its value for other speeds. These factors and their results are combined in Table VIII.

On first comparison of Tables VII and VIII it seems peculiar that the 4-pole connection having the lowest chord factor, which is 0.64 operates, at 484 volts, which is the highest voltage, while the 8- and 10-pole connections, having a high chord factor of 0.99, operate at 375 and 300 volts respectively. It must be remembered that the speed at which the magnetic field is rotating comes into effect and changes the result of the chord factor. Throughout this book we have considered the induction motor as being an alternating-current generator, generating the counter-electromotive force, or back voltage. Hence, in this case, the assumption has been made that the magnetic field in the air gap remains the same in density for all these connections, and

Table VIII.—Factors, Due to Change in Number of Poles, Modifying Induction-motor Voltage

Number of poles	4	6	8	10	12
Factor for changing voltage on account of changing speed	1.5	1	0.75	0.60	0.50
Factor for changing voltage on account of change in chord factor for new No. of poles ÷ 6-pole chord factor	0.74	1	1.14	1.14	1
Product of both factors	1.11	1	0.855	0.685	0.50
Resulting voltage = (440 × No. 4)	484	440	375	330	220

when connected for 4-pole this field will rotate twice as fast as when connected for 8-pole, and thus generate twice as much voltage. This is the reason that the two factors, one due to changing the speed of the field and the other due to changing the throw of the coil, are introduced, as shown in Table VIII. The product of these two factors governs the voltage which must be applied to the windings to give normal operation.

Table VIII determines the value of the proper voltage for the new connections as given in Table VI. The horsepower is determined just as if it were an alternating-current generator by taking the product of the volts × amperes × 1.73 × power factor and dividing by 746. The cross-section of the copper has not been changed, hence the amperes remain constant. The power factor is assumed the same, although it will be somewhat higher on high speeds and lower on low speeds. Therefore, the output in horsepower will vary as the voltage, assuming 100 hp. at 440 volts. The horsepower for the new connections is figured in this manner, as given in Table VI. Some general observations might be made about the examples chosen in this chapter: First, the question of starting torque or maximum torque required, or the saturation of the core when connecting for higher speeds might require a voltage somewhat higher or lower than Table VI; second, as pointed out in Chapter IV, on fractional-pitch windings it is not wise, in general, to chord up a coil so far that the chord factor is less than 0.707, which means that the coils span only halfway from the center of a north to the center of a south pole. The reason for this was shown in Chapter IV by plotting the shape of the magnetic field set up by windings having different coil pitches. For this reason the 4-pole connection, as shown and discussed in this chapter, should be avoided in practice, but the 6-, 8-, 10- and 12-pole connections would be satisfactory if the proper operating voltage could be secured.

Check Points in Changing Number of Poles.

From the foregoing it may be seen that there are three factors to be taken care of in changing the number of poles. These are:

First, if the new speed is to be higher than the original speed, the peripheral speed should not be allowed to exceed 7500 to 8000 ft. This figure is the diameter of the rotor in feet × 3.14 × revolutions per minute.

Second, the chord factor of the winding.

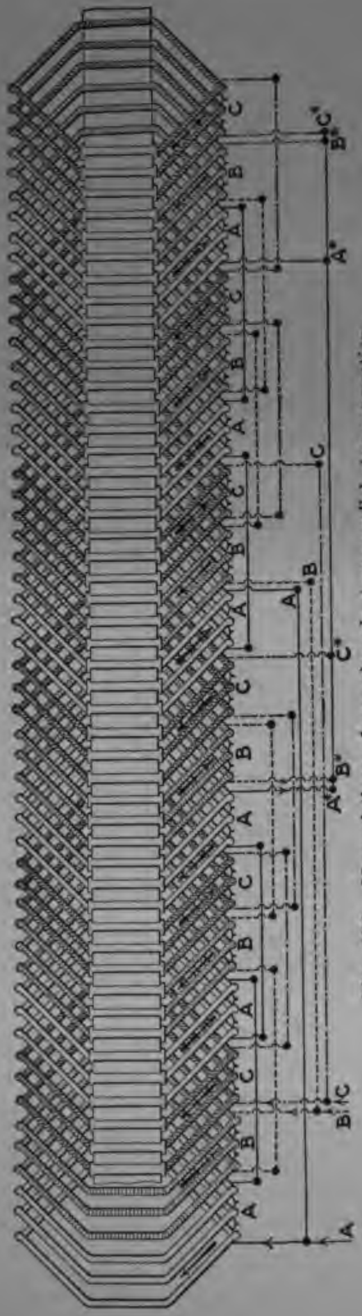

FIG. 132.—Normal three-phase, six-pole, two parallel star connection.

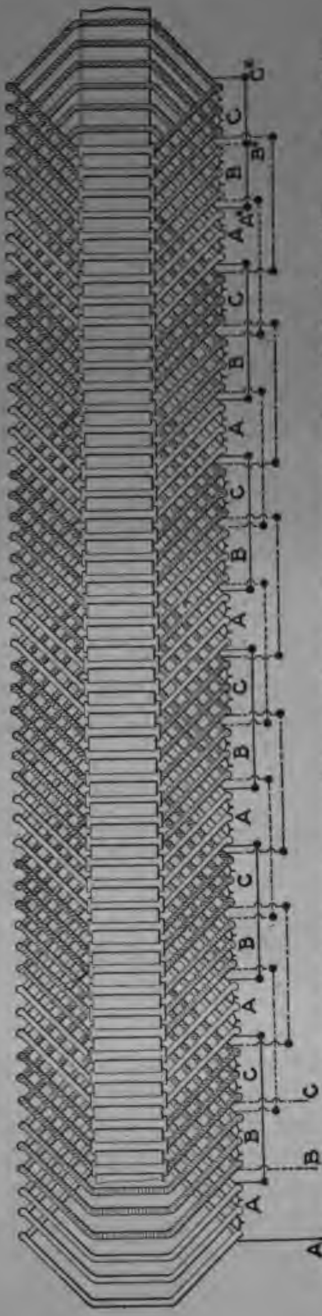

FIG. 133.—Same winding as Fig. 132 except connected for twelve poles by consequent-pole method. Note difference in position of leads between Figs. 132 and 133.

Third, the phase-insulation coils should be shifted so as to come at the beginning and ending of the new pole phase groups, as discussed in Chapter IV.

Sometimes, when a winding is connected in parallel star it is possible to reconnect it in series star with consequent poles, as explained in Chapter IX, and have the motor operate at one-half its original speed. This reconnection is shown in Figs. 132 and 133. Conversely, if the motor was originally connected for series star, it might be reconnected for parallel star and operate at double speed if the motor would stand up mechanically. The counter-electromotive force generated by the consequent-pole connection is only 86.6 per cent. as much as with the salient-pole connection, which means that if the motor was run on normal rated voltage on the consequent-pole connection it would operate as if it had an overvoltage of $\frac{100}{0.866} - 100 = 15$ per cent. Such a reconnection should not be attempted if the throw of the coils is exactly or nearly full pitch for the high speed. The reason for this was explained in Chapter IV.

The effect of chording the coils or making the throw less than full-pole pitch, as in Figs. 132 and 133, brings out the point that it is often possible in reconnecting a winding to raise the side of all the coils lying in the top of the slots, and to spring the coils one or two slots longer or shorter and thus help out materially on the operating conditions after the change is made. For example, in Fig. 133, if the coils are raised and wound in slots 1 and 6 instead of 1 and 7, the new chord factor would be sine one-half of $\frac{5}{4.5} \times 180$ deg. $= 200$ deg., or 0.98 instead of 0.866. The winding connected, as shown in Fig. 133, would then operate as if on 102 per cent. of normal voltage instead of 115 per cent., which would have cut down the iron losses and improved the power factor.

In Chapter IV a graphical explanation was given of the effect of chord factor and reconnecting for a different number of poles. This was shown by plotting the shape of the magnetic field set up by a three-phase winding connected for different numbers of poles and whose coils had different pitches. It showed the magnetic conditions inside the motor which give rise to the practical results discussed in this chapter.

CHAPTER IX

LESS COMMON CONNECTIONS USED FOR UNSYMMETRICAL CONDITIONS OR IN AN EMERGENCY

Chapter III discussed the usual forms of connection for windings using "diamond" coils in open slots. It is the purpose of this chapter to present some of the less usual forms. These are often of more importance in reconnecting old machines than are the standard forms, because it is by their help and "judicious" use that a job is pulled through in a hurry or a temporary workable connection made that will carry on an essential part of a larger work until such a respite can be obtained as will allow a more permanent connection.

The word "judicious" is used for the reason that short-cut methods of this type are sometimes used where there is no need for them and where their use is a positive detriment, since the extra operating expense caused by them soon offsets any immediate apparent gain. Such a case, for example, would be represented by reconnecting a three-phase 440-volt series-star winding for two phase 440 volts with the same coils, making no other change. The machine would probably operate in many cases, but the increased power bill would pay the interest on a considerably larger sum than would be represented by the cost of a proper set of two-phase coils. If this point is understood and given proper consideration, it is desirable to know some of these semistandard or possible schemes, as they may be of service in an emergency.

Number of Slots Not a Multiple of Phases Times Poles.

Among these schemes one which is not usually found in textbooks, but which is perfectly legitimate and largely employed by all manufacturers, is the use of a core having a number of slots that is not an exact multiple of the number of phases times the number of poles—for example, a 90-slot core wound for three-phase, eight poles. This connection is represented by Fig. 134. The Roman numerals on each pole-phase group represent the number of coils in that group, and it will be seen that each phase consists of 6 groups of 4 coils each and 2 groups of 3 coils each, or a total of 30 coils, and 90 coils in the complete winding. This irregularity introduces a slight displacement of the phase angle at certain places, but these places are so chosen around the machine that the net result is a perfectly balanced three-phase voltage at the terminals of the machine. E. M. Tingley originated an ingenious and simple method for arranging such windings with mathematical accuracy to give perfectly balanced voltage.[1]

It does not follow, however, that only the slot numbers recommended by Mr. Tingley can be made to give operating results. Other combinations are practically workable along the same general lines and can be laid out by inspection with reasonable regard to the best symmetry. But it is true that only the combinations pointed out by him can be made to give a theoretically perfect voltage balance at the motor terminals on all phases. This explanation is made in reply to the question frequently asked as to whether it is essential that the number of primary slots shall be a multiple of the number of phases times the number of poles. It does not necessarily have to be such a multiple, and connections of the type shown in Fig. 134 give practically as good operating results as any other.

The manufacturers make use of this type of connection in order to use the same core for as many combinations of phase, voltage, poles, cycles and horsepower as possible, thereby greatly reducing the stock of punchings or stampings that must be carried and also the expense necessary for dies to produce these punchings.

Particular reference is made to such diagrams in this chapter to insure that no one who is contemplating a reconnection need be discouraged or give up the attempt if it is discovered that the number of pole-phase groups does not divide exactly into the number of slots. In general, if the total number of coils in the winding is right for the voltage to be used, it will be satisfactory to put as many coils in each group as can be obtained by the even division of pole-phase groups into total number of slots and then to distribute the odd coils equally among the phases and insert them mechanically in various groups to give the greatest symmetry. Of course, if there are two or more parallels in each phase, there must be the same number of coils in each parallel. For example, in the case of Fig. 134 there are

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[1] In the "Electical Review" for Jan. 23, 1915, Vol. LXVI, pp. 116–8.

three phases and eight poles; 3 × 8 = 24 and 90 ÷ 24 = 3¾; therefore there will be four coils in each group excepting in the case of six groups which will have three coils. Two of these six groups are in each of the three phases, and one of these groups is in each of the two parallel legs of each phase. If this be followed, it may not give the perfectly balanced condition of Fig. 134, but when done by a careful man, it will usually give a safe operating condition.

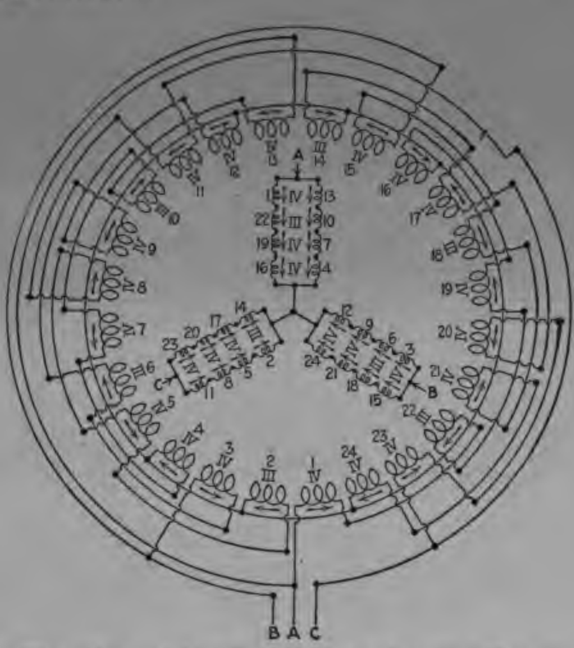


FIG. 134.—Three-phase, eight-pole, parallel star diagram with uneven grouping for a ninety-slot stator.

Consequent-Pole Windings for Two Speeds.

A second expedient which may be employed to connect a given winding for twice the original number of poles is the use of what is known as a "consequent-pole" connection. This is illustrated by Figs. 135 and 136, which show the usual connections for the three-phase motor wound to give two sets of poles or two speeds in the ratio of two to one. This change is accomplished by a single winding. In Fig. 135 the high-speed is parallel-star and the low-speed series-star. In Fig. 136 the high-speed is parallel-star and the low-speed series-delta. Either may be used at the discretion of the designer. Fig. 135 usually gives better results where a constant torque is desired and gives twice the horsepower on the high-speed that it develops on the low-speed. Fig. 136 gives somewhat better results where a constant horsepower is desired at both speeds, as is the case with most machine-tool applications.

Fig. 137 is an explanatory diagram showing schematically how the two sets of poles are produced by such windings. Considered

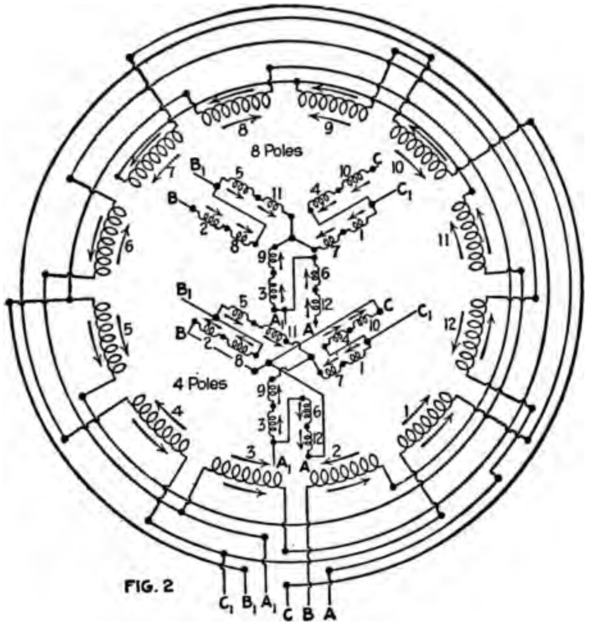


Fig. 135.—Two-speed, three-phase, four- and eight-pole parallel and series star diagram.

with Fig. 135, the inside set of arrows shows the parallel-star connection where four salient poles are produced directly by the winding, two north and two south. The set of arrows outside the winding circle shows the winding connected in series- tar and the current direction such as to produce four north poles by the winding. Since it is not possible to have north poles alone, there immediately result four consequent south poles, indicated by the dotted arrows, where the magnetic flux returns to the primary. This results in eight poles and half-speed. For the sake of simplicity the arrows shown are for one phase only.

The three phases interact to produce the combined magnetic pole as in any normal three-phase winding. These diagrams are shown to indicate that it may be possible in some cases to reconnect motors for half-speed by making use of a diagram of this nature. Such a connection, for example, makes it possible at times to reconnect a 25-cycle motor for 60 cycles and twice the number of poles, and so keep the r.p.m. of the motor nearly the same.

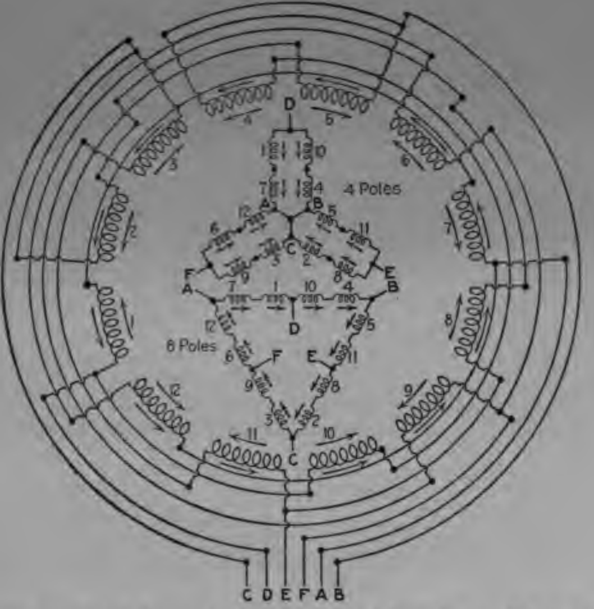


FIG. 136.—Two-speed, three-phase, four- and eight-pole parallel star and series delta diagram.

It will be noticed that the outside arrows on the pole-phase groups for checking the slow-speed, or eight-pole, connection in Figs. 135 and 136 all point in the same direction instead of alternately in opposite directions as the inside arrows do. This is because the eight-pole connection is "consequent-pole," or so connected that the current produced the same polarity in all the pole-phase groups, instead of alternate north and south as is usually the case. It will be recalled that in Chapter III mention was made of the fact that in such a case the check with the alternate arrows did not hold. It will be seen from Figs. 135 and 136 that in checking windings of this type, or consequent-pole, by placing arrows on the pole-phase groups in the direction from the lead toward the star in all three phases, the arrows will all point in the same direction. This can be explained in another way by saying that in a winding of this type there are only half as many pole-phase groups for the same total number of poles as there are in the usual form of winding. This is equivalent to saying that alternate pole-phase groups are omitted. Since in the check of the usual winding the arrows are alternately opposed, if alternate arrows are omitted the remainder will all be in the same direction, as is indicated in the check of the eight-pole connection of Figs. 135 and 136.

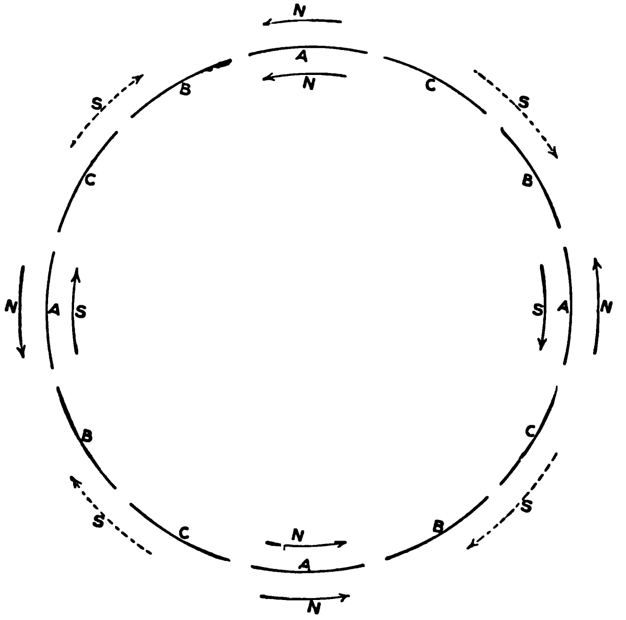


FIG. 137.—Schematic magnetic diagram explaining the eight-pole connection of Figs. 135 and 136.

A diagram for a two-phase two-speed connection where the winding is in parallel on the high-speed and in series on the low-speed is shown in Fig. 138. This winding is of particular and especial interest in that it overcomes one of the disadvantages of the corresponding three-phase connections shown in Figs. 135 and 136 by putting half of the winding in one phase for the low-speed connection and in the other phase for the high-speed connection. This is an advantage, because the so-called "winding factor," or "distribution factor," remains the same on both speeds as in a normal two-phase machine, while in the three-phase connections shown in Figs. 135 and 136 the winding factor is only 86.6 per cent. as good on the low-speed connection as on the high. This is because there are only four winding groups

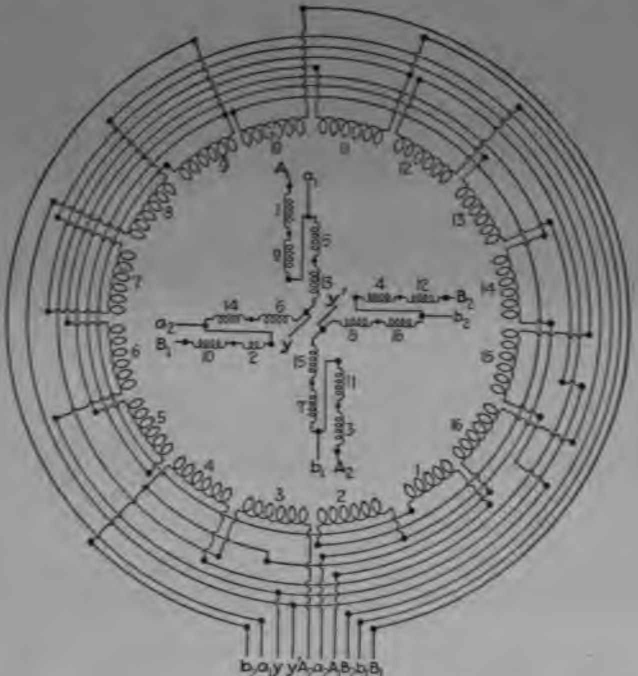


FIG. 138.—Two-speed, two-phase, four- and eight-pole, parallel and series diagram for same distribution factor on both connections.

per phase spread over the entire periphery, and yet eight poles are being produced.

Expressed in another way, the coils for one of the eight poles are spread over the usual span for a four-pole machine. Since the distribution factor is a measure of the induced voltage or counter-electromotive force generated, and since the capacity of the motor may be measured by its current-carrying capacity multiplied by the induced voltage, it can be concluded at once that the loss of 14.3 per cent. in the three-phase connection on the slow speed is avoided in the two-phase diagram, Fig. 138. In reality the gain is greater than this, for the reason that the two-phase distribution factor caused by consequent poles is only 70.7 per cent., as against 86.6 per cent. in the three-phase.

Speaking simply, if a series-parallel two-phase connection were used, similar to the three-phase, Fig. 135, and without changing the coils from one phase to the other as does Fig. 138, the loss in horsepower on the slow speed would be approximately 30 per cent., which is certainly a matter of prime importance. It is mechanically possible to make such an arrangement on a two-phase winding, but there seems to be no practical way of accomplishing the same result on a three-phase winding. As in the case of the three-phase two-speed diagrams, this connection shows the possibility of changing a standard motor to half-speed by the medium of such a connection.

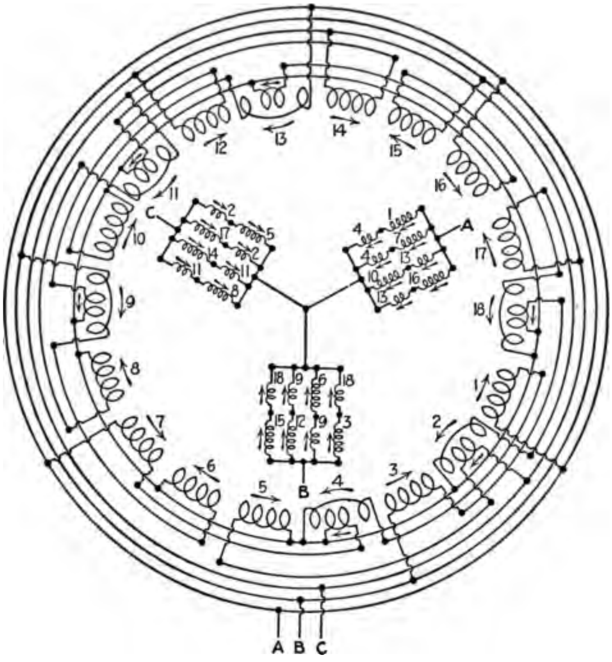


FIG. 139.—Three-phase, six-pole, series star diagram in four parallels. So-called "split group" diagram. Emergency make shift.

When operating from a three-wire two-phase system or any system having the two phases interconnected in any way, all four of the leads that connect to y and y', Fig. 138, should be brought out instead of tying them together in pairs and bringing out y and y' as shown. This is in order that the phase windings may be kept clean of each other on both speed connections.

Splitting Groups.

Fig. 139 illustrates a connection that is sometimes attempted, but usually with disastrous results. In all the foregoing diagrams the phase-pole group has been treated as a unit. That is to say, if there were four coils per pole per phase, these four were connected in series into a group and handled as a unit. Fig. 139, on the other hand, breaks up some of the groups into halves, Suppose, for example, that a three-phase six-pole motor has 72 coils total and is connected in series for 440 volts and it is desired to reconnect it for 110 volts. It can be parallel for 220 volts, and there will be three pole-phase groups in each of the two parallel legs of the winding. It cannot be paralleled four times, since 6 is not divisible exactly by 4. Since there are 6 poles and 3 phases, there are 18 pole-phase groups and $72 \div 18 = 4$ coils per group. It is therefore possible to split 6 of the 18 groups into halves of two coils each, and by putting a half-group in series with a whole group to get 4 parallels per phase having 1.5 pole-phase groups in each of the 4 parallel circuits. Such a connection is shown in Fig. 139. This is rather difficult to do properly unless there is an expert winder available, and it leaves the motor in an unsatisfactory operating condition when it has been done. This is explained by the vector diagrams in Figs. 140 to 144.

Let *ag* represent the voltage vector of one magnetic pole made by combining the three pole-phase vectors *ae*, *ef* and *fg*, Fig. 140. For clearness, one pole-phase vector *ae* is shown in Fig. 141 drawn to a larger scale and made up of the vectors of the four separate coils *ab*, *bc*, *cd* and *de*. The length of the line *ab*, for example, represents the voltage generated by the rotating field in a single coil of the winding, and four of them are considered together because there are four coils in series in any complete pole-phase group; as for example, group 16 in Fig. 139. If two or more circuits, each made up of one whole pole plus one half-pole, are to be connected in parallel, the two resulting vectors should be the same length and have the same direction or phase. Such a condition is shown in Fig. 142. This is a true parallel, and there will be no circulating current around the closed loop formed by the two parallels in the winding, since two equal voltages in phase with each other are opposed.

An inspection of the four vectors of which *ae* is composed will show that it cannot readily be divided into two parts and paralleled without there being circulating current. Suppose, first, that the winding group is split in the middle at *c*, leaving *ab* + *bc* for one half and *cd* + *de* for the other. The two resulting vectors are *ac* and *ce*. When each of these vectors is added to another complete pole and the two connected in parallel, the result is indicated in Fig. 143, where *ra* + *ac* is paralleled with *sc* + *ce*. Since *ac* and *ce* are not in phase, there is left a voltage equivalent to *em* + *nc*, which will set up current around the closed loop and produce increased heating. In order to avoid this to a certain extent, the two outside coils of the group, *ab* and *de*, are sometimes paralleled against the two inside coils, *bc* and *cd*. The two resulting vectors *ax* + *ze* and *bd* are in parallel, but they are of different lengths. The results are shown in Fig. 144, where a whole pole *tb* plus the half-pole *bd* is in parallel with *ra* + *ax* + *ze*. While these vectors are in phase, the difference in their numerical value leaves a component *ek*, which is unbalanced and which is free to cause circulating current in the closed loop of the parallel circuit.

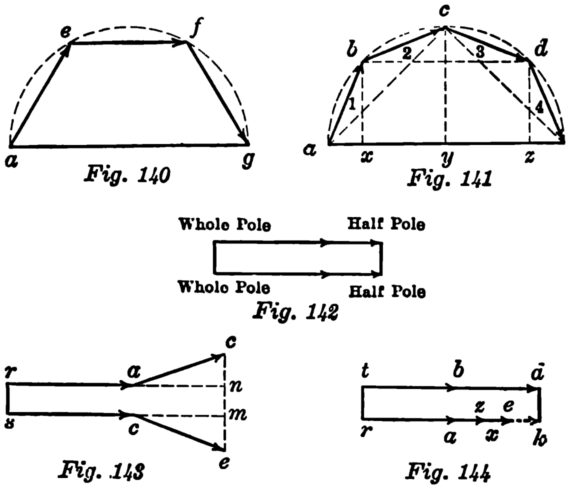


Fig. 140 Fig. 141

Fig. 142

Fig. 143 Fig. 144

FIGS. 140–141–142–143–144.—Vector diagrams of group voltages in Fig. 139.

TABLE IX.—COMPARISON OF A TWO-PHASE MOTOR CONNECTED "T" TO OPERATE ON THREE-PHASE WITH NORMAL WINDING

	Normal two-phase winding	Three-phase "T" connection	Normal three-phase winding
Full-load efficiency	88.0	86.9	88.5
Full-load power factor	89.0	84.8	90.0
Starting torque	1.75	1.20	1.94
Maximum torque	3.3	3.17	3.3
Deg. C. Rise at Full Load:			
Stator copper	22.5	32.0	21.0
Stator iron	20.0	32.5	19.0
Rotor copper	22.0	30.0	22.0

In addition to the difficulty of making this connection properly and the fact that there is at all times some circulating current, there is also likely to be trouble in keeping the phases insulated from each other. All things considered, this is an expedient which had better be left untried except in cases of emergency. For all ordinary operating conditions much better results will be secured by replacing the old coils in the machine by new coils wound for the proper voltage.

Table IX shows comparative performances of a two-phase motor reconnected for operation on three-phase by a "T" connection and the performance of the same motor when supplied with new three-phase coils and connected in a normal three-phase manner.

Fig. 115 shows a possible three-phase "T" connection which may be made from a two-phase winding by a method similar to the Scott transformer connection. The effect of this connection upon the performance is shown in the table and was discussed in Chapter VI under "Changes in Phases." It is a connection that should be used only as a temporary expedient until better arrangements can be made. It is possible to devise other makeshifts, but they are usually attended with so great a sacrifice in the heating and efficiency of the motor, that it is safer to leave them untried. It happens that a connection that looks feasible from the standpoint only of the number of coils in series, falls down on trial because these coils are not strictly in phase. Experiments of this nature are better left to the electrical manufacturing establishments.

CHAPTER X

RECONNECTING AN OLD WINDING FOR NEW CONDITIONS

General Fundamental Considerations.

An electric motor is a device for transforming energy in the form of an electric current into mechanical energy in the form of turning effort, or rotating force. This turning effort, or driving force, is called torque and is measured in the pounds pull that a motor would develop at the rim of a pulley one foot radius. This torque is produced by the force exerted by a current flowing through a conductor located in a magnetic field. From this it is evident that the capacity of a motor to produce torque is limited both by the capacity of the copper circuit to carry current and the iron circuit to carry magnetic lines of force.

The amount of current, or flux, that is being carried by a given cross-section of copper or iron determines the heating of the motor. It may be assumed that in a normal motor operating under the conditions for which it was designed, there is a reasonable current flowing in the copper and a reasonable flux in the iron, which the designer believes will give the most satisfactory operating results. Therefore, if changes are to be made in the speed, phase, frequency and voltage at which the machine is to operate, the winding must be reconnected so as to have approximately the same number of magnetic lines per unit cross-section of iron and the same current density in the copper that existed before the change was made in the motor. This statement is true over a wide range of conditions, and would be true universally if it were not for the fact that the high-speed machine will generally run cooler than the same machine operated at low speed with the same current density in the copper and number of magnetic lines per unit cross-section of iron, because of the larger amount of air that the high-speed machine will force through its parts. For this reason it is generally true that the capacity of a motor may increase in the same proportion as the speed when the speed is being increased, but may decrease somewhat faster than the speed is being reduced. As a concrete example of this, it may be stated that a 75-hp. motor operating at 450 r.p.m. may be made to develop 150 hp. at 900 r.p.m., assuming that the mechanical design will stand the stresses due to the increased speed; but conversely, a motor originally designed for 150 hp., at 900 r.p.m., when cut down to 450 r.p.m. might not be able to develop more than 65 hp., on account of reduced ventilation.

There are certain fundamental mechanical relations that govern all motors whether alternating or direct current. The idea given in the foregoing of the reaction of the electric current upon a magnetic field concerns the production of a mechanical pull tending to rotate the movable member of the motor. This pull is usually expressed in pounds at one foot radius. This in turn is expressed in horsepower when multiplied by r.p.m. and by 2 π and divided by 33,000, and may be expressed by the equation:

$$Hp. = \frac{Torque \times r.p.m. \times 2\pi}{33{,}000} = \frac{Torque \times r.p.m.}{5{,}252}$$

from which

$$Torque = \frac{hp. \times 5{,}252}{r.p.m.}$$

Since the current in the copper and the flux in the iron are to be held approximately constant whatever change may be made in the motor winding, it follows that the torque will be kept constant and the horsepower will vary with the speed. In other words, if the copper and iron are carrying the same current and flux at all times, twice the horsepower will be developed at twice the speed or approximately one-half the horsepower at one-half the speed.

It is essential, in getting a clear conception of the motor, either for purposes of making changes or for other reasons, that a plain distinction be made between torque and horsepower. It is the function of a motor to produce torque, or turning effort. It is incidental that when the same force is allowed to rotate at one speed or another, a different horsepower is produced. For this reason it is incorrect to speak of a motor and say "It required 20 hp. to start the load," because, when starting, the motor was generally at a standstill; therefore there was no rotation and hence no horsepower. The motor, however, was taking current and developing torque, and the correct expression would be the current taken at start was equivalent to the current taken by the motor when developing 20 hp. at full speed.

It is often possible to reconnect a motor and adapt it to new conditions leaving it entirely normal, and the performance in all essential respects remains the same as before reconnection. Such changes, for example, are represented by connecting the polar groups of a winding in series for 440 volts and in parallel for 220 volts. These are classified as strictly legitimate changes.

A second class of changes leaves the performance in some respects unchanged and alters it in others. These may be represented by operating a motor in star on 440 volts, and in delta on 220 volts. In this change there is little change in efficiency or power factor; the starting and maximum torques on 220 volts, however, are only 75 per cent. of their value on 440 volts. In such a case the advisability of the change depends entirely on the work that the motor is doing. If the torques at their altered values are sufficient to start and carry the driven load easily, there is no objection to operating the motor indefinitely as so reconnected, since the motor will not run any warmer than before and its efficiency and power factor may be better. Such changes may be classified as possible changes.

A third class of changes leaves a motor operative in the sense of producing torque enough to do the work required, but so alters its performance as to heating, or efficiency, or power factor, or insulation, that it is undesirable to leave the motor operating indefinitely in such a condition. Such changes might be exemplified by taking a three-phase motor and reconnecting the coils as they stand for two-phase. This is equivalent to operating the three-phase motor at 125 per cent. of normal voltage, and in addition, the coils which should have extra insulation where the phases change, have only group insulation. The iron loss and heating may be increased to a dangerous degree and the power factor greatly decreased. Such changes should be used only in an emergency and the proper permanent changes made at as early a date as possible. These changes should be classified as make shift or undesirable changes.

The main principles which operate to fix the limits of the different combinations, such as series, parallel, series star, parallel star, series delta, parallel delta, etc., possible with a single winding, may be enumerated somewhat in the following manner:

1. The mechanical output of a motor is limited by the cross-

section of copper available to carry current and by the cross-section of iron available to carry magnetic flux.

2. An induction motor is also at all times an alternating-current generator as well, and the voltage generated by its own rotating field cutting the conductors of its own stator coils must at all times very closely approximate the applied line voltage.

3. It is necessary that the pitch or throw of the coils bear some reasonable physical relation to the number of poles that the machine has. For example, in a 4-pole motor the coils should throw somewhere near ¼ of the circumference of the stator bore, in a 6-pole motor somewhere near ⅙ the circumference, and so on. The practical limits to the throw are from ½ to 1½ times this full-pitch value. That is to say, in a 72-slot 6-pole motor the full or exact pitch for the coil throw would be $\frac{72}{6} = 12$ slots, or the coil would be in slots 1 and 13. Using the limits ½ to 1½ as given, the throw of the coil should be not less than 6 slots nor more than 18 slots for possible operation; that is, the coils should not spread less than slots 1 and 7 nor more than slots 1 and 19.

4. All changes in operating conditions whether of horsepower, voltage, phases, frequency or poles, may be reduced to terms of change in voltage and so considered.

5. An induction motor is similar to a transformer in that the number of turns in series in the winding must be varied in the same direction and by the same percentage as any change in the voltage applied. In addition to these principles the following practical considerations must be remembered:

(*a*) The new voltage which is applied to a reconnected motor must not exceed the limiting value of the insulation which is on the coils. For example, 2200 volts should not be applied to a 550-volt winding even though it has been reconnected with four times as many turns in series.

(*b*) In reconnecting for higher speeds the peripheral speed of the rotor must be kept down to a safe value so that the centrifugal force does not damage the rotor core or winding mechanically.

(*c*) In a wound-rotor motor the rotor winding must be connected for the same number of poles as the stator winding.

(*d*) In a squirrel-cage motor if radical changes are made in the number of poles, a change may also be required in the short-circuiting rings of the squirrel-cage rotor winding in order to keep the proper starting torque.

(*e*) In a polar-group winding the individual coils at the beginning and end of the phase groups have usually heavier insulation than the inside coils of the groups. Where this is the case, when reconnecting for change in phase or poles the coils with the heavier insulation should be shifted to their proper new places in the winding.

These principles have been thoroughly covered in preceding chapters, but in recapitulation some additional comments may be made bearing on the practical application.

1. Cross-Section of Copper and Iron.

From the existing connection of the winding in the machine which is to be reconnected, it is a simple matter to check the current flowing in the turns of the coils which are in series. This is done by checking the connection of the winding; that is, whether it is series or parallel, star or delta, etc. From this fact and the rated current of the machine can be derived directly the current in the coils themselves. For example, a three-phase machine has a normal rating of 50 amperes per terminal and is connected 2-parallel delta, Fig. 145. The current in the individual coils themselves is $\frac{50}{2 \times 1.73} = 14.5$ amperes, as shown. Then the load which is put on the motor after reconnection

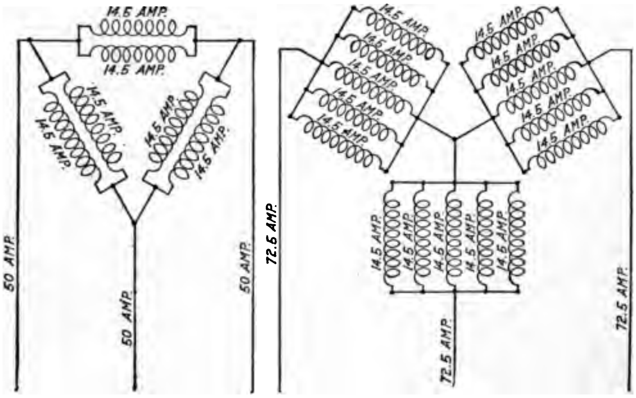


FIG. 145. FIG. 146.

FIGS. 145 and 146.—Checking current carrying capacity of a winding to be reconnected.

should not be greater than that which would cause 14.5 amperes to flow in the coils themselves. Under the new connection the polar groups might be 5-parallel star, as in Fig. 146, in which case the new current per lead would be 5 × 14.5 amperes = 72.5 amperes, but the current in the individual coils would still be 14.5 amperes as indicated.

If the new connection is for a greater number of poles and hence a slower speed, it would be well not to put quite so much current through as originally on account of the reduction in ventilation. Regarding the cross-section of iron, this remains constant so far as the teeth are concerned, but in the core back of the slots this changes with the number of poles. This is illustrated by Fig. 147, which shows a cross-section of a motor indicating the magnetic conditions in the iron when the motor is connected for 4, 6, 8, 10 or 12 poles.

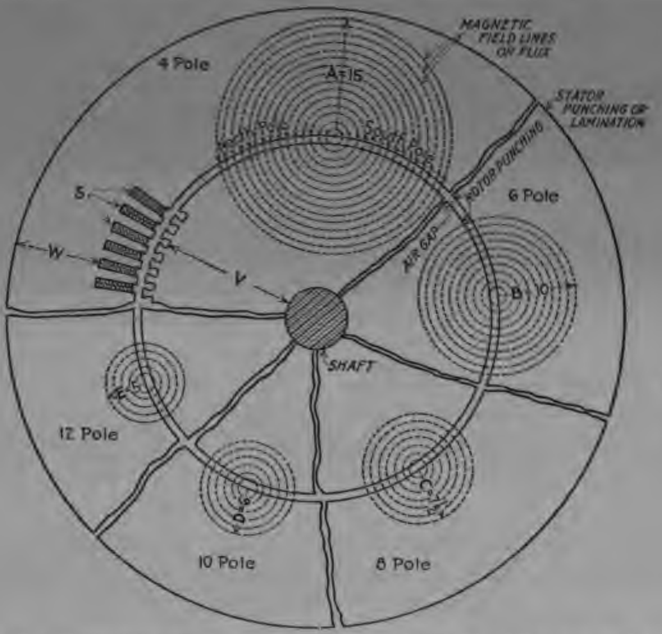


FIG. 147.—Cross-section of stators wound for four, six, eight, ten and twelve poles showing radial depth of iron behind slots required for the magnetic field.

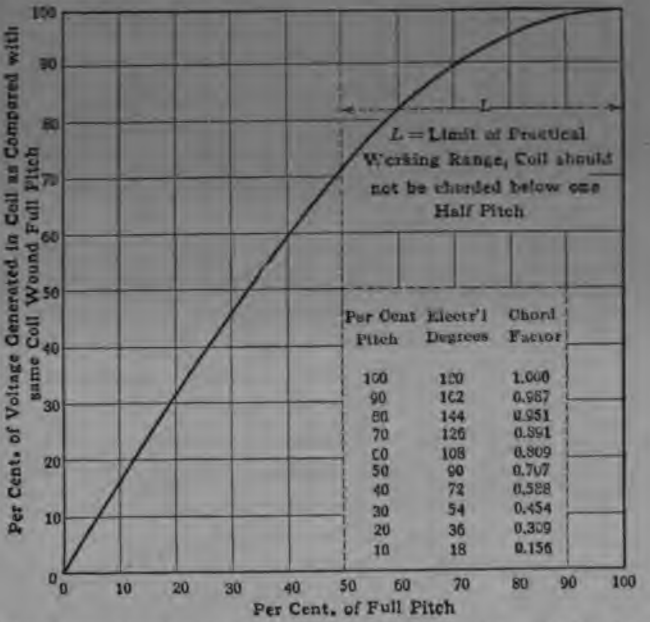
Considering the 4-pole sector, the coils in the stator slots *S* set up a magnetic field represented by the 15 concentric circles causing a north pole where they leave the stator and a south pole where they reënter the stator, as indicated by the arrowheads. The proximity of these 15 circles at the air gap indicates the density of the magnetic field at this location. It will be noted that all 15 of these circles must pass through the core back of the slots or through a cross-section represented by the dimension W.

If, now, consideration is given to the sector marked 6-pole, it will be noticed that the magnetic density in the air gap as indicated by the proximity of the concentric circles is the same as in the case of 4 poles, but the iron back of the slots now has to carry only 10 circles and hence has only $^{10}/_{15}$ the magnetic density as in the case of 4 poles. There is still the same total flux in the machine, since $4 \times 15 = 60 = 6 \times 10$, and this explains why the air-gap density stays the same, but this total flux is now separated into six magnetic circuits instead of four and hence the iron in the core back of the slots is not worked nearly so hard.

Similarly, in the case of 8 poles there are only 7½ circles, since $8 \times 7\frac{1}{2} = 60$, and in the case of 10 poles 6 circles and 12 poles 5 circles, since $10 \times 6 = 60$ and $12 \times 5 = 60$. In other words, there is the same total flux in the machine for all these connections and the same magnetic density in the air gap, but the core iron back of the slots works at a higher density the smaller the number of poles and at a lower density the larger the number of poles for which the winding is connected. The obvious precaution to be drawn from this consideration is that when reconnecting a winding for a smaller number of poles some check should be made to insure that the magnetic density in the core does not exceed a safe value. Reference will be made to this in Chapter XII on estimating a new winding for an old core.

2. Generator Action of the Winding.

This has been referred to several times and will not be elaborated here beyond calling attention to the fact that the rotating magnetic field will always assume such a value that as it cuts the stator coils it will generate in them a voltage practically equivalent to the applied line voltage. Since both the number of turns in series in the coils and the magnetic density in the iron may be varied, there are evidently several combinations that would generate the line voltage, some having more turns and less field and some having less turns and more field. The practical difference between these combinations would be that the fewer the turns and the stronger the field the greater would be the maximum torque, this being limited by the saturation of the iron in the core. A little thought brings out the fact that this is equivalent to raising and lowering the voltage on a fixed winding. The higher the voltage the greater will be the magnetic field and the greater the torque. This consideration of the generated voltage or counter-electromotive force or back electromotive force is one of the simplest checks on the number of turns required in a winding.



Per Cent Pitch	Electr'l Degrees	Chord Factor
100	180	1.000
90	162	0.987
80	144	0.951
70	126	0.891
60	108	0.809
50	90	0.707
40	72	0.588
30	54	0.454
20	36	0.309
10	18	0.156

FIG. 148.—Curve showing the variation of the "chord factor" with the throw of the coil.

3. Changing the Throw.

The effect of changing the throw has been thoroughly covered, and only the effect on the applied voltage will be shown here as a curve, Fig. 148. In this figure full pitch is called 100 per cent. For example, in a 72-slot 6-pole motor the winding would be 100 per cent. pitch if the coils lay in slots 1 and 13, it would be 66.66 per cent. pitch if the coils lay in slots 1 and 9 or 50 per cent. if they lay in slots 1 and 7. The curve indicates how the voltage applied to a coil or a winding should be reduced as the coil is chorded up if the same magnetic conditions are to be kept, or the reciprocal of the curve values indicates how the density of the magnetic field will increase if the voltage is held constant while the throw of the coils is decreased.

4. All Changes can be Handled as Voltage Changes.

The statement is here made that any change in the operating characteristics of a motor may be reduced to terms of a voltage change and that if the corresponding voltage be applied the operation under the new conditions will approximate the normal operating conditions under the original conditions. Since there are five main operating characteristics—namely, volts, phase, poles, cycles and horsepower—a brief résumé is in order stating how each one of these may be considered as a voltage change. In other words if, for example, the horsepower or phase of a motor is to be arbitrarily changed, what will be the new operating voltage to secure this result? Taking these characteristics in order, a voltage change is self-evident since everything is to be reduced to voltage. In the case of a phase change, two to three or vice versa, the voltage on a three-phase connection should be 5/4 of that on the corresponding two-phase connection. For example, if a two-phase motor is connected for three-phase and everything else left the same, the three-phase connection should be operated at 5/4 the rated voltage of the two-phase, or a two-phase 440-volt motor when reconnected for three-phase becomes a 550-volt motor, etc. In Fig. 149 is shown a 48-coil winding grouped for two-parallels two-phase 4-poles, if this winding will operate on 220 volts two-phase it will also operate on 550 volts three-phase when grouped 4-pole series star, as in Fig. 150.

In the case of a change in the number of poles, if the voltage be changed in the same direction and by the same amount as the change in speed, the torque will remain essentially constant and the horsepower will vary with the speed, being greater at higher speed and less at lower speed in exact proportion. However, if for reasons explained in connection with Fig. 147, there is not enough iron back of the slots to permit of keeping the same total flux and dividing it into fewer circuits with greater flux per circuit, the voltage may be kept constant and the horsepower will remain practically constant. The latter condition would mean that there is less total magnetic flux and less torque at higher speeds and greater total flux and greater torque at lower speeds, as must necessarily be expected since the horsepower is constant and horsepower = torque × r.p.m. ÷ 5252.

A varying frequency can be readily reduced to a corresponding voltage change by remembering that a change in frequency without any other change would result in a change in speed and since

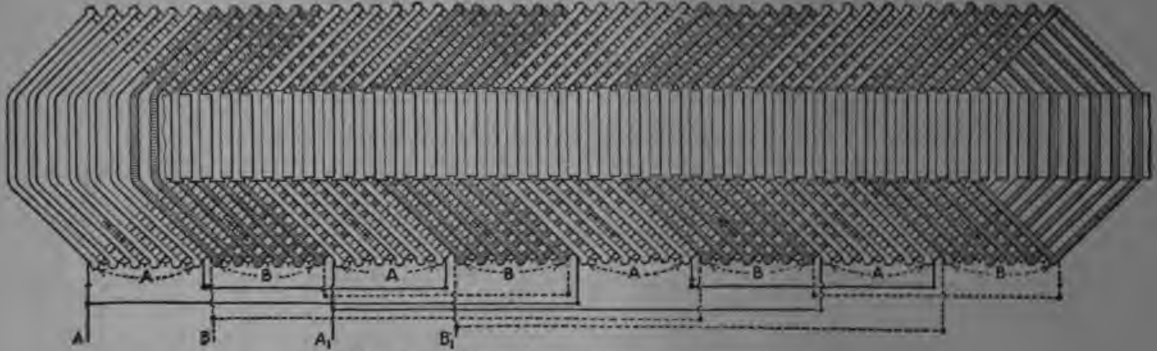


Fig. 149.—Two-phase, two parallel connection.

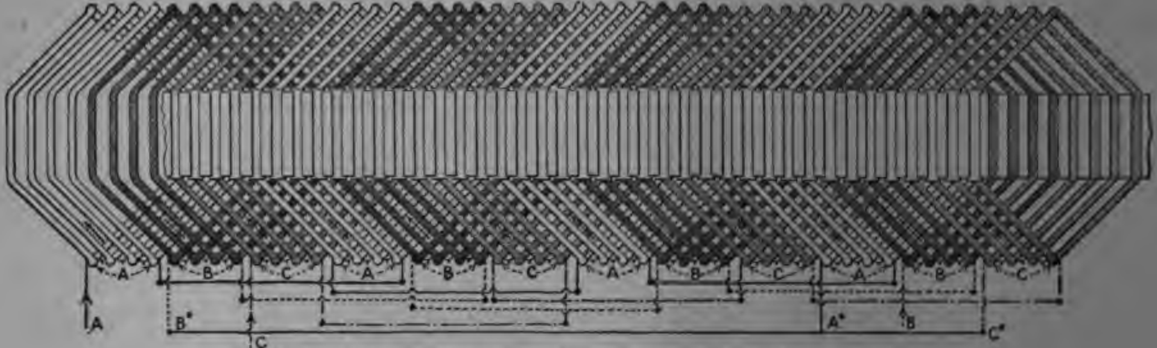


Fig. 150.—Same winding as Fig. 149 reconnected three-phase series star.

the basic idea of this method is that the motor is also an alternating-current generator, generating the applied voltage, it is evident that with an increased speed the generated voltage will be increased and with decreased speed the generated voltage will be decreased. Hence, it follows directly that when the frequency or cycles of the supply circuit are changed the voltage should be changed by the same amount and in the same direction. For example, if a 60-cycle motor is run on 50 cycles it should have applied only $\frac{5}{6}$ the voltage if the same magnetic condition is to be kept, and consequently the horsepower will be only $\frac{5}{6}$ of the 60-cycle value. Viewed mechanically, the torque remains the same on 50 cycles, but the speed is only $\frac{5}{6}$ as great, hence there is only $\frac{5}{6}$ the horsepower which checks the electrical result.

There remains only a change in horsepower to be converted into a voltage change, and this is apparent from the fact that in any motor the horsepower is proportional to the product of the voltage and amperes. Since the cross-section of the copper conductor remains the same and hence the amperes remain the same, the only thing that can vary is the voltage, and it follows directly that to get more horsepower out of a motor requires the application of a higher voltage and less horsepower will permit the use of a lower voltage.

From these considerations it appears that the effect of a change in any of the characteristics of the motor can be balanced by the proper change in the voltage. This statement at once arouses the comment that while it might be found that 273 volts or 346 volts or something of the kind was proper to give normal operation on a motor under changed conditions of phase or poles or what not, still such information would be of little use since there are no commercial circuits having such voltage values. The answer to this is that the number of turns in the winding or the connection of the groups may be changed so as to increase the total number of turns in series by the amount that the voltage should be decreased; and *vice versa*, it may be possible to decrease the total number of turns per phase in series by the amount that the voltage should be increased.

Consideration of a simple case under each of the five characteristics of horsepower, poles, cycles, phase and voltage will bring out the manner of applying the "voltage method" to any and all changes in the motor-operating conditions.

TABLE V.—COMPARISON OF MOTOR VOLTAGES WITH VARIOUS CONNECTIONS AND PHASES

If a motor connected originally, as shown in any horizontal column, had a normal voltage of 100, its voltage when reconnected, as indicated in any vertical column, is shown at the intersection of these two columns.

Form of connection	Three-phase series star	Three-phase 2-parallel star	Three-phase 3-parallel star	Three-phase 4-parallel star	Three-phase 5-parallel star	Three-phase 6-parallel star	Three-phase series-delta	Three-phase 2-parallel delta	Three-phase 3-parallel delta	Three-phase 4-parallel delta	Three-phase 5-parallel delta	Three-phase 6-parallel delta	Two-phase series	Two-phase 2 parallels	Two-phase 3 parallels	Two-phase 4 parallels	Two-phase 5-parallels	Two-phase 6 parallels
Three-phase series star.	100	50	33	25	20	17	58	29	19	15	12	10	81	41	27	20	16	14
Three-phase 2-parallel star.	200	100	67	50	40	33	116	58	39	29	23	19	162	81	54	40	32	27
Three-phase 3-parallel star.	300	150	100	75	60	50	173	87	58	43	35	29	243	122	81	60	48	41
Three-phase 4-parallel star.	400	200	133	100	80	67	232	116	77	58	46	39	324	163	108	80	64	54
Three-phase 5-parallel star. . . .	500	250	167	125	100	83	289	144	96	72	58	48	405	203	135	100	80	68
Three-phase 6-parallel star.	600	300	200	150	120	100	346	173	115	87	69	58	486	243	162	120	96	81
Three-phase series delta.	173	86	58	43	35	29	100	50	33	25	20	17	140	70	47	35	28	23
Three-phase 2-parallel delta. . . .	346	173	115	87	69	58	200	100	67	50	40	33	280	140	94	70	56	47
Three-phase 3-parallel delta. . . .	519	259	173	130	104	87	300	150	100	75	60	50	420	210	141	105	84	70
Three-phase 4-parallel delta. . . .	692	346	231	173	138	115	400	200	133	100	80	67	560	280	188	140	112	93
Three-phase 5-parallel delta . . .	865	433	288	216	173	144	500	250	167	125	100	83	700	350	233	175	140	117
Three-phase 6-parallel delta. . . .	1,038	519	346	260	208	173	600	300	200	150	120	100	840	420	280	210	168	140
Two-phase series.	125	63	42	31	25	21	72	37	24	18	15	12	100	50	33	25	20	17
Two-phase 2-parallels.	250	125	84	63	50	42	144	73	49	37	29	24	200	100	67	50	40	33
Two-phase 3-parallels.	375	188	125	94	75	63	216	111	73	55	44	37	300	150	100	75	60	50
Two-phase 4-parallels.	500	250	167	125	100	84	288	148	97	73	58	49	400	200	133	100	80	67
Two-phase 5-parallels.	625	313	208	156	125	105	360	165	122	91	73	61	500	250	167	125	100	84
Two-phase 6-parallels.	750	375	250	188	150	125	433	217	144	108	87	72	600	300	200	150	120	100

1. **Change in Voltage.**

A motor is connected series-star for three-phase 440 volts, as in Fig. 151. How should it be connected for 220 volts? [For convenience Table V is here reproduced.] Looking at the table and following the horizontal line "Three-phase Series Star," there appears under vertical heading "Three-phase Series Star," also, the figures "100." That is to say, the motor as it stands on 440 volts is considered 100 per cent. The new voltage is to be 220, which is 50 per cent. of 440. Hence, the same horizontal line in the table, namely, "Three-phase Series Star," is followed along until the desired figure of 50 is found, which is under the vertical heading "Three-phase 2-Parallel Star." This is the correct answer: that is, if a motor is connected three-phase series-star for operation on 440 volts, it must be connected three-phase 2-parallel star, as in Fig. 152, to operate correctly on 220 volts.

2. **Change in Phase.**

Refer again to the table and assume that a three-phase 440-volt motor is to be reconnected for two-phase 440 volts. Inspection shows that the winding as it stands on 440 volts is four-pole three-phase series-delta, as in Fig. 153. Select the horizontal column in the table marked "Three-phase Series Delta" and follow it across, looking for a vertical column showing the value "100," since the desired two-phase voltage is the same as the present three-phase voltage, or 100 per cent. Inspection shows that there is no "100" under any two-phase connection. This indicates at once that a three-phase series-delta connected motor which is normally operated on 440 volts cannot be changed and operated on two-phase 440 volts, without rewinding. The nearest value to "100" under a two-phase column is "70," shown under "Two-phase 2-Parallels." This means that if a three-phase 440-volt motor which is connected series delta, be reconnected for 2-parallel two-phase, as in Fig. 154, it should be operated on 70 per cent. of 440, or 308 volts.

3. **Change in Frequency.**

It is desired to operate a three-phase 440-volt 60-cycle motor on 50 cycles at the same voltage. What change should be made in the connections? Inspection indicates that as the motor stands it is connected for three-phase 5-parallel star on 60 cycles. A change in frequency should be offset by a change in voltage in the same direction and by the same amount; hence, if a motor is operated on 100 per cent. voltage on 60 cycles, it should be

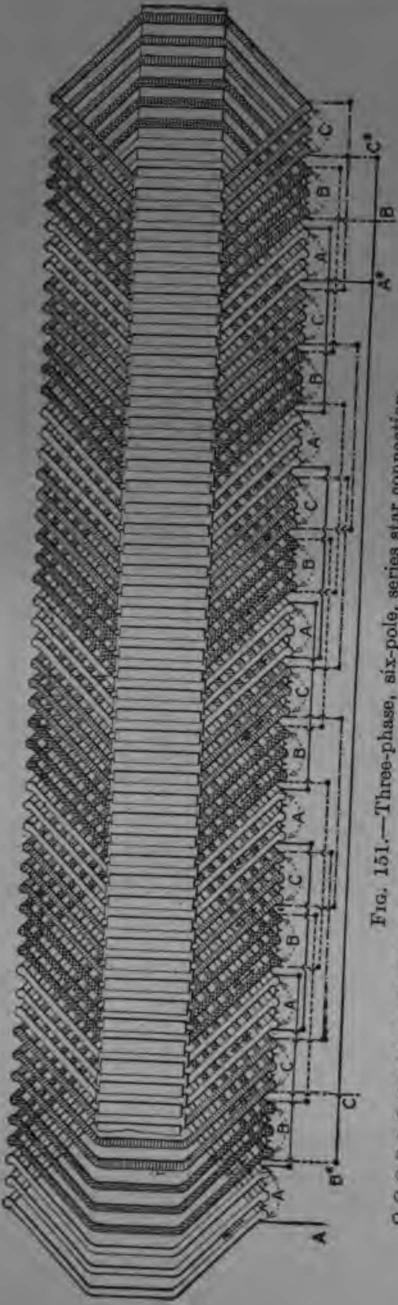


FIG. 151.—Three-phase, six-pole, series star connection.

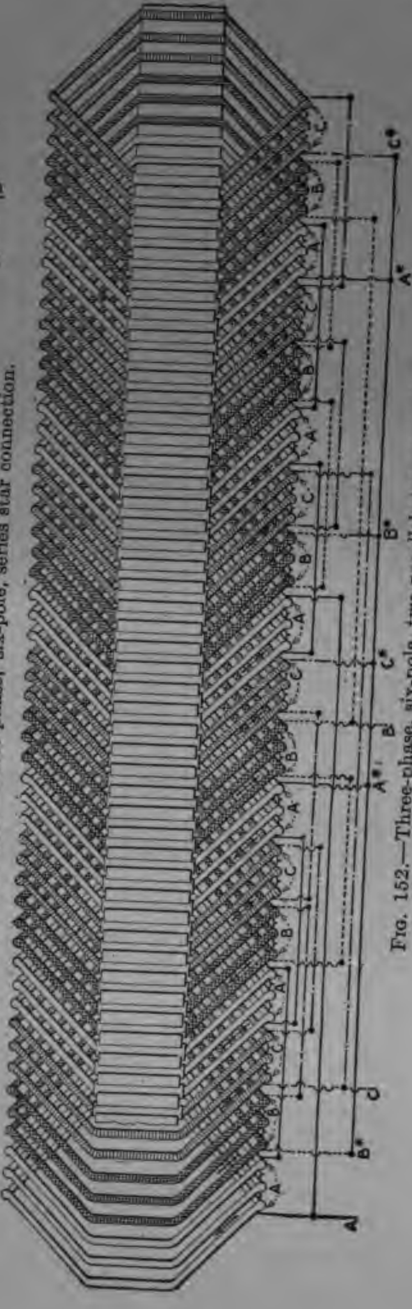


FIG. 152.—Three-phase, six-pole, two parallel star connection.

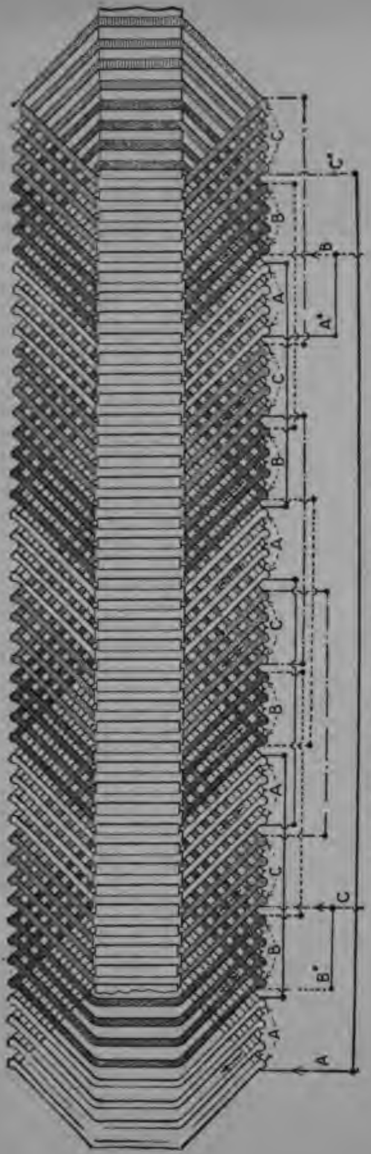


FIG. 153.—Three-phase, four-pole, series delta connection.

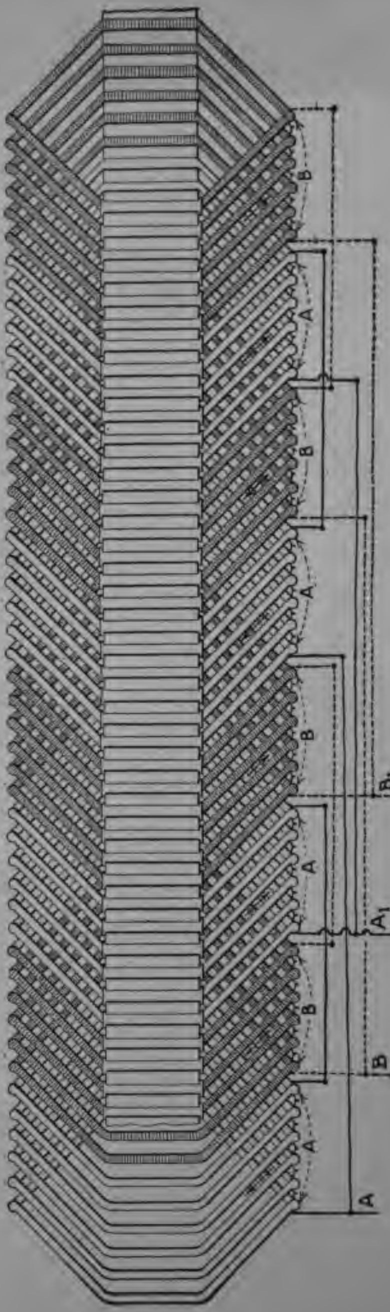


FIG. 154.—Two-phase, four-pole, parallel connection.

connected for $\frac{5}{6}$ of 100, or $83\frac{1}{3}$ per cent., voltage on 50 cycles. However, the voltage is to remain the same on 50 cycles as on 60 cycles, so this result must be obtained in another way. If the voltage cannot be decreased the number of turns in series can be increased. Another way of saying this is that we can reconnect the winding so that ordinarily it would be good for a higher voltage and then if it is operated on the same voltage the effect will be the same as if a lower voltage had been applied to the original connection. In the case in hand the motor should, when connected on 50 cycles, be operated on $83\frac{1}{3}$ per cent. of the 60-cycle voltage. Only 100 per cent. is available, so the winding will have to be reconnected with $\frac{100}{83\frac{1}{3}} = 120$ per cent. of the original number of turns in series. This would ordinarily mean the winding was good for 120 per cent. of the original voltage. Hence, in looking up the change in the connection table the figure "120" is located instead of $83\frac{1}{3}$.

Referring to the table and following the horizontal line "Three-phase 5-Parallel Star" across, search is made for the figure "120," the nearest thing to it is "125," found under the vertical heading "4-Parallel Star." The number of poles in the motor would have to be divisible by both 4 and 5, in order to make this change possible; or, in other words, it would have had to be either 20 poles or 40 poles. As it may have been 10 poles, for example, the nearest connection that could be made would be for 144 under "Three-phase 2-Parallel Delta." This would mean the correct operating voltage on 50 cycles would be $\frac{144 \times 440}{120} = 528$ volts; or, if operated on 440 volts, it would be working under $\frac{440}{528} = 83\frac{1}{3}$ per cent. normal voltage, which would usually not be permissible on account of lowered torque and increased heating.

4. Change in Number of Poles or Speed.

A 60-cycle three-phase motor is operating on 550 volts at 850 r.p.m.; it is desired to operate at 690 r.p.m. on the same voltage. What change in connections should be made, if any, in addition to changing the number of poles? Inspection shows the motor is connected 4-parallel star for 8 poles, as in Fig. 155. To get 690 r.p.m. would require to connect for 10 poles, since this would give a no-load speed of about 720 r.p.m. and a full-load speed of about 690 r.p.m. Since the motor is a generator also, it will generate only $\frac{690 \times 550}{850} = 446$ volts when connected for 10 poles and a slower speed. However, it is desired to continue at 550 volts, so that the connections will have to be changed to get the effect of $\frac{550}{446} = 123$ per cent. of the old voltage. In the table opposite the horizontal line "Three-phase 4-Parallel Star," the nearest figure to "123" is "116," which is found in the vertical column headed "Three-phase, 2-Parallel Delta." Hence, the conclusion is drawn that if an 8-pole motor, Fig 155 is connected three-phase 4-parallel star and operated on 550 volts and it is reconnected for 10-poles 2-parallel delta, Fig. 156, it may be still operated on 550 volts, although, strictly speaking, its normal voltage would be $\frac{116 \times 550}{123} = 520$ volts. In this example no consideration was given to the fact that the throw of the coil in electrical degrees was changed in changing from 8 poles to 10 poles. This can be taken account of in the following way:

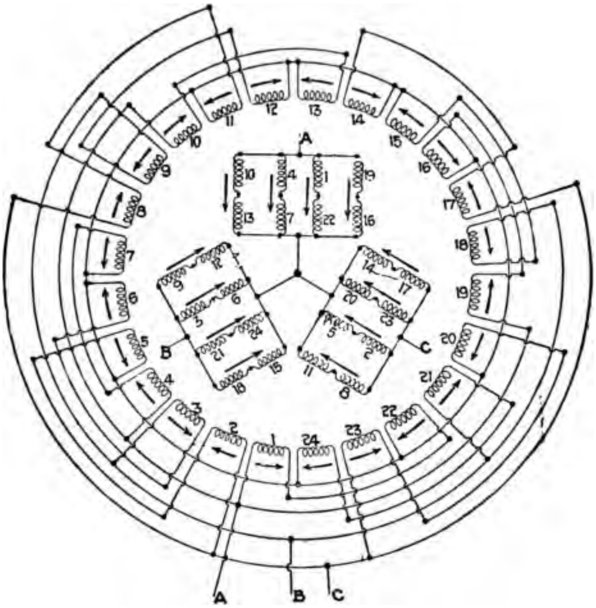


FIG. 155.—Normal three-phase, eight-pole, four parallel star connection.

Suppose the motor as it stood had 120 stator slots and the coils lay in slots 1 and 13. Full pitch would be 1 and 16, since $\frac{120}{8} = 15$. Since the coils throw 12 slots and full pitch is 15 slots, the per cent. pitch $= \frac{12}{15} = 80$ per cent., and from Fig. 148 the chord factor for 80 per cent. pitch $= 0.95$. When reconnected for 10 poles, the throw of the coils is still 1 and 13, but this is now 100 per cent. pitch since $\frac{120}{10} = 12$ and 1 and 13 does span 12 slots. Therefore, when connected for 10 poles the coils are more effective in the ratio of $\frac{1.00}{0.95}$ since the chord factor for 100

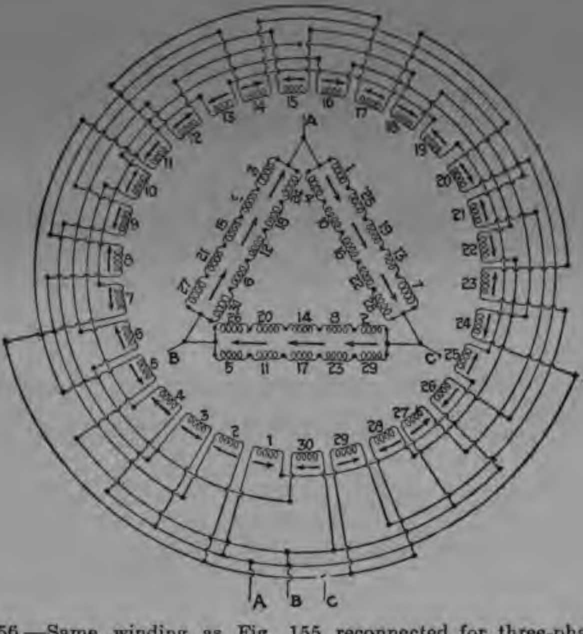


FIG. 156.—Same winding as Fig. 155 reconnected for three-phase, ten-pole parallel delta.

per cent. pitch $= 1.00$ from Fig. 148. Therefore, when the change in chord factor is also taken account of, the new normal operating voltage is 520, as obtained in the foregoing, multiplied by $\frac{1.00}{0.95} = 548$ volts, or almost exactly right for operation on 550 volts.

5. Change in Horsepower.

A 10-hp. 220-volt motor is operating above the allowable safe temperature, on its normal voltage, and it is found by experiment that when the voltage is raised to 250 its temperature is reduced to within safe limits. Can any change be made in the connections which will allow the motor to be operated still on 220 volts and duplicate the conditions when operating on 250 volts? An inspection of the winding shows the motor to be connected three-phase series delta, as in Fig. 153. The experiment which was made showed that the voltage should be increased to $\frac{250}{220} = 114$ per cent. of its original value. It has been pointed out that reducing the number of turns in series in a winding has the same effect as increasing the voltage on the same number of turns. In this case if the voltage was raised to 114 per cent. the same effect could be obtained by reducing the turns to $\frac{1.00}{1.14} = 87.5$ per cent. Consequently, in referring to the voltage change table, in this case, search is made for "87.5" and not "114."

Selecting, therefore, the horizontal line "Three-phase Series Delta" in the table and looking across the nearest figure to "87.5 is "86," which occurs under the vertical heading "Three-phase Parallel Star." Consequently, the conclusion is at once drawn that if a 220-volt motor has its connections changed from series-delta, Fig. 153, to parallel-star, Fig. 152, it will act in every way as though $\frac{220}{0.86} = 256$ volts had been applied to the series-delta connection. This is equivalent to increasing the horsepower of the motor, since on the original connection the motor was overloaded when carrying its rated load, but when the connections of the winding were changed the machine could drive its rated full load without distress. The reason for this is that, although the density of the magnetic flux was increased the cross-section of the copper in the winding was increased, consequently the copper losses were reduced. The latter being considerably greater than the former resulted in a reduced temperature. The capacity in horsepower has actually been increased to $\frac{256}{220} = 116$ per cent. of its original value.

From these five examples, which could be multiplied many times and from all sorts of combinations that could be made by changing the characteristics in pairs, it can be readily seen that any contemplated change can be reduced to an equivalent change in the applied voltage and the proper connection, if it is a feasible and rational change, selected from the table of phase and voltage given herewith.

CHAPTER XI

LOCATING FAULTS IN INDUCTION MOTOR WINDINGS

NOISE AND VIBRATION

After the coils have been placed in a motor and the cross-connections completed according to the desired diagram, a check is necessary to insure that the connections are properly made before load is put on. The simplest way of making this check is to start up the motor and run it light on a circuit of the proper phase, frequency and voltage. Observation of the behavior of the motor under these conditions indicates to the trained observer whether there are any serious discrepancies in the winding or connections. This observation should cover five points; namely, speed, noise, mechanical vibration, general heating of the whole winding and local heating of one or more separate coils.

The speed, if correct, should be of nearly synchronous value when the motor is running without load; that is, equal to cycles times 120 divided by the number of poles.

The motor should give a low humming noise similar to that made by transformers, but there should be no irregular or "growling" noise. There may also be a considerable volume of air noise or whistle caused by the ventilating air passing through the air ducts in the rotor and stator. The magnetic noise may be distinguished from the air noise by the expedient of opening the switch for a second or two while the motor is running full speed without load. Opening the switch breaks the current and removes the magnetic field, and consequently the magnetic noise ceases, but leaves the rotor running at practically the same speed owing to its inertia or stored energy, and hence the windage, or air noise, is practically unaffected. In this way, by opening and closing the switch two or three times, it becomes readily apparent what part of the total sound made by the motor is magnetic and what part is windage. It also indicates whether either or both of these sounds are abnormal. If the speed is correct and the motor makes no more than a reasonable singing or humming noise, the hand should be placed on the frame to note the mechanical vibration.

If there is noticeable mechanical vibration, it may be due to purely mechanical causes or to magnetic causes or possibly to both. By opening and closing the switch, as described in the foregoing, the mechanical vibration due to the magnetic field can be easily separated from that due to strictly mechanical causes, because when the switch is open there is no magnetic field present. Suppose, for example, that when the motor is running at full speed there is a marked vibration or trembling that can be felt when the hand is laid on the frame of the motor. Suppose, then, that when the switch is opened for a second or two the vibration disappears and the motor rotates smoothly at nearly the same rate of speed. This, then, is evidence that the vibration was caused by the action of the magnetic field on the stator and rotor. However, if the motor vibrates whether the switch is open or closed, it is evidence that the action is purely mechanical and is affected little or not at all by the presence of the magnetic field.

When the trouble is traceable to the magnetic field, it may indicate improper connection of the winding or it may indicate that the mechanical clearance between stator and rotor is not symmetrical or that there is some similar combination of mechanical and magnetic features that is responsible for the vibration noticeable. The commonest mechanical causes for vibration are rotor out of balance, either standing or running; bent shaft; too great clearance between shaft and bearings; unbalanced or eccentric coupling or pulley or a combination of two or more of these faults. These mechanical conditions are easily determined and can be corrected. The commonest causes of mechanical vibration due to a combination of mechanical and magnetic conditions are rotor out of round, stator out of round, too great clearance in the bearings, or rarely, uneven or eccentric air gap or clearance between stator and rotor. The latter point seldom gives trouble and a polyphase motor will practically always run without giving any trouble until the bearing wear allows the rotor to strike on the stator. Single-phase motors are more sensitive to eccentricities in the air gap or clearance between stator and rotor and sometimes show a considerable variation in torque in motors otherwise duplicate due to such irregularities.

There are a number of elements that may cause the rotor or stator to be out of round. In the first place there is a slight variation due to the punch-and-die work, which may amount to 0.005 in. between individual punchings. In the second place some allowance around the outside of the punching must be made in the fixture or frame in which they are built up so that they will assemble readily, and this allows the punchings to stagger more or less. In the third place when the punchings are actually assembled in the frame, the frame may spring out of shape slightly after machining, owing to the release of casting strains when removing the material in the cut. Of course none of these variations is in itself large, but when they all accumulate in the same direction, perceptible eccentricity may result amounting to a good many thousandths of an inch. This is not serious, since it is present to some extent in all motors, but under extreme or extraordinary conditions it may cause mechanical vibration.

Mechanical vibration caused by the windings may be due to either the rotor or the stator. For example, in a squirrel-cage rotor there may be bad contacts between certain bars and the short-circuiting rings, resulting in more resistance in some parts of the winding than in others. This in turn affects the distribution of current in the different bars and hence affects the magnetic field and varies the mechanical pull from point to point. Or if the winding on the rotor of a wound-rotor type motor is ground in a number of places, it will also cause unequal distribution of the current in the windings, which in turn causes severe vibration during the starting period. However, this generally disappears to a large extent after the motor comes up to full speed. From this it may be seen that where mechanical vibration is absent the conclusion may be drawn that the windings are symmetrical and are functioning properly, but where vibration is present it may be caused by a number of things, some of them obscure, and must not immediately be attributed to improper winding connections until a further examination is made.

The next point to be observed is the general temperature of the entire winding as determined by passing the hand around the ends of the windings. It is best practice in making this examination to shut down the motor after it has run three to five minutes. If the examination is made while the motor is running, care should be taken to avoid injury by coming in contact with moving parts and also to avoid injury from electric shock, if the circuit is 550 volts or over. If the winding as a whole is cool, inspection should be made for individual coils that are much hotter than the rest of the winding, as these may indicate short-circuits or improper connections in that particular coil.

If a motor is operating freely and easily at the proper speed without undue noise or mechanical vibration and if there is no general or local heating of the winding, the next step is to measure the current in each phase. This may be done as indicated in Figs. 157, 158 and 159. If possible an ammeter should be connected in each phase so that the readings of all phases may be taken simultaneously. For a two-phase motor two ammeters are required, as in Figs. 157 and 158, and for a three-phase motor three ammeters are required, as in Fig. 159. The no-load, or magnetizing current as it is called, will usually be somewhere between 15 and 35 per cent. of the full-load current with an average value of perhaps 25 per cent. If the no-load current in all phases is equal and approximately 25 per cent. of the full load, it is safe to assume that the winding connections are properly made. If a wattmeter is available, a further check might be made on the total watts taken by the motor running light, but that does not add greatly to the ammeter check. The connections for connecting two wattmeters in a two-phase four-wire circuit are given in Fig. 160 and for a three-phase circuit in Fig. 161. The connections for a three-wire two-phase would also be the same as those in Fig. 161; where only one wattmeter is available, it may be connected into a three-phase circuit with a single-pole

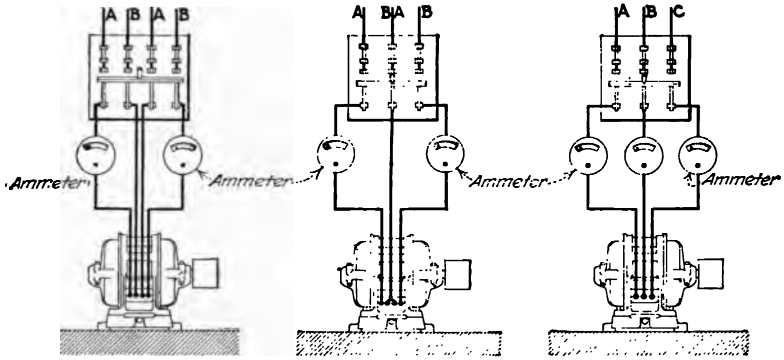


FIG. 157.—Two-phase, four wire circuit.

FIG. 158.—Two-phase, three wire circuit.

FIG. 159.—Three-phase circuit.

Measuring the current in each phase.

switch, as in Fig. 162, so that the two readings may be taken by simply throwing the switch. In a two-phase circuit the total watts will always be the sum of the two readings, but in a three-phase circuit this is true only when the power factor is greater than 0.50. Where two wattmeters are used to measure the no-load watts of a three-phase motor, the difference of the two readings gives the correct value of the watts, since the power factor of an induction motor at no load is always less than 0.50. The watts taken at no load and full speed and voltage cover the iron loss, bearing friction, windage and a small amount of copper loss. The total no-load watts will in general be in the order of 5 per cent. to 8 per cent. of the rating of the motor in watts varying with the capacity and speed of the motor. The motor rating in watts would be the horsepower from the nameplate multipled by 746.

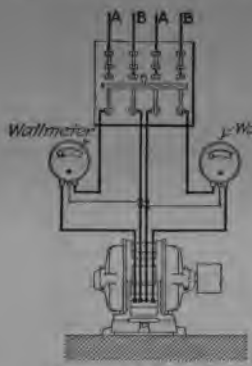


FIG. 160.—Two-phase, four-wire circuit with two wattmeters.

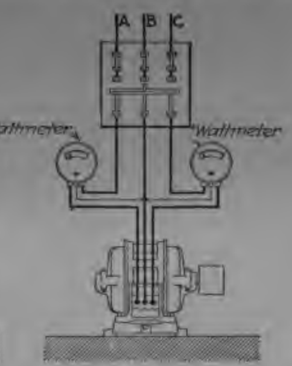


FIG. 161.—Three-phase circuit with two wattmeters.

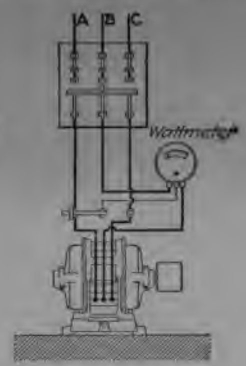


FIG. 162.—Three-phase circuit with one wattmeter.

Measuring the total watts.

If the foregoing checks indicate that the motor is not acting normally, they should also give some evidence that there is a fault in the coils of the winding or in the manner in which these coils are connected, and further search is made to analyze the nature of this fault so that it may be located and corrected.

The winding of an induction motor is made up of a number of similar coils connected into groups. These groups in turn are connected in such a manner that when an alternating current of the proper characteristics flows through them, a magnetic field having alternate north and south poles is set up and caused to rotate in the motor. The coil itself is usually made up of two or more turns of wire or strap so that there are at least ten chances for defects in the winding after the coils are all in place and connected. Some of these faults are simple and readily rectified, while others are more obscure and difficult to handle.

The Ten Most Common Defects.

These ten most common defects in the order of their likelihood are:

1. The winding grounded on the core.
2. One or more turns in one or more coils short-circuited.

FIG. 163.—Placing the coils in the core of an induction motor.

FIG. 164.—Typical "diamond" coil.

3. One or more complete coils short-circuited at the coil ends or at the "stubs."

4. A complete coil reversed or connected so that the current flows through it in the wrong direction.

5. A complete group of coils or pole-phase group is reversed; that is, connected so that the current flows through the group in the wrong direction, making a north pole where a south should be or *vice versa*.

6. Owing to lack of care in counting, two or more pole-phase groups may include the wrong number of coils.

7. A complete phase in a three-phase star or delta winding is reversed.

Fig. 165.—Coils in place unconnected.

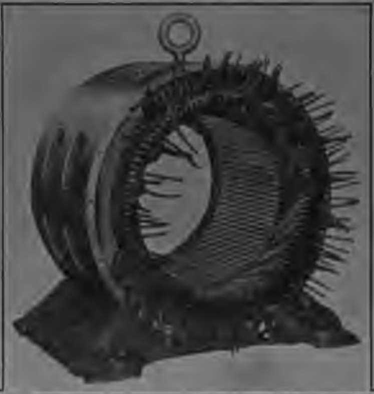


Fig. 166.—Coils connected into pole phase groups.

Fig. 167.—The completed connection of winding.

The three stages of connecting a winding.

8. The winding connections may be properly made in themselves, but not right for the voltage upon which the motor is to be operated. That is, the motor may be connected properly for 110 or 440 volts, but the motor is to operate on 220 volts.

9. The winding connections are properly made, but they are

for the wrong number of poles, and hence the motor runs at a different speed from that which was intended.

10. An open circuit somewhere in the winding, or one or more coils are omitted and left out of the winding, known as "dead" coils.

The manner in which these various faults occur can be best understood by referring to what takes place, first, in winding and insulating the coils, and, second, in placing them in the core and connecting them.

Fig. 164 shows a coil of the usual form wound up from several turns of wire and insulated ready to be used in the slot; Fig. 163, the operation of winding these coils in place in the core; and Fig. 165, the coils all in place ready for connecting. The coils connected into pole-phase groups, with the coil ends at the beginning of each group bent into the bore and the coil ends at the end of each group bent out toward the frame are shown in Fig 166. The cross-connections are made in Fig. 167, thus completing the winding connections. Fig. 168 shows the coil in Fig. 164 as it would appear if the insulation were stripped off and individual turns of wire separated.

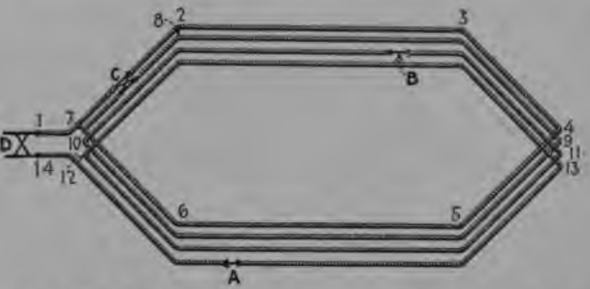


FIG. 168.—Individual coil with insulation removed to show "shorts" and "grounds."

Grounds.

The first fault listed—grounding of the winding on the core—occurs when in some manner the insulation becomes stripped from the coil and also the cotton covering from the wire so that at some point, as at *A*, Fig. 169, the bare-copper conductor touches the laminated-iron core and by so doing "grounds" the winding. This means that a live current-carrying part is touching the metal structure of the motor, and when this condition exists anyone who touches the frame of the motor actually touches a live conductor. This may not be detected if the entire winding and the supply circuit otherwise is free from grounds, but it often happens that other grounds are present somewhere in the system so that in standing on the ground and touching the frame of the machine the chances are very good of getting a shock at a voltage that may equal that of the supply circuit.

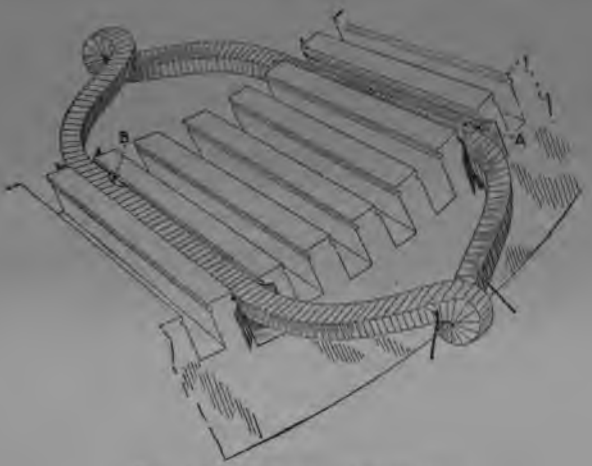


Fig. 169.—Coil grounded on core.

Referring to Figs. 168 and 169, should two grounds occur simultaneously, as for example, at *A* and *B*, a short-circuit would be formed in the loop, Fig. 168, from *B* through 11, 12 and 13 to *A*; and if the normal voltage remained on the motor, this short-circuited turn would immediately become hot enough to destroy the insulation on the complete coil. This is the second fault listed and may occur without grounding by the touching of the bare conductor of adjacent turns as at *C*, where the complete short-circuit follows the path of *C* 2, 3, 4, 5, 6, 7 and *C*.

Short-Circuits.

The third fault—short-circuiting a complete coil—can also be seen from Fig. 168 and exists when the insulation of the ends of the coil 1 and 14 become damaged and allow these two wires to touch, as at *D*. A current then flows in the entire coil, in addition to and aside from the line current, equal to the voltage of the coil divided by its impedance. In other words, what happens is equivalent to removing that particular coil from the main winding where it is generating its share of the useful counter-electromotive force and using up this same generated or induced counter-voltage, simply, to force current through the coil itself. This coil would heat up practically as fast as would any induction motor winding if the rotor was held from rotating and full-line voltage applied to the stator winding.

Reversed Coil.

The fourth fault occurs when the two leads of a coil are interchanged, as at X, Fig. 170. This has the effect of causing the one coil, or in this case coil Y, to "buck" all the other coils in the same pole-phase group. Expressing this in another way, the cross-connected coil is trying to produce a magnetic north pole when all the other coils in its group are producing a south pole. The effect of this is magnetic dissymmetry and manifests itself, as do most irregularities in winding, in noise and heating.

Reversed Group.

The fifth fault, and one that can occur readily in connecting, is when an entire pole-phase group is reversed, as at Z, Fig. 170. This can be understood from Fig. 166. The beginnings of all pole-phase groups are bent in toward the center of the bore, and the endings are all bent out. Should one of the ends bent out be used as a beginning and the other end as an ending, the entire group would be reversed with consequent magnetic distortion and trouble due to noise and heating.

Wrong Grouping.

The sixth fault is one due wholly to wrong counting in grouping the coils. In a three-phase four-pole motor with 48 coils there should be in each group $48 \div (3 \times 4) = 4$ coils, and the presence of 3 coils or 5 coils in any group constitutes the sixth fault as they are here listed. This is also shown in Fig. 170, where all the groups have 4 coils except A^1 and B^1, which have 5 and 3 coils respectively.

Reversed Phase.

The seventh fault is present only in the case of three-phase motors and consists in reversing the ends of one-third of the winding so that one leg of the star or one side of the delta is connected in such a way that the voltages generated in the three phases are only 60 electrical degrees apart, whereas the currents

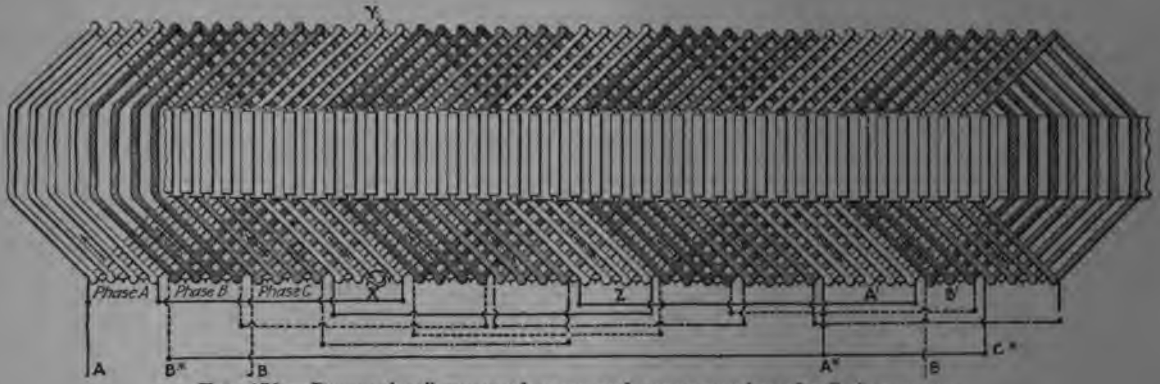


FIG. 170.—Reversed coil, reversed group and wrong number of coils in a group.

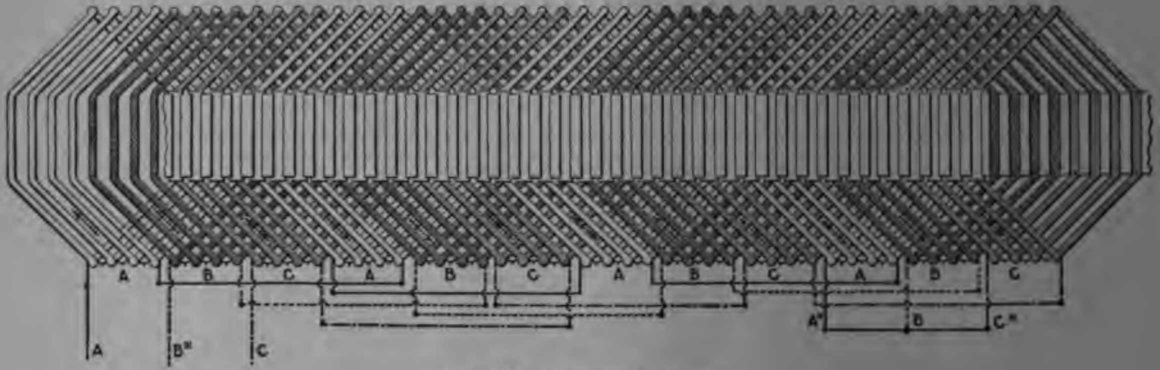


FIG. 171.—Reversed phase.
Faults in completed connections.

supplied from any normal three-phase generator are 120 electrical degrees apart, and hence these three voltages and currents cannot combine to produce power as they properly should. This can be understood by referring to Figs. 172 and 173. Fig. 172 shows the three voltages generated in a three-phase winding as represented by three arrows or vectors arranged 120 deg. apart. If, however, one phase of the winding was reversed and the lead connected to the star point and *vice versa*, the back, or counter-electromotive, force generated in that winding would be reversed and would no longer be 120 deg. from the voltages in the other two phases, but would be 60 deg. from them, as in Fig. 173. This would mean that the magnetic field in the stator, instead of being a balanced succession of north and south poles rotating and pulling the rotor around, would become unbalanced and would no longer rotate properly. According to another method of looking at the matter, there would be one field rotating clockwise and another different kind of a field rotating counterclockwise, and the natural result would be that these two fields would interfere, and instead of rotating, the motor would remain at a standstill, emitting an unusual amount of noise and reaching a dangerous temperature in a very short time.

FIG. 172.—Normal winding relation.

FIG. 173.—Wrong connection in one phase as in Fig. 171.

Effect of reversing a phase.

A four-pole three-phase winding with the *B* phase reversed is shown in Fig. 171. It will be observed that instead of the arrows on the pole-phase groups pointing in alternate opposite directions, as they should for a correct connection, they point in opposite directions in groups of three. Further consideration will be given this feature later in this chapter.

Connected for Wrong Voltage.

In the eighth fault the winding connections are all made properly to form the magnetic poles in their proper sequence, but there are only half as many turns in series or perhaps twice as many as there should be. When this is discovered, the winding may be such as to permit connecting in series instead of parallel or vice versa, but under the worst conditions it may be necessary to remove the entire set of coils and replace with a new set having the proper number of turns for the required voltage.

Wrong Number of Poles.

The ninth fault is sometimes overlooked unless the speed is taken with a tachometer or speed counter, in which case it is readily detected. Its correction is not always either evident or simple, but can often be accomplished without change in coils by following some one of the various methods described in Chapters IV and VIII.

Open-Circuits.

The tenth fault, "open-circuits," may be due to failure to solder a joint properly or to a joint being broken mechanically after having been once made. "Dead" coils are usually purely inadvertent and are sometimes present without being discovered at all. Such an occurrence could hardly happen unless there were a large number of small coils crowded together.

After the enumeration of the commonest errors made by the winder, as outlined above, the next step is to consider them in turn with particular reference to how each may be detected and corrected.

First Fault: Grounds. If the ground is fairly low resistance—that is, the bare copper of the winding touches the core—the defect may be detected by using an incandescent lamp arranged as shown in Fig. 174. One of the lamp leads is touched to a bare spot on the winding—for example, a terminal connector or a "stub" where two adjacent coils are connected—and the other is touched to the bare metal of the motor frame at some point not protected by paint. If there is a ground present, the lamp lights up. Another common method is by "ringing out" with a magneto similar to that used in telephone work. In this method the terminals of the magneto are applied, one to the winding and the other to the frame similar to the procedure in Fig. 174, and the handle is turned. If the bell rings, there is probably a ground in the winding. A third method employs a "testing box," which is really a transformer for obtaining voltage much higher than the normal voltage of the motor under test. These boxes give 2,000 or 3,000 or more volts and readily detect grounds on windings of 550 volts and below. The test box is so arranged that when the terminals are applied as in Fig. 174, the presence of a ground instantly opens a circuit-breaker on the side of the box.

Having established the fact that the winding is grounded by some one of the foregoing methods, the next problem is to locate in which coil or what part of the winding it has occurred. This can sometimes be done by inspection, but sometimes requires other means. The most usual of these is to put enough voltage on the ground with the lamp device of Fig. 174, or the test box, so that the resulting current heats up the contact that is causing the ground and it becomes evident through smoke or slight arcing. This will generally require two or more lamps connected in parallel. When the ground is definitely located, it is corrected by repairing the insulation at this point by retaping the coil, or replacing the defective slot cell or whatever may be causing the trouble. Sometimes the ground cannot be "smoked out" in this manner, and it then becomes necessary to open up the winding at two or three places and test out the different pieces to find in which one the ground is present. If it is still not evident, the

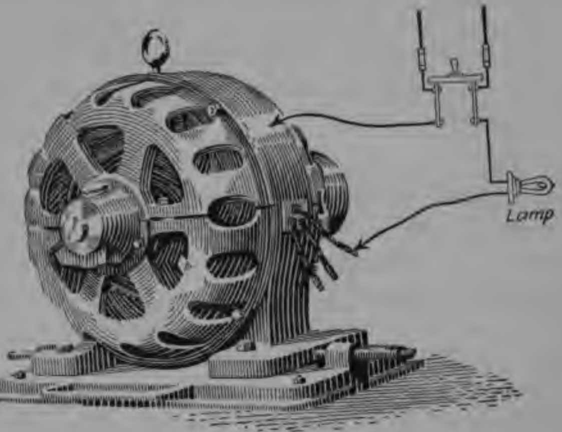


FIG. 174.—Lamp test for grounds.

defective section of the winding is further broken into smaller pieces and the search pursued until the trouble is finally run down to the individual coil which is defective. It is seldom necessary to go so far, as the ground furnishes evidence of its location as soon as the voltage is put across it.

Second and Third Faults: Short-circuit of a few turns in a coil, or a single coil completely short-circuited, becomes hot in a short time if the motor is run light on normal voltage. Their presence can be detected by feeling around the winding with the hand immediately after starting the machine and noting if some individual coils are much warmer than others. A device for detecting such short-circuits before the rotor is put in the stator and without applying any voltage to the winding itself is shown in Fig. 175. This device is somewhat similar to a large horseshoe magnet excepting that the iron part is built up of laminations, or it may be considered as a core-type transformer having a primary coil only with one side of the iron core missing. The coil is excited with alternating current of suitable voltage, and then the complete device is passed slowly around the bore of the machine being tested as shown in Fig. 176. In passing around, if the testing device passes over any short-circuited turn or coil,

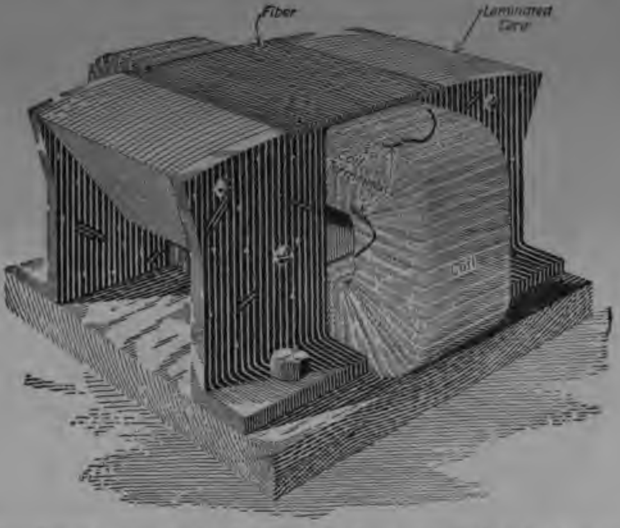


Fig. 175.—Transformer device for locating short-circuited coils in a completed winding.

such short-circuit immediately acts as a short-circuited secondary coil on a transformer of which the exciting coil on the testing device is the primary and whose magnetic circuit is made partly by the testing device and partly by the core of the machine under test. As in any short-circuited transformer, an increased current flows both in the primary and secondary coil and can be detected by an ammeter in series with the device or by the heating

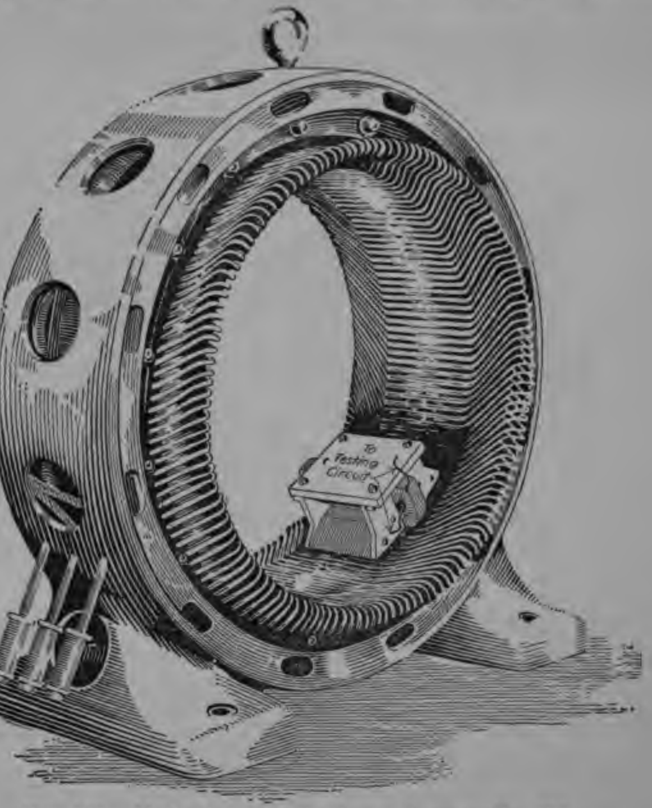


FIG. 176.—Method of using the device shown in Fig. 175.

that immediately takes place in the defective coil, or by the attraction that the short-circuited coil has for a strip of sheet iron. By passing the device slowly around the core and observing its behavior from point to point, short-circuits can readily be detected. This refers particularly to short-circuits in individual turns or in one complete coil. A short-circuit of a complete pole-phase group is more readily located by a compass test, and a short-circuit of an entire phase can be located by a "balance test."

The "**compass test**" referred to in the preceding paragraph consists in passing a compass slowly around the bore of the stator from which the rotor has been removed and which has the winding excited by direct current of the value of about one-third the full-load alternating current. The effect of this direct current is to set up north and south poles alternately in the phase which is excited, and as the compass is passed slowly around the bore its needle reverses with the polarity, and by marking the polarity plus and minus with chalk marks in the bore, the chalk marks immediately indicate the correctness or faults in the winding. If it is a two-phase machine, the direct current is put on each phase separately and the check is made. For a three-phase star winding cause the direct current to flow from each lead to the star by making three observations, and mark the polarity only on the groups from the lead to the star in each phase separately. This can be readily understood by referring to Fig. 177 and 177*a*. For the first observation put the direct-current plus lead on *A* and the minus on the star connection, then pass the compass around the bore and mark the polarity of the groups from *A* to the star point with an arrow, the arrow pointing in the same direction as the compass needle. For the second observation put the direct-current plus lead on *B* and the minus lead on the star connection and passing the compass around marking the polarity of the groups from *B* to the star point. For the third observation put the direct-current plus lead on *C* and the minus on the star, and by means of the compass determine and mark the polarity of the groups from *C* to the star point. If the three observations have been made correctly, there will be a chalk arrow on each pole-phase group of the winding, and if the winding is correctly connected, these chalk arrows will alternate north and south, as shown in the Fig. 177. In case of a short-circuit of a complete pole-phase group the compass needle will not be deflected. If a three-phase delta winding is being checked, open the delta connection at one lead, as in Fig. 178, and 178*a* connect the direct-current source in so that the current flows through the three phases in series, and if the pole-phase groups be checked for polarity, the arrows will reverse as just described for the star winding.

The "**balance test**" referred to consists in checking each phase

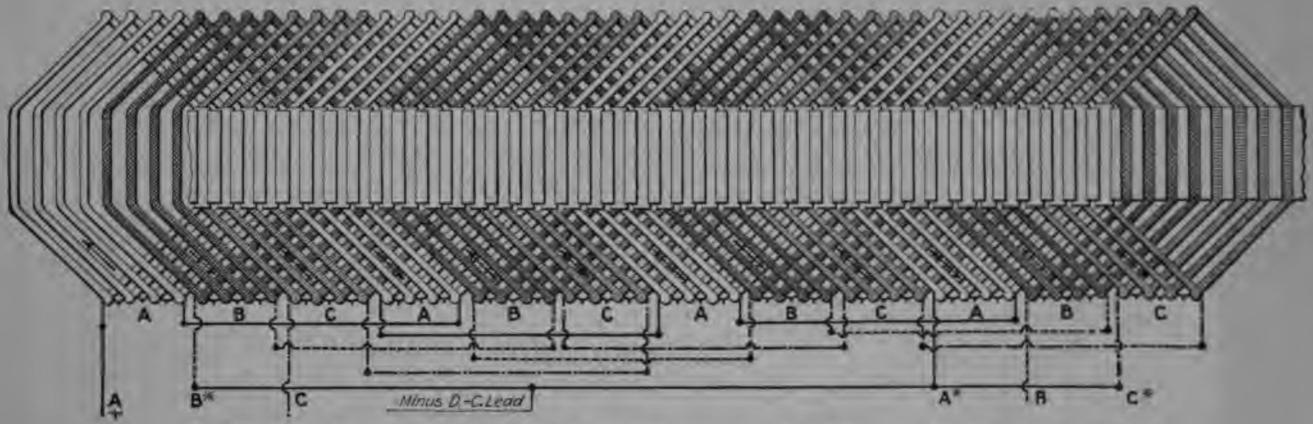


FIG. 177.—Manner of connecting d.c. in making compass test for reversed pole phase group.

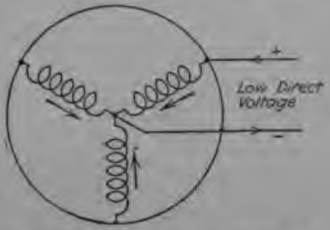


FIG. 177a.—Schematic diagram for Fig. 177.

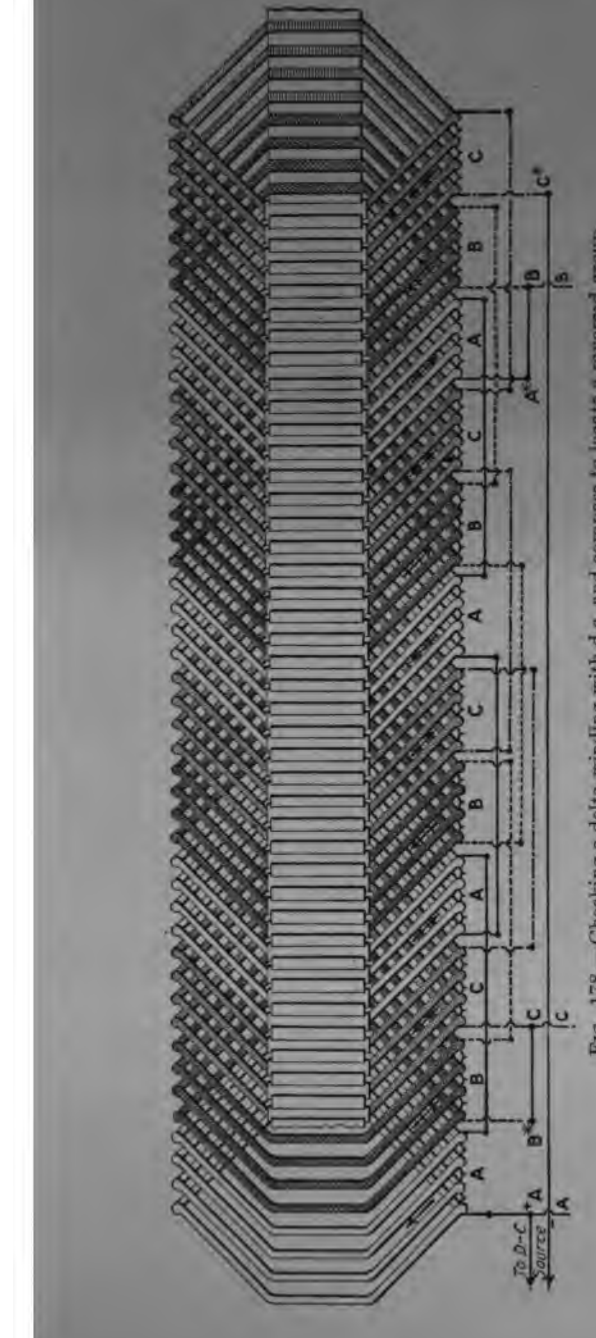


FIG. 178.—Checking a delta winding with d.c. and compass to locate a reversed group.

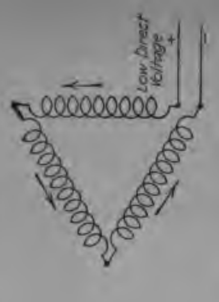


FIG. 178a.—Schematic diagram for Fig. 178.

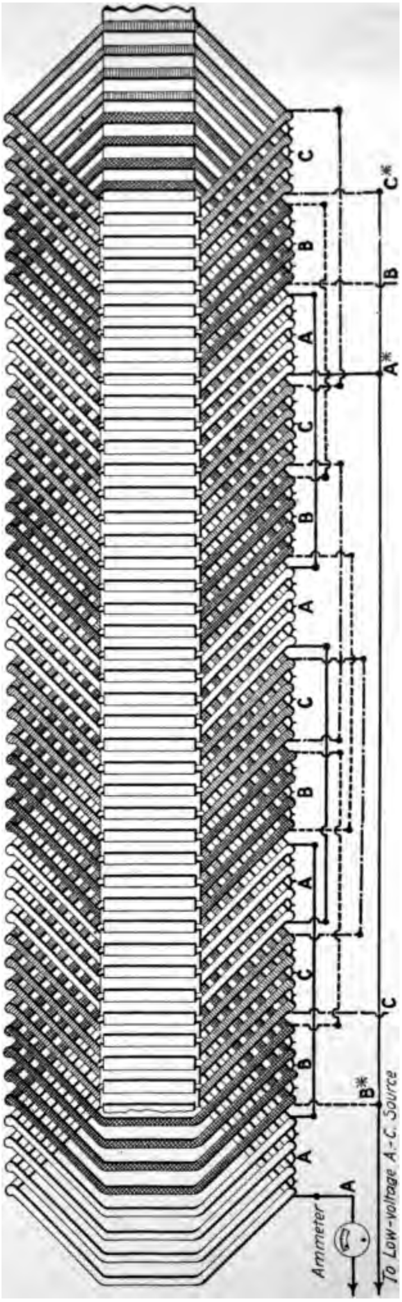


FIG. 179.—Connections for making a "balance test."

of the winding separately with low-voltage alternating current, say 20 per cent. of normal full voltage, and measuring the amperes to check the impedance roughly and see if it is the same in all phases. The connections for a star-connected winding are made, as in Fig. 179, so that the current can be measured in each phase, with an ammeter. The low-voltage alternating-current source is, in all cases, connected across one terminal, A, B, or C, and the star as in the figure. The ammeter should read the same in all three leads. For a delta-connected winding it is necessary to open the delta connections at some point, as at A, then test across each phase separately. This test is made on the stator only and with the rotor removed.

Fourth and Fifth Faults: Reversal of one or more coils in a group or group of coils. It happens that individual coils or sometimes entire groups are connected in backward. If the error is confined to one coil it does not usually show up on a "balance test" and would not be found on a resistance test, since the resistance would be the same no matter which way the coil was connected. Such reversed coils or groups can be located by means of the compass test described under "Short-Circuits." If an individual coil is reversed, it will show a tendency to reverse the compass needle when the needle is directly over that coil. If an entire pole-phase group is reversed, the compass needle will indicate the same direction of field on three successive groups, as at Z, Fig. 180. Also if a coil is left out of circuit, or "dead," as listed under the tenth fault, the compass needle will indicate an irregularity at the instant of passing over that particular coil. By checking the three phases of a three-phase winding separately, with a compass, as described under the second and third faults, it is possible to check for the reversal of an entire phase.

Sixth Fault: This is the case where one coil too many or too few is connected in a pole-phase group, as at A' and B', Fig. 180. The best check on this is a visual inspection and count of the "stubs" at the end of each group, and when the trouble is located it is corrected by disconnecting, regrouping and reconnecting.

Seventh Fault: The reversal of an entire phase in a three-phase winding usually manifests itself in a very pronounced manner when the motor is run light. If the rotor turns over at all it is probably at a speed very much less than normal and emits a loud, growling noise and immediately becomes hot. This fault may also be detected by the compass test, as described under

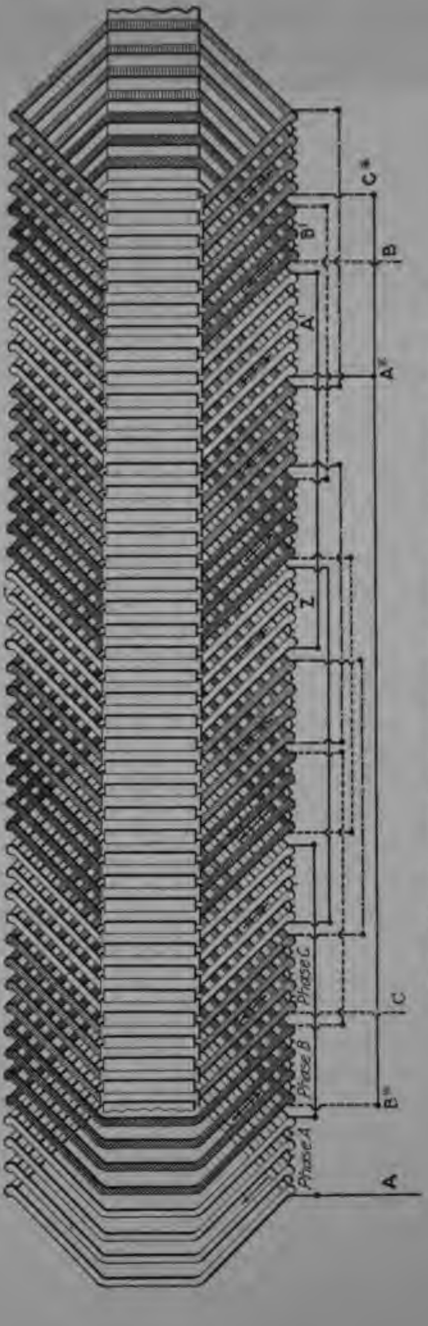


FIG. 180.—Reversed group and wrong count in a three-phase winding.

faults two and three. The arrows on the windings will point in groups of three in opposite directions, as in Fig. 181. The remedy when the defect is found is to open the star point and use the star point on the defective phase, which is the *B* phase in Fig. 181, for a lead and bringing the end that was a lead to the star, thus giving the connection, Fig. 177. In a two-phase winding there is no trouble with reversed phase for the reason that if the direction of rotation of the motor is wrong, the leads may be easily reversed outside of the motor and the correct rotation secured.

Eighth Fault: Connection for wrong voltage. If a motor is connected for a lower voltage than the circuit upon which it is operating, the no-load current becomes excessive and may even approach full-load value. There is a pronounced magnetic hum and a vibration indicating that the field is very strong, which is the case. On the other hand, if the motor is connected for a higher voltage than that upon which it is being tried, the no-load current is very small and the motor apparently "pulls out" on much less than its rated full load. If these faults are a matter of half-voltage or double voltage, for example, they can usually be detected without much trouble; but if the variation is less, this becomes a more difficult matter and in the absence of any other official data it sometimes becomes necessary to take a brake test to determine what the trouble is. After the difficulty and its extent have been determined, a reconnection of the groups can usually be made which will give the proper operating conditions. For example, if it is found that the winding is connected series-star as in Fig. 177, and the motor is connected for 440 volts, when it is to be operated on a 220-volt circuit the winding should be changed to parallel star, as in Fig. 182, and the operation will be normal.

Ninth Fault: The easiest way to detect a connection for the wrong number of poles is to run the motor light and take the speed with a tachometer or speed counter. When it is found that the winding is connected for the wrong number of poles, the possibility of reconnecting can be determined by methods suggested in Chap. X.

Tenth Fault: Open-circuits are manifest from the fact that the motor will not start, but acts as if it were operating single-phase. It is easy to determine, in a star-connected winding, in which phase the open-circuit exists by connecting all phase leads to the starting transformer and opening them one at a time to

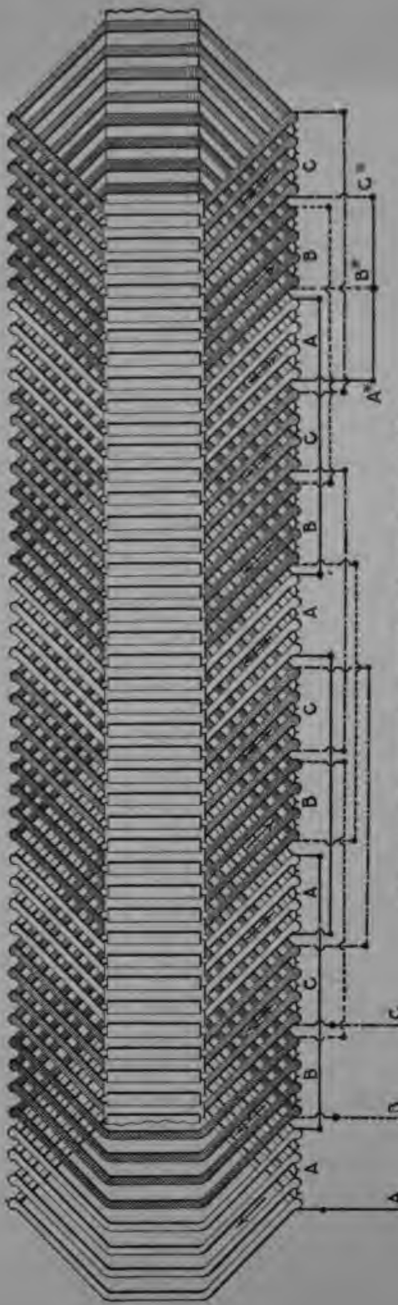


FIG. 181.—Reversed phase in a three-phase winding.

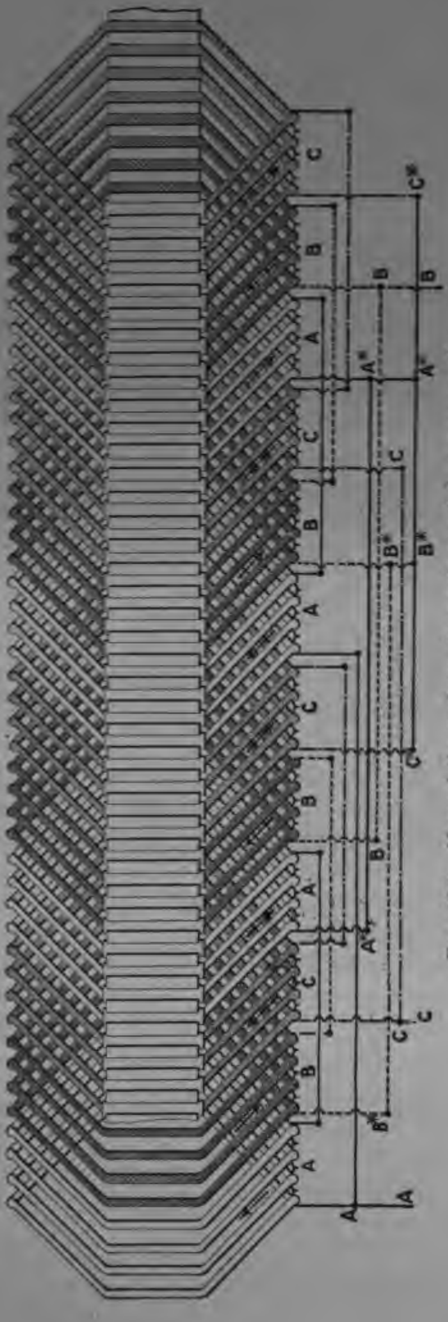


FIG. 182.—Normal three-phase, four-pole parallel star connection.

see in which lead no current is flowing. In Fig. 183 assume that the open is in phase *C* at *X*. Then if lead *A* is open, no current will flow through the motor, since the path is from *B* to *C* and is open at *X*. If the *B* lead is disconnected with *A*, and *C* connected, no current can flow, since the *C* phase is still in circuit. If *C* is disconnected with *A* and *B* lead connected in circuit, then *C*, the defective phase, will be cut out of circuit and current will flow in the *A* and *B* windings of the motor and it will act as if operating single-phase, which will be indicated by the motor emitting a humming sound. When the defective phase is located, it is not always apparent just where the break is. A visual inspection may fail to show the break on account of tape over the defect or for some other reason. If this point cannot be located by inspection, a simple method of finding it electrically is indicated by referring to Fig. 183. A test voltage somewhat lower than normal or whatever is convenient is then applied to *B* and *C*, and a suitable voltmeter is used to measure the voltage between *B* and various points along the *C* phase, as, for example, 1, 2, and 3, which are chosen at random along the "studs," or coil-to-coil connections, or on the group cross-connections, as in the figure. With the condition as shown in Fig. 183, assume that 110 volts has been applied to the *B* and *C* terminals of the winding, as shown. If one lead from the voltmeter be attached to *B* and the other lead touched successively to *C* and 1, 2 and 3, the voltmeter will read 110 volts between *B* and *C*, *B* and 1, *B* and 2, and zero volts between *B* and 3, since the *C* phase is open at *X*. The conclusion is immediately and properly reached that the break is between 2 and 3 and with the inspection narrowed down to this small section of the winding the break is usually apparent. However, should the break not be discovered by inspection, points can be selected with finer steps between 2 and 3 and voltage readings taken until the defect is narrowed to the exact coil or piece of cross-connection where it exists.

In the case of a delta connection one of the simplest ways to detect an open-circuit would be to open the connection at one terminal of the delta, such as *A* in Fig. 178, and connect a test circuit across the open. If the winding is open no current will flow. The phase with the open in may be located by testing across each phase separately. If a lamp is used to make the test, the defective phase will be indicated by failure of the lamp to light. After the faulty phase has been located, the location of

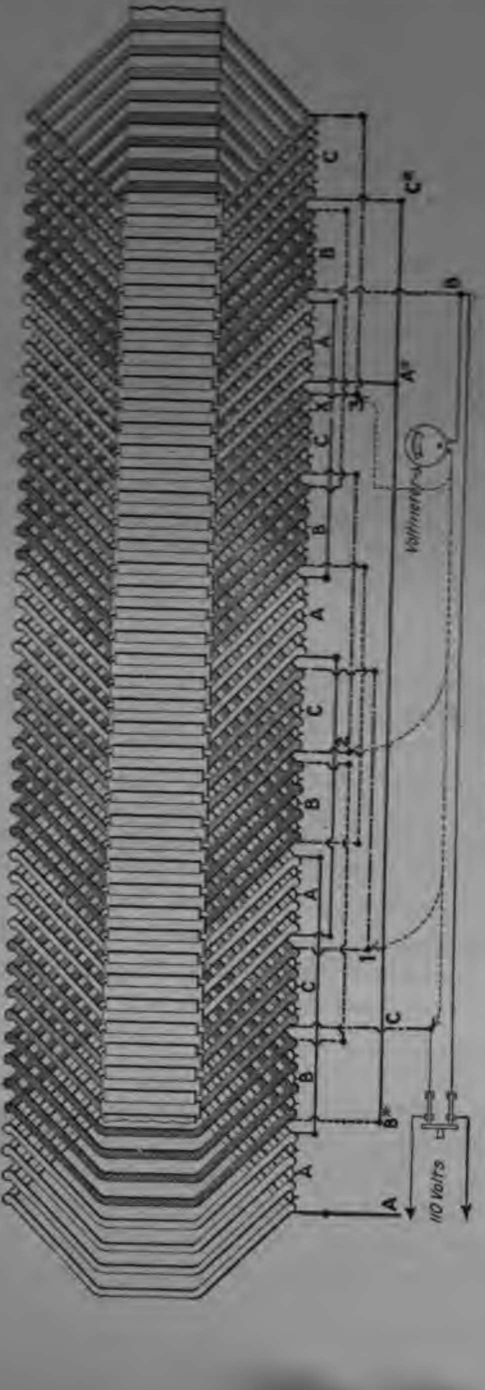


FIG. 183.—Checking for open circuits.

the defect can be determined as for the star connection, Fig. 183. There are all manners of parallel-star and other groupings in which it is difficult to locate an open-circuit, since an open in one parallel group does not open the circuit through the phase, but in only one of the parallel groups. For example, in Fig. 184 an open in phase C at X will not open the phase between terminals B and C, but only through C''. Therefore, to detect the open group it will be necessary to break the winding up into its parallel groups and test each group separately. The defective phase could be detected by the balance test as previously described.

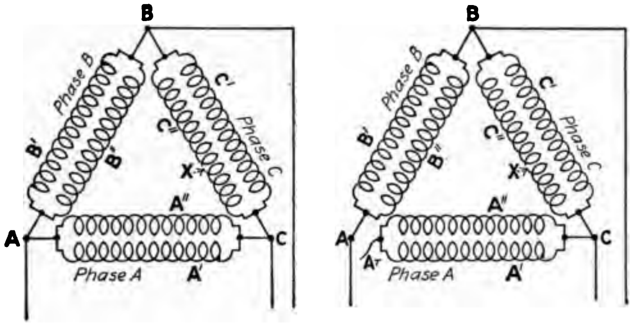


FIG. 184. FIG. 185.

FIG. 184 and 185.—Locating open circuits in parallel delta connection.

First, open the delta connection, for example, at A, Fig. 185, then apply the low-voltage alternating current between points A and B and measure the current with an ammeter, test between A and B, B and C and between C and A_T. The phase with the open circuit, which in this case is C, will show a lower reading than the other two phases, after which all that is necessary is to break the phase up into its parallel groups and test the defective group for opens, as explained in Fig. 183.

Usual Order of Locating Defects.

These are the defects that commonly occur and the usual method of locating them. In checking for these defects the order usually observed is as follows: After the winder has completed the connection of the entire winding, his work is checked, preferably by a second winder, against the winding diagram specified for that particular job. The coils per group are counted and a visual inspection made for short-circuits, open circuits and reversed coils, groups or phases. A balance test is made on the stator alone with low voltage to see if, roughly, the same current flows in the various phases. A high-voltage test is then made on the insulation to insure that the coils are not grounded on the iron core, or that there is no short-circuit between the conductors of the different phases. If everything is satisfactory up to this point, the rotor is then assembled in the stator and the machine prepared for a running test. The resistance of the winding is measured on all phases, and if alike, the machine is passed for running test without load. Sufficient voltage is applied to start the rotor, and if it comes up to speed quickly without apparent distress or irregularity of any kind, the speed is checked, to verify whether the winding has the proper number of poles. The temperature of the winding is then tested with the hand, passing completely around the machine and using care that the rotating member and its parts do not strike the observer. If neither general heating nor hot spots are observed, the voltage is raised to normal and the no-load current in all phases and the total watts are read. If these values check with the previous tests on similar machines or with calculations, the windings are considered to be correctly connected. If the motor does not readily come up to speed or the phases do not balance or there are signs of unequal heating in the winding or other distress, the rotor is removed and the connections again checked. If the error is still not apparent and a source of direct current is available, the compass test may be applied. Having exhausted this resource without avail, the problem is one that can be solved only by some expedient at the command of an experienced designing engineer, but such appeals are very seldom required, as the trouble usually appears from the simple tests described.

CHAPTER XII

HOW TO FIGURE A NEW WINDING FOR AN OLD CORE

It is felt by the author that this book is not quite complete without giving some idea of how a winding may be figured for a given core without reference to any winding that might previously have been on the core, but simply with a view to getting a given horsepower out of it at a given voltage, speed, phase and frequency. Obviously in a chapter with the limited space assigned to this one, there cannot be attempted a complete treatise on the design of induction motors with detailed methods of calculation which will make him who reads a finished designer. There are many excellent books on this subject and a few which are so written as to be useful to the practical man in his work, If the foregoing chapters have aroused sufficient interest in the general matter of design, some of these longer works can be consulted for an exhaustive treatment of the entire subject. The author feels, however, after personal knowledge of many cases of windings roughly estimated by practical winders which performed satisfactorily, that an approximate idea of what is required in a winding to do a certain job can be had without involving so great a mass of calculation that errors creep in through the volume of figures alone, or without an advanced theoretical training in all the phenomena of alternating currents which are involved in the operation of induction motors. It should be understood that with the short cut methods and the abbreviated consideration herewith presented, it is not intended or expected that anyone will produce finished and elegant designs; but it is believed that in an emergency, when time is of the essence of the consideration and some chances can cheerfully be taken, the method presented will give an approximation to the correct winding which will be satisfactorily operative in a high percentage of cases. If the writer is checked by his peers, the designing engineers, he should like to have it understood that he is not attempting to tell all the experience he has accumulated nor to elaborate a new system of design calculation, but he is attempting to tell our friends, whose concern it is to make motors run and keep them running, what they may do to help themselves when all these designing engineers are a thousand miles away and the job has to be running next week. Therefore in this discussion while reference is made to all the points considered by the designing engineer only those points are covered in detail which it is felt are the most vital and these are handled in as elementary a manner as possible.

Effect of the Winding on the Performance.

The performance of an induction motor is made up of a number of different things. It must be able to start its load without drawing from the supply circuit an abnormal amount of current. It must be able to carry its load, as long as it runs, with a reasonable temperature rise and at a reasonable power factor.

It must have a good efficiency, that is to say it must not draw from the supply circuit an amount of energy greatly in excess of that represented by the work being done. It must have as much mechanical clearance as possible between the stationary and rotating members so as to increase the life of the bearings. It must have a momentary overload capacity of from one and one half to two times normal full load torque without "pulling out" or stalling. And it must have all these things without an appreciable amount of noise due to magnetism or windage. Some of these characteristics may be favored at the expense of others as, for example, it is possible to get a high power factor at the expense of having a very small clearance between stator and rotor, or it is possible to have a high efficiency at a cost of low starting torque and high starting current. For this reason in selling motors the selling talk is often confined to those points which are high in that particular design and the corresponding points of disadvantage are dwelt upon lightly; but to get a true comparison of the relative merits of two competitive ratings or designs all these points must be considered and given their due weight in view of the service in which it is intended to use the motor.

It is understood that all these characteristics are affected in various ways by the different features of the design, that is to say by the axial length of the iron core as compared to the rotor diameter, or by the number of slots, or the kind and thickness of the laminated steel used and matters of this kind; but the thing which has the greatest effect and which can most easily be modified is the number of turns in the stator or primary winding. In figuring this detail, which is of prime importance, it is therefore wise to have at all times a mental picture of what happens to each characteristic when the cross-section of the conductors or the number of turns in the primary winding is changed. In order to summarize this quickly the various characteristics are listed in order and considered separately. The main considerations in the operation of any induction motor are—starting torque, starting current, air gap or clearance, power factor, efficiency, heating, maximum torque, or pull out, noise, and mechanical vibration.

If there were two motors which were exact duplicates in materials and all mechanical dimensions, except that one motor had more turns in the winding than the other, when comparing the characteristics just named, the motor having the most turns would have a lower starting torque and a lower starting current. It would probably have a higher power factor. It might have a higher or a lower efficiency for the reason that the copper loss would be higher and the iron loss lower and whichever one preponderated would determine whether the efficiency was higher or lower, in other words, whether the copper loss increased faster than the iron loss decreased and *vice versa.* Similarly the heating would be more or less, depending on the sum of the losses. In general this motor would be a little more quiet and have less tendency toward mechanical vibration.

On the other hand, considering the motor with the fewer number of turns, it will have relatively, a higher starting torque and a higher starting current. It will probably have a lower power factor. It will have a higher or lower efficiency depending on the proportion of iron to copper loss, as explained in the preceding paragraph; similarly, the heating will vary with the amount of total losses. This motor would have a tendency to be noisier and have more mechanical vibration.

It will be noted that these changes are the same as would occur if the voltage were raised or lowered on any motor. Increasing the number of turns in a winding has the same effect as lowering the voltage and decreasing the number of turns has the same effect as raising the voltage on the winding. This can be seen from Fig. 186 where three windings are shown across 100 volts in parallel. Winding number 1 has eight turns in series and there are 12-½ volts effective on each turn. Winding No. 2 has ten turns and there are 10 volts effective on each turn; similarly winding No. 3 has 12 turns and the effective voltage on each turn is 8⅓ volts. Since the performance of the motor as regards torque and other characteristics is proportional to the voltage per turn in the winding, the No. 1 or 8 turn winding will operate as if on over-voltage and the No. 3 or 12 turn winding will operate as if on undervoltage. Expressing this another way, if we consider the No. 2 winding as the normal winding for 100 volts the No. 1 winding on 100 volts would operate and give the same result as the No. 2 winding if there were 125 volts applied to the No. 2 winding and similarly the No. 3 winding on 100 volts would operate and give the same result as would the No. 2 winding if the No. 2 winding had 83⅓ volts applied to it. From this it may be seen that perhaps the most essential thing to determine in figuring a winding is the proper number of turns in series in the stator winding which will be put across the line voltage. Another vital consideration is the cross section of the copper wire or conductor used in the winding, necessary to carry the amperes required to develop the desired horsepower. In order to get an idea of all the points which have to be considered in making the complete design of an induction motor a brief enumeration is here given of the different items considered by the designing engineer with a brief statement of how and why each is taken in to account.

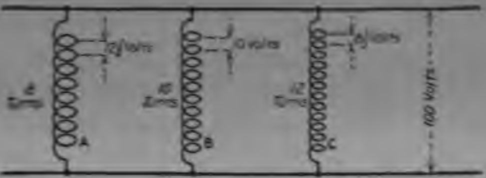


FIG. 186.—The voltage per turn or "transformer volts" on a winding.

1. Diameter and length of laminated iron core necessary to get the horsepower desired at the given speed and voltage.

2. Magnetic flux or field required to generate the line voltage.

3. Number of turns of wire in series in the stator winding which, when cut by the rotating field, will generate the line voltage.

4. Cross-section of stator conductor to carry the current required to develop desired horsepower at the power factor and efficiency that the design will probably give.

5. Number and size of stator slots, width and depth, to accommodate winding (3) and (4) when insulated for the required voltage.

6. Magnetic densities in the stator teeth, core, rotor teeth, core and air gap due to magnetic field (2).

7. Magnetizing or no load current required to set up the field mentioned in (2) with the number of turns in (3) with lengths of path required by (1) and (5).

8. Iron loss due to densities (6).

9. Iron loss due to primary slot openings.

10. Number and size of slots in rotor.

11. Is rotor winding squirrel cage or phase wound.

12. Figure rotor volts and amps. if phase wound.

13. Figure "Slip" or rotor copper loss.

14. Figure stator copper loss.

15. Estimate bearing friction and windage.

16. Figure leakage reactance for stator and rotor slots and coil ends, also zigzag, and belt, or differential leakage.

17. From (7) and (16) figure power factor.

18. From (13) and (16) figure starting and maximum torque.

19. From output and (8), (9), (13), (14) and (15) figure efficiency.

Since the consideration for the moment assumes an old core which already exists, many of these things are already determined and some can be assumed. The facts that require checking in determining a new winding for new conditions of speed or horsepower or voltage or phase or frequency, and which may be considered as fundamental are:

1. Is the core large enough to wind for the horsepower and speed that is desired?

2. Is there cross-section of iron enough below the slots to carry the magnetic field that is needed in the air gap to do the work desired?

3. How many turns are required in the stator winding?

4. What should be the cross-section or size of the wire or conductor used in the stator winding?

5. What should be the cross-section of the bars in the rotor and what should be the cross-section of the resistance rings at the ends of the rotor bars, assuming a squirrel-cage rotor winding?

6. Will the rotor diameter permit operating at the proposed r.p.m.?

These are comparatively few questions that can be readily answered and broad general limits laid down against which the individual case can be checked. This will assume some points but in general if the winding falls within these limits the motor will be sufficiently operative to fill the immediate requirement.

Proceeding at once to the determination of these quantities (1) is answered by checking the so-called "output coefficient," that is to say, the horsepower of which a given core is capable at a given r.p.m. This may be expressed by the formula:

$$Hp. = K \times D^2 \times L \times r.p.m.$$

Where K is the so called "output coefficient" which varies somewhat with the size and speed of the motor and the operating voltage, D = diameter of the stator bore in inches, L = axial length of the laminated iron core in inches measured parallel to the shaft and *r.p.m.* = revolutions per minute. Suitable values for this output coefficient may be found in several textbooks but perhaps the most convenient reference is to the Standard Handbook published by McGraw-Hill Book Co., Inc. The table given in Section 7 paragraph 246 of the fourth edition is reproduced herewith.

TABLE X.—OUTPUT COEFFICIENT VALUES

Pole pitch in inches	Values of output coefficient, K, when output is expressed in horsepower, linear dimensions in inches, and speed in rev. per min.					
	4 pole	8 pole	12 pole	16 pole	20 pole	24 pole
5	....	0.000025	0.0000265	0.0000263	0.0000254	0.0000248
7	0.0000222	0.0000329	0.0000331	0.0000331	0.0000331	0.0000331
10	0.0000336	0.000039	0.0000394	0.0000394	0.0000394	0.0000394
12	0.0000392	0.0000436	0.0000438	0.0000440	0.0000443	0.0000443
16	0.0000434	0.0000482	0.0000484	0.0000486		
20	0.0000454	0.0000505				

The following example is given to illustrate the use of this table. A stator core having a bore of 17 inches and an axial length of 6 inches was brought into a repair shop and a request made to put in a winding for 50 hp. at about 730 r.p.m. on 25 cycles. To determine whether it was physically possible the following calculation was made. *Pole pitch in inches* = $\frac{\textit{Diameter} \times 3.14}{\textit{Number of poles}} = \frac{17 \times 3.14}{4} = 13.4$. The nearest figure to this in the table above is 12 inches and opposite 12 inches under 4 poles is the figure .0000392. Then the horsepower that this core will develop at 730 r.p.m. is given by the equation:

$$h.p. = .0000392 \times 17^2 \times 6 \times 730 = 49.6$$

Hence the conclusion is reached that this core would wind satisfactorily for 50 hp. at 730 r.p.m. since the output coefficient for 13.4 inches would be a little greater than for 12 inches in the table which was used in the trial calculation.

The second question as to whether there is sufficient cross section of iron in the core between the bottom of the slots and the outside periphery can be determined by figuring the actual amount of magnetic flux per pole that must be set up to do the required work. This can be readily understood by a reference to Figs. 187 and 188, which illustrate the manner in which the magnetic flux is divided into as many groups or circuits as the motor has poles. In passing from the stator to the rotor through the teeth, then behind the rotor slots and back to the stator and again behind the stator slots to the starting point, it will be noted that there must be enough iron behind the slots to carry the flux or the motor will overheat. Referring again to Fig. 188 it is evident that the more poles the motor has, the less iron is required in the core behind the slots of both stator and

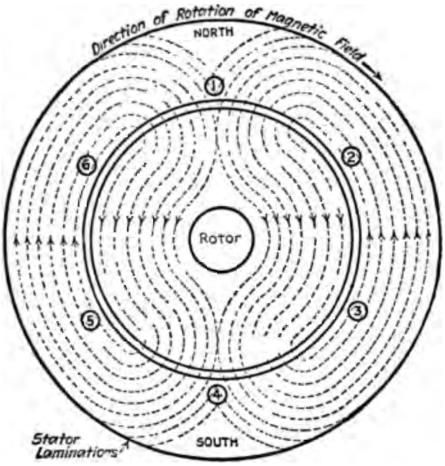


FIG. 187.—Cross-section of two-pole motor showing distribution of magnetic field.

rotor. Therefore, the correct way to determine this point is to figure the amount of magnetic flux per pole and figure the cross section of the core behind the slots and see that there are not more than 80,000 to 100,000 magnetic lines per square inch and if so, and other conditions are proper, the core should be satisfactory for the assumed conditions of the winding. Here we are confronted with a peculiar problem which often faces the designer, which is, that he must know part of his answer before he can solve the problem and find the rest of it. In other words the amount of magnetic flux in the core will depend on the number of turns of wire in the coils and the problem which he is trying to solve is how many turns should be put in the coils. So it is apparent that he must either guess the number of turns required and find out if the amount of magnetic flux is reasonable or else he must figure how much flux can be carried in the core he is using and from that figure check back and see how many turns are required in the winding to give this magnetic result. When the number of turns is settled and the cross-section of the copper

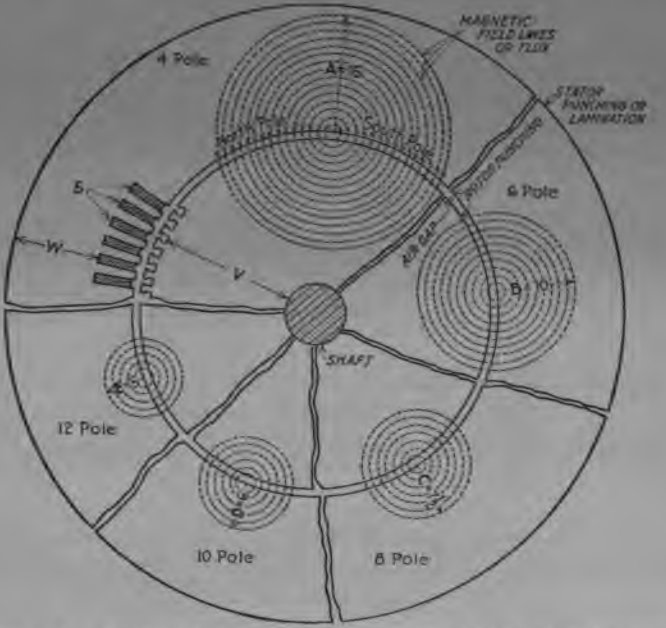


FIG. 188.—Core section, showing effect on magnetic field by changing number of poles.

is figured for the desired horse power and voltage, there is at once a question whether the slots will accommodate that many conductors of that cross-section after taking room enough to allow for the insulation required on the coil at that particular voltage. If the result is unfavorable and the copper so figured will not go in the slot at all, it means that the motor is not good for that much horsepower and the desired rating will have to be reduced. The number of turns cannot readily be reduced as that would mean more magnetic flux and the core back of the slots is already figured for 80,000 to 100,000 lines per square inch which is all it will stand. The reason why the number of conductors and the magnetic flux are tied in together in this way is because the conductors which are in series, when cut by the rotating magnetic field must generate or produce practically line voltage. This fact has been referred to many times in previous chapters.

The formula for the field flux per pole or per magnetic circuit is

$$\textit{Flux per pole} = \frac{45\ 000{,}000 \times \textit{Volts per phase}}{\textit{Cycles} \times \textit{Conductors per phase} \times K_1 \times K_2}$$

where

Volts per phase = line volts in the case of a two-phase winding or a delta-connected three-phase winding

and = $\frac{\text{line volts}}{1.73}$ in the case of a star-connected three-phase winding.

Cycles = the frequency of the supply circuit as expressed in cycles, that is, 60 or 25 or whatever the circuit may be.

Conductors per phase = number of wires per slot which are in series × number of slots ÷ number of phases.

K_1 is a so-called "distribution factor" and is .905 for two-phase and .955 for three-phase.

K_2 is the so-called "chord factor" and depends on the pitch or throw of the coil. Its technical value is the sine of one-half of the electrical angle spanned by the coil.

A practical method of getting this factor which is close enough for general purposes is to use the expression

$$\textit{Chord factor} = K_2 = \sqrt{\frac{\textit{Number of slots per pole})^2 - 2(\textit{Number of slots dropped})^2}{(\textit{Number of slots per pole})^2}}$$

or taking a concrete example: suppose there is a 72 slot motor wound for six poles and having a coil throw of 1 and 8, what is the chord factor or K_2, which is under discussion? Since there are 72 slots and six poles there are 12 slots per pole and full pitch would be slots 1 and 13. Winding 1 and 8 drops 5 slots and thus our formula above becomes the square root of twelve squared minus two times five squared divided by twelve squared, or mathematically

$$\sqrt{\frac{12^2 - 2(5)^2}{12^2}} = \sqrt{\frac{144 - 50}{144}} = \sqrt{\frac{94}{144}} = .80$$

To illustrate how this flux formula is applied, assume a core having dimensions as shown in Fig. 189 which it is desired to wind for 50 h.p., 25 cycles, 3 phase, 4 poles, 440 volts and 730 r.p.m. full load speed. The outside diameter O of the stator laminations = $25\frac{1}{2}$ in., the inside bore D of the stator laminations = 17 in. The axial length of the core L = $6\frac{3}{4}$ in. but it contains two ventilating ducts each $\frac{3}{8}$ in. wide so that the net iron core length = 6 in. The primary slots are 1.7 in. deep, so that the dimension C or the radial depth of the laminations below the slots = $(25\frac{1}{2} - 17) \div 2 - 1.7$ = 2.55 in. and the actual cross-section of the core below slots through which all of the flux per

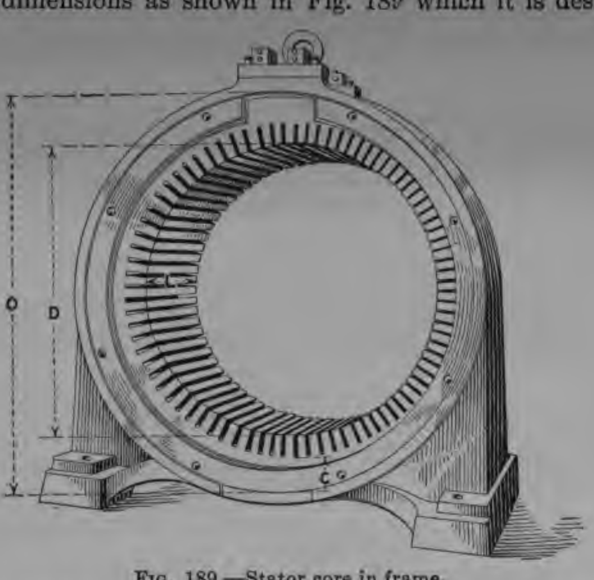


FIG. 189.—Stator core in frame.

NOTE.—Do not figure the new winding from the core density alone, but check the density in the teeth also, as cautioned on page 194, since the density in the teeth is frequently the limiting factor.

pole must pass is equal to $C \times L$ or in this case $2.55 \times 6 = 15.3$ square inches. A reference to Fig. 188 indicates that when the flux per pole passes from the rotor into the stator, it divides and half goes one way and half the other way. Hence in the present case the total available cross section of iron to carry the flux per pole is not 15.3 square inches, but twice that or 30.6 square inches. As stated above 80,000 lines per square inch is a permissible density, so that a total flux per pole of $30.6 \times 80{,}000$ can be used or 2,448,000 lines. The only other factor missing from the flux per pole formula which is necessary to give at once the total number of conductors per phase is the chord factor. This depends upon the slots in which the two sides of any coil are placed. In the core which is under consideration there are 48 slots and since a 4-pole winding is under calculation, the full pitch for the winding would be slots 1 and 13. Full pitch is too long mechanically and some space endwise can be saved and some copper as well by chording it a few slots, so for illustration it is assumed that the coils lie in slots 1 and 10. Using the approximate formula given for chord factor above, this factor becomes

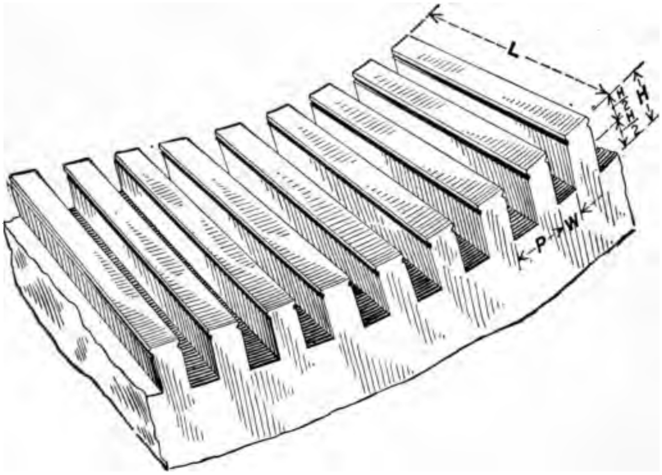


FIG. 189*a*.—Section of stator core.

$$\sqrt{\frac{12^2 - 2(3)^2}{12^2}} - \sqrt{\frac{144 - 18}{144}} = \sqrt{.875} = .93$$

Expressing the flux per pole formula in terms of conductors per phase, this expression follows:

Conductors per phase =

$$\frac{45{,}000{,}000 \times \textit{volts per phase}}{\textit{cycles} \times \textit{flux per pole} \times \textit{chord factor} \times \textit{dist. fact.}}$$

Remembering that the distribution factor for 3 phase equals .955 and substituting the values calculated above, and assuming a delta connected winding,

Conductors per phase =

$$\frac{45{,}000{,}000 \times 440}{25 \times 2{,}448{,}000 \times .93 \times .955} = 362$$

Since there are 3 phases, there will be required a total number of conductors 3 × 362 = 1086 and since there are 48 slots there will be 1086 ÷ 48 = 22.6 conductors per slot. What a designer would do in this case would be to either wind 22 conductors per slot and throw the coil 1 and 11 instead of 1 and 10 or else wind it 24 per slot and throw the coil 1 and 9, either of which would be a good winding without much difference between the two.

The reason for this is that there are 2 coils per slot and hence with 22 wires per slot there would be 11 wires in each coil. As the wires are arranged in 2 or 3 layers, 11 would not be exactly divisible by either 2 or 3, hence, in the case of a two layer coil there would be one layer of 5 wires and one layer of 6 wires side by side, or in the case of a 3 layer coil there would be 2 layers of 4 wires each and one layer of 3 wires. Either of these arrangements would be wasteful of space and hence it would be preferable to have 12 wires per coil which is evenly divisible by either 2 or 3. If the coil is wound in slots 1 and 11 the chord factor is .97 and if it is wound in 1 and 9 the chord factor is .866. Hence, the real, effective number of wires in one case is 22 × .97 = 21.3 and in the other case is 24 × .866 = 20.78 which would give very close to the same result so far as torques are concerned.

In this calculation it was noted that the figure 440 was used for the voltage. This assumed a series delta connection. If, for example it had been desired to connect the winding in two parallel delta for the same voltage, there would have been required twice as many conductors per phase and each conductor would have had one half the cross section, since there would be two paths in parallel for the current instead of one in series.

Similarly, if the winding was to have been connected in series star instead of series delta the voltage used in the equation would have been $440 \div 1.73 = 254$ instead of 440. Hence, in the result, the conductors required per phase would have been $\frac{362}{1.73} = 209$ instead of 362. It is well to remember this fact: that with a star connection only about one half as many turns are required in series as with a delta connection. It sometimes makes an easier coil to wind and a coil which is mechanically stiffer and stronger, if less turns of a larger size wire can be used. This is one of the principal reasons why a star connection is used much more frequently than a delta connection.

Having found the number of conductors per slot from the above equation there would seem to be nothing more to do but figure the required cross section of the conductor to carry the full load current, and the space required for insulation and see if the coil so figured and insulated would go into the slot. There is a check calculation that should be made first to see how hard the iron is working in the stator teeth. The calculation that was made concerned itself only with the density of the magnetic flux in the stator core behind the slots and was checked first to make sure the required field had room to get through the core. However, before accepting this figure the teeth should be checked also to see how hard they are working. This is a simple check from the figures already employed. The diameter of the stator bore of the core under calculation is 17 in. The depth of the slots is 1.7 in., therefore the diameter to the middle of the slot = 18.7 in. and the slot pitch at this point or the dimension P from Fig. 189a, $C = \frac{18.7 \times 3.14}{48} = 1.22$ in. The slot width $W = .65$ in. Hence the tooth width $P - W = 1.22 - .65 = .57$ in. and since the net core length $L = 6$ in., the cross section of one tooth at its mid-section $= 6 \times .57 = 3.42$ square inches. There are 48 teeth total and 4 poles, hence there are 12 teeth per pole through which the magnetic flux of one pole may pass. Therefore, the total iron cross section of 12 teeth $= 12 \times 3.42 = 41.04$ square inches. It was calculated above that there were 2,448,000 magnetic lines per pole and it would seem that all that was necessary to check the tooth density would be to divide this figure by 41.04. This is not the case as in the core for the reason that all the teeth do not carry the flux equally but those in the center of a pole at a given section carry a maximum and those half way between poles carry nothing so that in order to take care of the maximum, the result above is divided by .636. Hence in the problem in hand the maximum density in the teeth is $\frac{2{,}448{,}000}{41.04 \times .636} =$ 94,000 lines per square inch. As a matter of fact it is actually about 96,000 lines since the 2,448,000 was figured with 362 conductors per phase and a throw of one and ten, whereas there are now $24 \times 48 \div 3 = 384$ conductors per phase, but the throw is only one and nine and substituting back in the original flux equation,

Flux per pole =

$$\frac{45{,}000{,}000 \times 440}{25 \times 384 \times .955 \times .866} = 2{,}480{,}000 \text{ lines.}$$

This value namely, 96,000 for density in the teeth is perfectly permissible. It should not be allowed to exceed, say, 130,000 for 25 cycle machines, nor about 110,000 for 60 cycle machines.

Figuring the cross section of the stator conductor.—Having determined the number of conductors required in the slot, that is 24, the next step is to figure the necessary size of the conductor or cross section and see if the coils will go in the slot after being properly insulated. In order to figure this it is necessary to know what the full load current of the motor will be. The formula for finding the full load current of a two phase motor is,

Full load current per lead =

$$\frac{\textit{Horsepower} \times 746}{2 \times \textit{volts per phase} \times \textit{efficiency} \times \textit{power factor}}$$

Where the efficiency and the power factor are the full load values and are expressed in hundredths, that is with a decimal point in front of each. For example 90 per cent. is written .90 and 85 per cent. power factor is written. 85, etc. For a three phase motor the formula changes to,

Full load current per lead =

$$\frac{\textit{Horsepower} \times 746}{1.73 \times \textit{volts per phase} \times \textit{efficiency} \times \textit{power factor}}$$

which it will be noted is similar to the two phase formula except 1.73 is used in the denominator instead of 2. One thing must be specially noted about the three phase and that is that the full load current so found is the current in the outside motor lead or the current drawn from the line. If the motor is star connected inside this same current flows in the motor winding itself and hence in the conductors in the slots, unless the winding is in 2 or more parallels in which case of course, the lead or line current splits up into as many parts as there are parallel paths. On the other hand if the windings inside the motor are delta connected as they are in the case we are considering, the current in the windings will be less than the current coming in the lead as figured above and it is necessary to divide by 1.73 a second time to find out what the current is, which must actually be provided for in the coils themselves.

Preparing to apply the above formula, at once the problem arises, What is the full load efficiency and the full load power factor of the motor for which this winding is being figured? Of course there is a wide variation in these figures between small and large motors, and between high and low speeds, and between 25 and 60 cycles and these variations are shown as well as may be in the Standard Hand Book referred to in the foregoing and other text books. For the purpose here, which as has been stated, is somewhat rough and ready, an approximation must be assumed. The handiest approximation the author has ever used and one that has given good results is to assume that a three phase, 550 volt motor, draws from the line in each lead just about one ampere per horsepower. This is very closely true in most lines of commercial motors over a wide range of sizes and speeds. Then if the motor in question is not 3 phase or if it is not 550 volts the current can readily be changed to other voltages. For example assume a 40 hp. motor. Then at 550 volts 3 phase it follows that its full load current per lead is 40 amperes, at 440 volts its full load current would be $\frac{550}{440} \times 40 = 50$ amperes and at 220 volts it would be $\frac{550}{220} \times 40 = 100$ amperes and at 110 volts it would be $\frac{550}{110} \times 40 = 200$ amperes and so on. Similarly to convert to two phase multipy these values by $\frac{1.73}{2.00} = .86$ because the current of any two phase motor is always that much less than the corresponding three phase.

Referring again to the formula above for the full load current of a 3 phase motor, to give one ampere per horsepower at 550 volts would mean that the product of the efficiency and power factor would be .785. This might be assumed to be 89 per cent. efficiency and 88 per cent. power factor or any other combination whose product gave .785. At all events this is an average value and sufficiently near correct for the present purpose.

Since the present calculation assumes a 50 hp. 3 phase 440 volt rating it may be assumed that the full load current per lead is $\frac{50 \times 550}{440} = 62.5$ amperes. Since the winding is to be delta connected the current in the coils themselves will be $\frac{62.5}{1.73} = 36.1$ amperes. There is no fixed rule that can be followed for the cross section of copper required in the coil per ampere. It may be as low as 400 circular mils in some cases and may have to be as high as 1,000 circular mils in others. Slow speed motors and higher voltages (where there is more insulation to pass the heat through) require larger copper than do higher speeds and lower voltages. In the present case and in most average cases a figure of 750 circular mils can be used. For the present case then the circular mils required would be $36.1 \times 750 = 27{,}075$ circular mils. Looking in a Brown and Sharpe wire table the nearest size to this is No. 6 round wire which shows 26,250 circular mils. This is near enough and it is selected. The problem now is, will 24 No. 6 wires go in a slot .65 in. wide by 1.70 in. deep and allow for the retaining wedge at the top and the proper insulation for 440 volts? To answer this it is necessary to know something about insulation requirements. As there are commonly only two voltage classes met with, it can be stated that voltages up to and including 550 volts will require a space in the width of the slot of about .1 of an inch and in the depth of the slot of about .15 inches and voltages above 550 up to and including 2,200 will require about .16 inches in width and .26 inches in depth. These figures in depth do not include any retaining wedges or so called "top sticks," but must be allowed in addition to the wires between the bottom of the wedge, and the bottom of the slot. In the case just being figured the wires will evidently go in better 3 ×8 than any other way. The diameter of No.6 round wire over double cotton covering is .178 inches. Three wires in width would be $3 \times .178 = .534$ in. adding .1 in. for insulation gives $.534 + .1 = .634$ which goes very well in the width of the slot which is .65 in. In depth 8 wires would require $8 \times .178$ inches $= 1.424$. The allowance for insulation is .150 in. and the usual coil retaining wedge requires .125 in. so that the total required depth will be 1.424 + .150 + .125 = 1.699 in. which just exactly fills the available depth. It should be under stood that the 24 wires are not 3 × 8 in one coil but 3 × 4 in each coil and two coils in the slot according to the usual practice. If the wires had not fitted in the slot as shown it would have been necessary to choose a wire small enough to go in the space and then by trial after the winding was complete find out how many horsepower the winding would carry without over heating. If it were not possible to get 50 horsepower it would probably develop 45 hp. without trouble if the output coefficient checked to 50 as shown in the beginning of this chapter.

With regard to the rotor winding if it is of the wound rotor type the number of wires per slot can be made any number that is convenient, provided the total weight of copper in the rotor winding is made approximately 80 per cent. to 85 per cent. of that in the complete stator winding.

Voltage Between Collector Rings.—In the case of a wound rotor motor it is often useful to know the voltage at stand still between the rotor collector rings in order to determine how much resistance should be used in the starting or speed regulating controller. This may be determined very closely from the formula:

$$\textit{Volts between collector rings} = \frac{E_1 \times W_2 \times K_2}{K_1 \times W_1 \times K_3}$$

Where E_1 = line voltage applied to the stator
W_1 = number of conductors in series per phase in the stator
W_2 = number of conductors in series per phase in the rotor
K_1 = 1 if stator winding is two phase or three phase delta
K_1 = 1.73 if stator winding is three phase star
K_2 = 1 if rotor is connected delta
K_2 = 1.73 if rotor is connected star
K_3 = chord factor of the stator coils as explained in Chapter IV

The number of conductors in series per phase in either stator or rotor is equal to the total number of slots multiplied by the number of wires in each slot, divided by the number of phases and divided by the number of parallels in which the winding diagram shows the winding to be connected.

For example, what is the voltage between collector rings on a wound rotor motor with the following data? The line voltage is 220. There are 72 slots in the stator and 10 wires per slot. The stator winding is three phase, two parallel star, 6 pole and the coil throw is slots 1 and 9. There are 54 slots in the rotor, two conductors per slot and the rotor winding is connected series star.

Setting down the data for use in the formula given above $E_1 = 220$, $W_1 = \frac{72 \times 10}{3 \times 2} = 120$, $W_2 = \frac{54 \times 2}{3} = 36$, $K_1 = 1.73$, $K_2 = 1.73$, K_3 = primary chord factor = sine of 60 deg. = .866, because $^{72}\!/_{6}$ = 12 slots = 180 deg. and one slot = 15 deg. Hence, a throw of 1 and 9 spans 8 slots or 8 × 15 = 120 deg. and the chord factor = the sine of one-half the angle spanned by the coil = $\frac{1}{2} \times 120$ deg. = 60 deg. = .866. Therefore, *volts between collector rings* =

$$\frac{E_1 \times W_2 \times K_2}{K_1 \times W_1 \times K_3} = \frac{220 \times 36 \times 1.73}{1.73 \times 120 \times .866} = 76 \textit{ volts.}$$

If phase wound the coils must, of course, be connected for the same number of poles as the stator. If there should be an old winding on the rotor for a different number of poles it may be possible to reconnect it for the number desired, but as rotor windings are nearly always of the "wave" type or something of the same order it is usually impossible to reconnect for any other number of poles.

If the rotor winding is squirrel cage the number of bars and their cross section is probably fixed. The cross section of the end rings if of rolled or drawn copper should be so chosen that the weight of bars plus rings is about 75 per cent. to 80 per cent. of the total weight of the stator coils. If the rings are cast copper or cast brass it should be remembered that a larger cross section will be required since the conductivity of the best cast copper is only 80 per cent. to 85 per cent. of the conductivity of rolled copper and cast brass is as low as 18 per cent. to 25 per cent. of the conductivity of drawn or rolled copper. This would mean that a ring of cast brass would have to be 4 to 5 times the cross section of the corresponding rolled copper ring to carry the same current. It should also be remembered that a two pole motor would have proportionately the heaviest ring on the squirrel cage, a four pole next, then a six and so on, and that when 10 poles or 12 poles are reached the ring would probably be no larger in cross section than would be required for mechanical strength and construction.

Such in its briefest form is the simplest calculation that can be made which it is safe to make in the hope of getting the desired result. It will be noted that no attention has been paid to calculating the leakage reactance, nor the no load current, nor the starting and maximum torques, nor the circle diagram nor any of the refinements which the designing engineer commonly employs; and yet if care is used in employing the checks that are made the experimenter should be rewarded with reasonable results.

To sum up, the available core is first checked by the output coefficient to see if it will develop the horsepower at the desired speed. Next a check is made to see how much magnetic field can be handled in the core and teeth. Then the proper number of conductors is chosen to generate the line voltage when acted upon by the permissible magnetic field. These conductors are then made of the proper size to carry the working current and insulated for the working voltage and fitted in the slots. This is all that is attempted and it is assumed that if these conditions are met, all the other conditions of operation will fall reasonably in line or can be adjusted after trial without too much change to meet the desired requirements.

Naturally, such broad assumptions may not result in a design of finished nicety, but they may sometimes give quick results where results must be had quickly or not at all.

CHAPTER XIII

STANDARD GROUP DIAGRAMS FROM 2 TO 14 POLES

The form of diagram which is most often used in connecting induction motor windings is the so-called "group" diagram so often illustrated in the foregoing chapters where the coils are "stubbed" or grouped into pole-phase groups and then cross connected to form magnetic poles. This form of diagram is practically universally used for stators with open slots and because it is so often employed, it is considered desirable to give in this chapter a series of diagrams covering all possible combinations both two and three phase, star and delta, from two to fourteen poles.

To attempt to show "developed" windings, that is a picture of the actual coils rolled out flat for all possible numbers of poles, phases, slots, coils per slot, etc. would require several hundred diagrams even for full pitch windings and with the slots always an integral multiple of the phases times the poles, and if to this is added the possibilities of chording and using a total number of slots not an even multiple of the phases time the poles, the number of pictures required to show all the connections would run into thousands. However, by the relatively simple scheme of considering the group of coils which forms one pole-phase group as a unit, the possible number of combinations becomes greatly limited, and as shown by the following diagrams all the combinations from two to fourteen poles can be shown by means of diagrams shown in Figs. 190 to 270 inclusive.

From the nature of the diagrams here given it will be seen that they are not dependent on the total number of slots in the machine, nor upon the number of coils per group, nor upon the throw or pitch of the coils, but are general for all machines of the same number of phases and poles. Each one of the small arcs in the circle represents the ends of the coils in a single pole-phase group in the winding. In order to illustrate this, photographs have

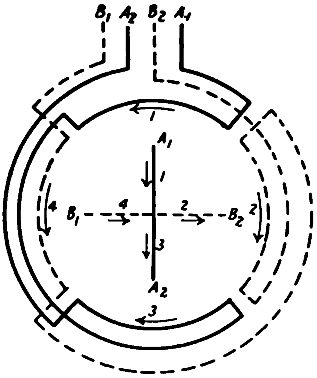


FIG. 190.—Two pole, two phase, series.

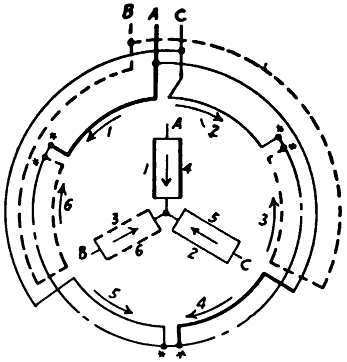


FIG. 193.—Two pole, three phase, parallel star.

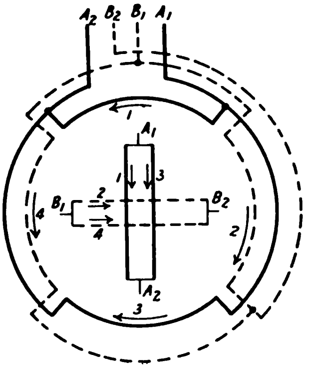


FIG. 191.—Two pole, two phase, parallel.

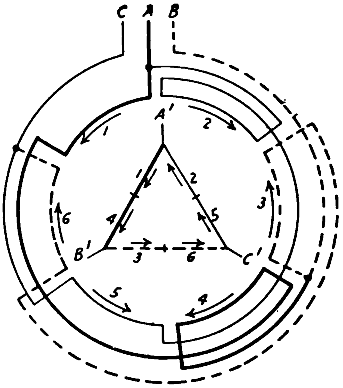


FIG. 194.—Two pole, three phase, series delta.

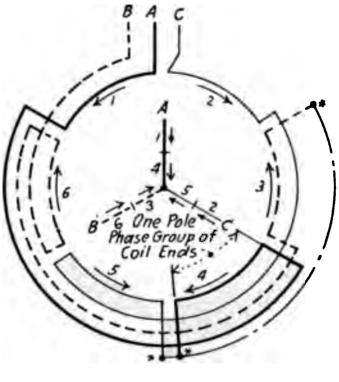


FIG. 192.—Two pole, three phase, series star.

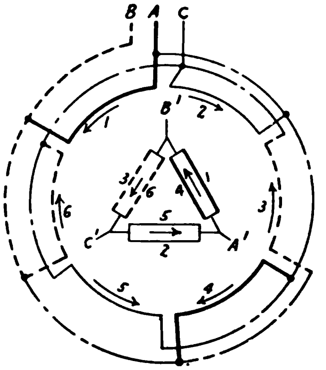


FIG. 195.—Two pole, three parallel, phase delta.

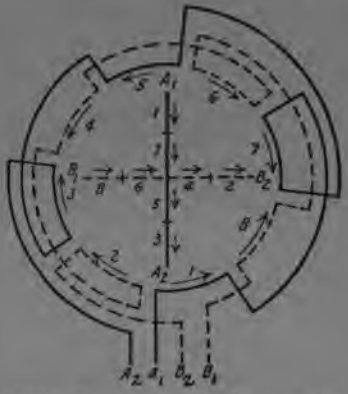


FIG. 196.—Four pole, two phase, series.

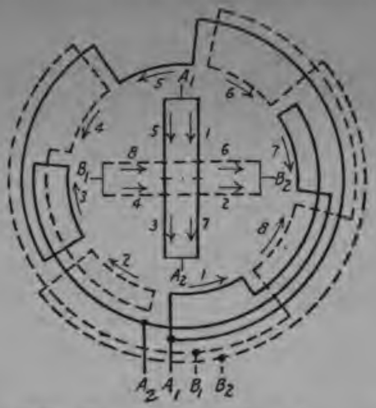


FIG. 197.—Four pole, two phase, two parallel.

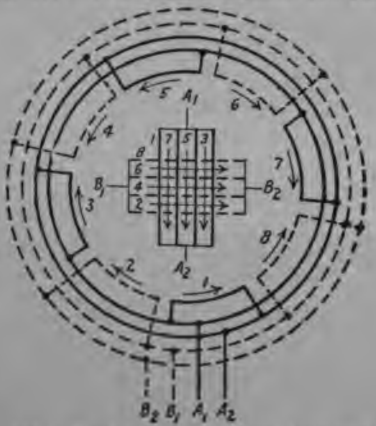


FIG. 198.—Four pole, two phase, four parallel.

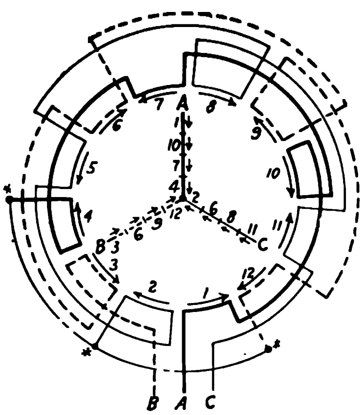


FIG. 199.—Four pole, three phase series star.

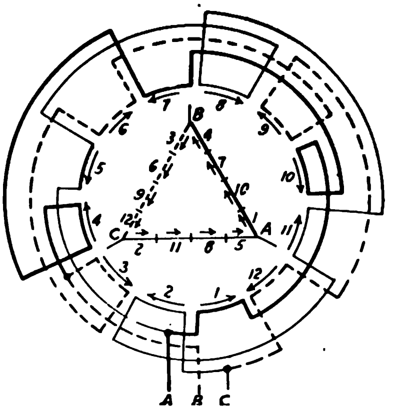


FIG. 202.—Four pole, three phase, series delta.

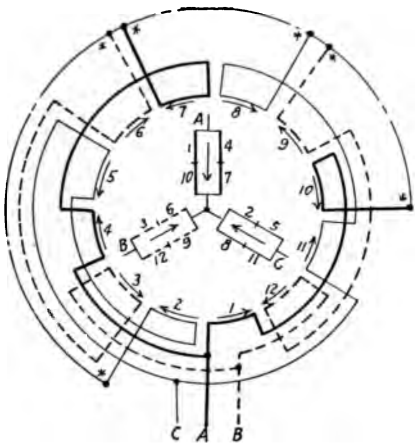


FIG. 200.—Four pole, three phase, two parallel star.

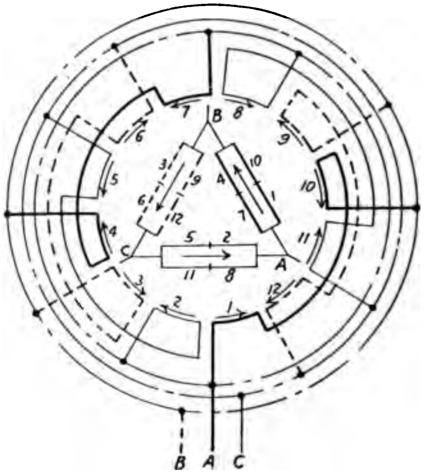


FIG. 203.—Four pole, three phase, two parallel delta.

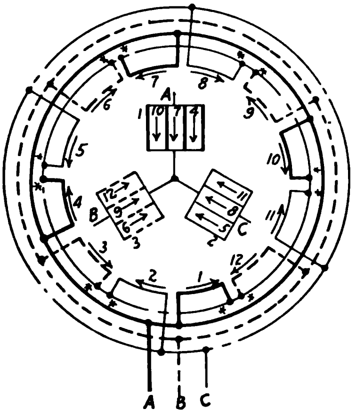


FIG. 201.—Four pole, three phase, four parallel star.

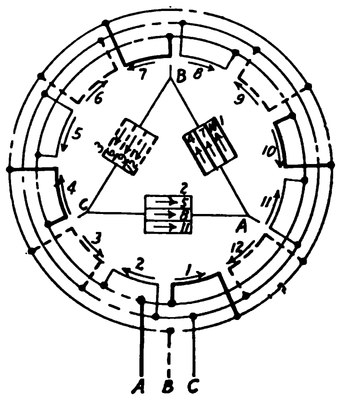


FIG. 204.—Four pole, three phase, four parallel delta.

FIG. 205.—Six pole, two phase, series.

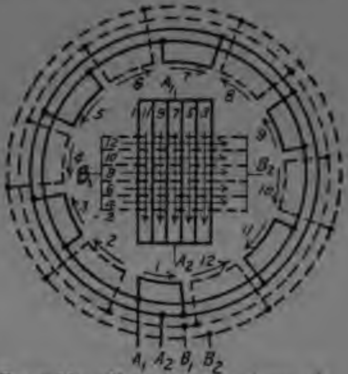


FIG. 208.—Six pole, two phase, six parallel.

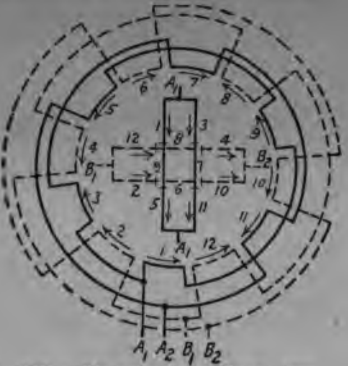


FIG. 206.—Six pole, two phase, two parallel.

FIG. 209.—Six pole, three phase, series star.

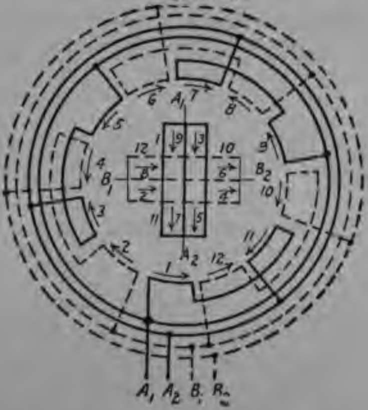


FIG. 207.—Six pole, two phase, three parallel.

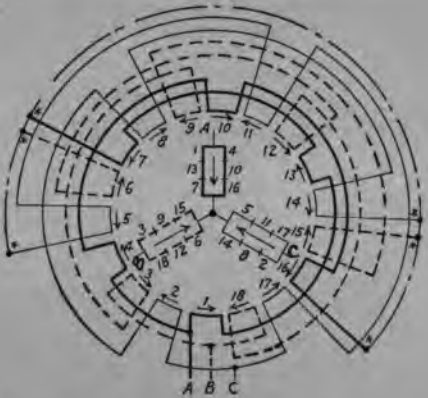


FIG. 210.—Six pole, three phase, two parallel star.

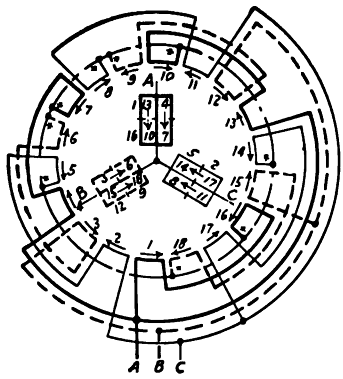


FIG. 211.—Six pole, three phase, three parallel star.

FIG. 214.—Six pole, three phase, two parallel delta.

FIG. 212.—Six pole, three phase, six parallel star.

FIG. 215.—Six pole, three phase, three parallel delta.

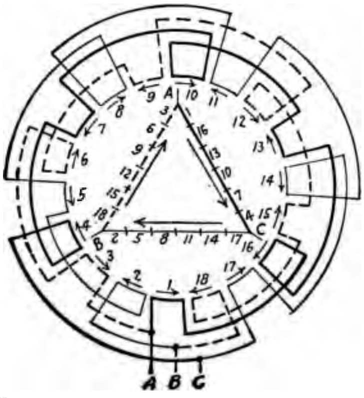


FIG. 213.—Six pole, three phase, series delta.

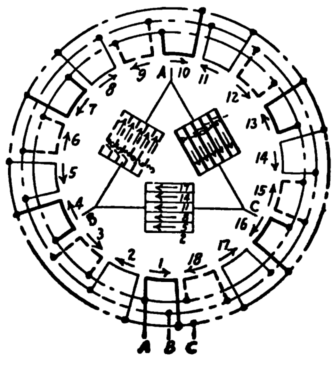


FIG. 216.—Six pole, three phase, six parallel delta.

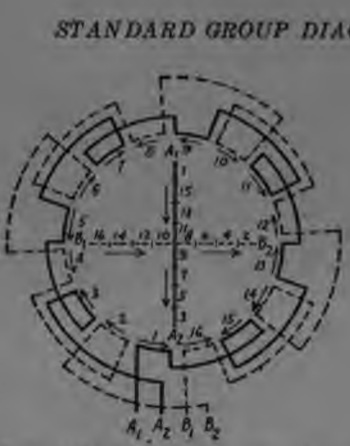


FIG. 217.—Eight pole, two phase, series.

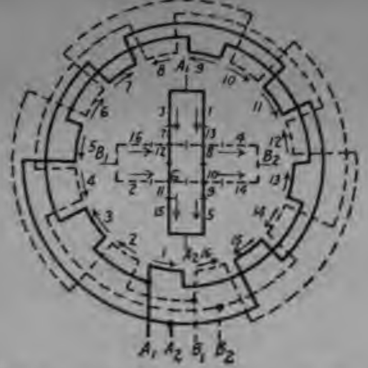


FIG. 218.—Eight pole, two phase, two parallel.

FIG. 219.—Eight pole, two phase, four parallel.

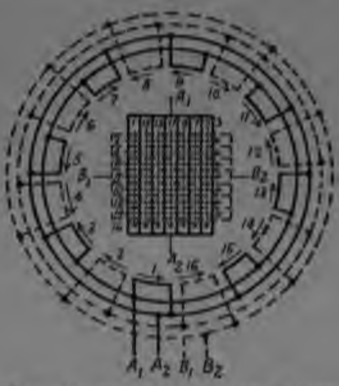


FIG. 220.—Eight pole, two phase, eight parallel.

FIG. 221.—Eight pole, three phase, series star.

FIG. 222.—Eight pole, three phase, two parallel star.

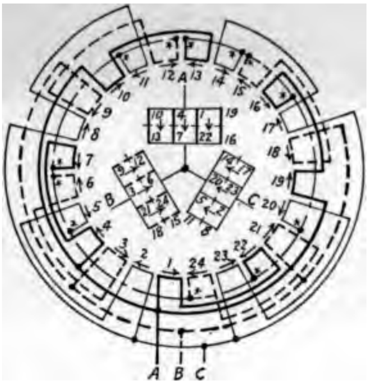


Fig. 223.—Eight pole, three phase, four parallel star.

Fig. 224.—Eight pole, three phase, eight parallel star.

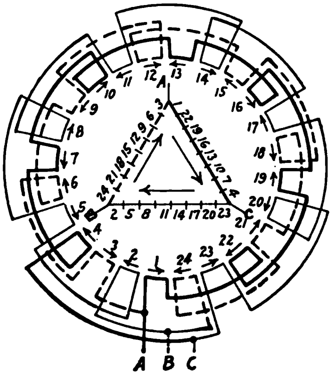


Fig. 225.—Eight pole, three phase, series delta.

Fig. 226.—Eight pole, three phase, two parallel delta.

Fig. 227.—Eight pole, three phase, four parallel delta.

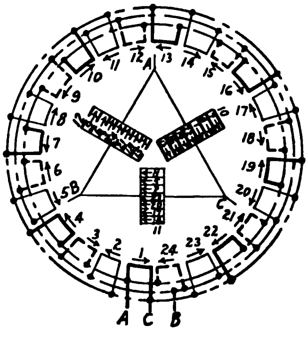


Fig. 228.—Eight pole, three phase, eight parallel delta.

FIG. 229.—Ten pole, two phase, series.

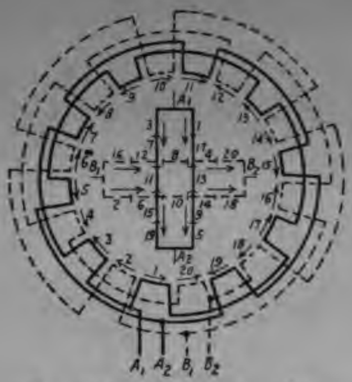


FIG. 230.—Ten pole, two phase, two parallel.

FIG. 231.—Ten pole, two phase, five parallel.

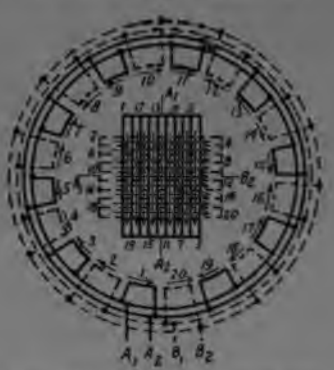


FIG. 232.—Ten pole, two phase, ten parallel.

FIG. 233.—Ten pole, three phase, series star.

FIG. 234.—Ten pole, three phase, two parallel star.

FIG. 235.—Ten pole, three phase, five parallel star.

FIG. 236.—Ten pole, three phase, ten parallel star.

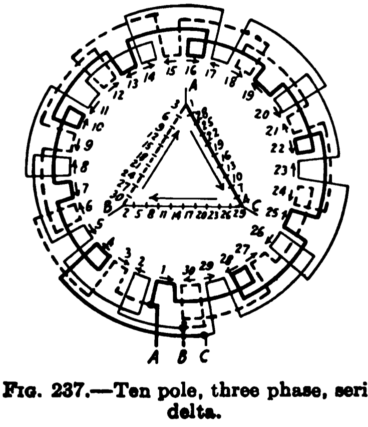


FIG. 237.—Ten pole, three phase, series delta.

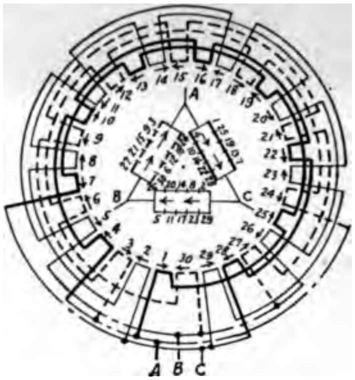


FIG. 238.—Ten pole, three phase, two parallel delta.

FIG. 239.—Ten pole, three phase, five parallel delta.

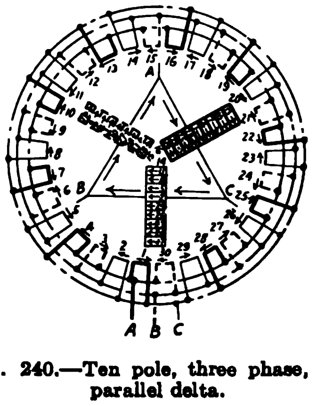


FIG. 240.—Ten pole, three phase, ten parallel delta.

FIG. 241.—Twelve pole, two phase, series.

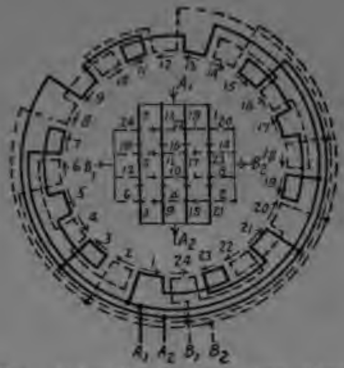


FIG. 244.—Twelve pole, two phase, four parallel.

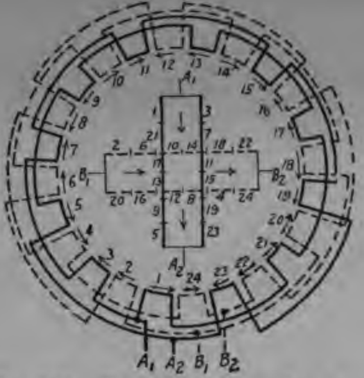


FIG. 242.—Twelve pole, two phase, two parallel.

FIG. 245.—Twelve pole, two phase, six parallel.

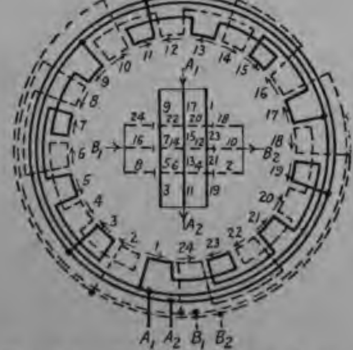


FIG. 243.—Twelve pole, two phase, three parallel.

FIG. 246.—Twelve pole, two phase, twelve parallel.

FIG. 247.—Twelve pole, three phase, series star.

FIG. 250.—Twelve pole, three phase, four parallel star.

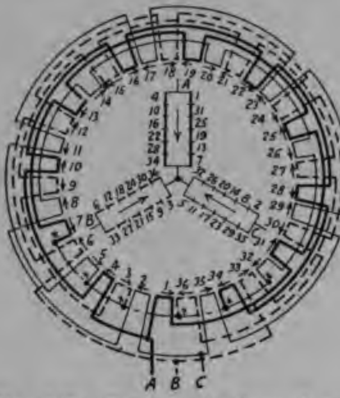


FIG. 248.—Twelve pole, three phase, two parallel star.

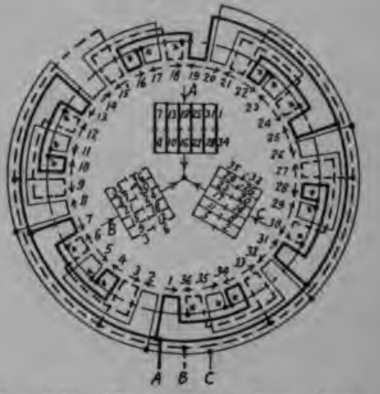


FIG. 251.—Twelve pole, three phase, six parallel star.

FIG. 249.—Twelve pole, three phase, three parallel star.

FIG. 252.—Twelve pole, three phase, twelve parallel star.

Fig. 253.—Twelve pole, three phase, series delta.

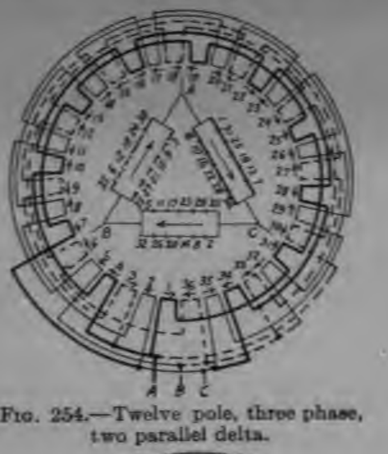


Fig. 254.—Twelve pole, three phase, two parallel delta.

Fig. 255.—Twelve pole, three phase, three parallel delta.

Fig. 256.—Twelve pole, three phase, four parallel delta.

Fig. 257.—Twelve pole, three phase six parallel delta.

Fig. 258.—Twelve pole, three phase, twelve parallel delta.

FIG. 247.—Twelve pole, three phase, series star.

FIG. 250.—Twelve pole, three phase, four parallel star.

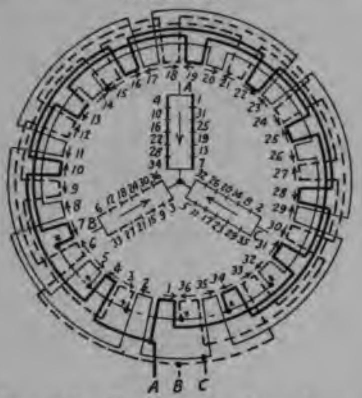


FIG. 248.—Twelve pole, three phase, two parallel star.

FIG. 251.—Twelve pole, three phase, six parallel star.

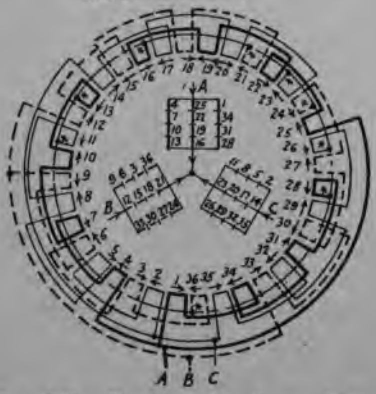


FIG. 249.—Twelve pole, three phase, three parallel star.

FIG. 252.—Twelve pole, three phase, twelve parallel star.

FIG. 253.—Twelve pole, three phase, series delta.

FIG. 254.—Twelve pole, three phase, two parallel delta.

FIG. 255.—Twelve pole, three phase, three parallel delta.

FIG. 256.—Twelve pole, three phase, four parallel delta.

FIG. 257.—Twelve pole, three phase six parallel delta.

FIG. 258.—Twelve pole, three phase, twelve parallel delta.

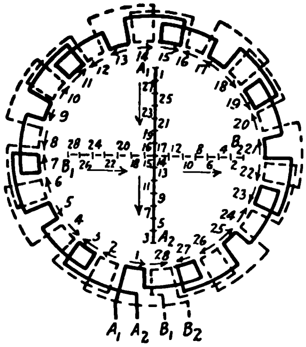


FIG. 259.—Fourteen pole, two phase series.

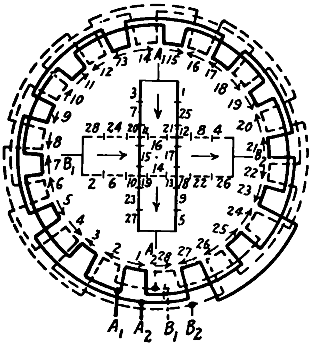


FIG. 260.—Fourteen pole, two phase, two parallel.

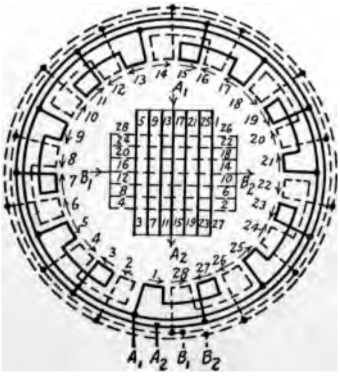


FIG. 261.—Fourteen pole, two phase, seven parallel.

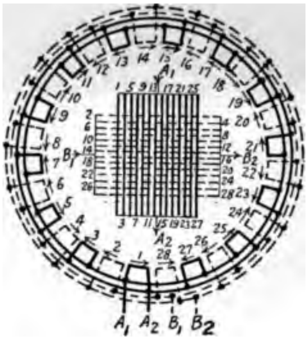


FIG. 262.—Fourteen pole, two phase, fourteen parallel.

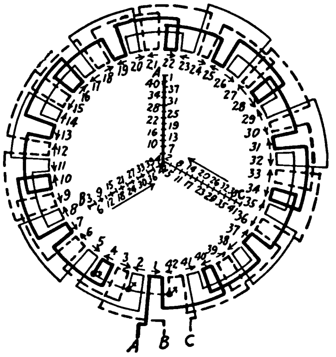


FIG. 263.—Fourteen pole, three phase, series star.

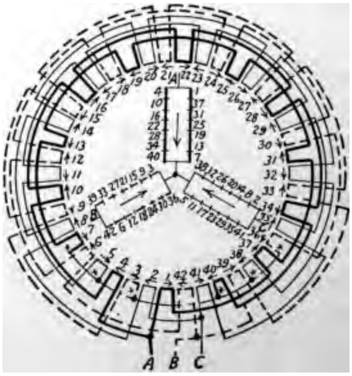


FIG. 264.—Fourteen pole, three phase, two parallel star.

FIG. 265.—Fourteen pole, three phase, seven parallel star.

FIG. 268.—Fourteen pole, three phase two parallel delta.

FIG. 266.—Fourteen pole, three phase, fourteen parallel star.

FIG. 269.—Fourteen pole, three phase, seven parallel delta.

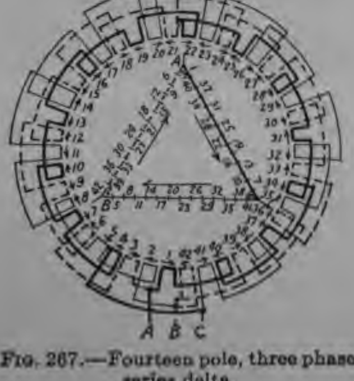


FIG. 267.—Fourteen pole, three phase, series delta.

FIG. 270.—Fourteen pole, three phase, fourteen parallel delta.

been taken of a machine in three stages. In Fig. 271 a machine is shown in which the coils have simply been placed in the slots by the winder and no connections have been made. The wires which are the beginnings and endings of the coils are sticking

FIG. 271.—Coils wound but unconnected.

FIG. 272.—Coils "stubbed" or connected with pole phase groups.

FIG. 273.—The completed connection.

out at random. In Fig. 272 the coils have been connected into several distinct groups, and the remaining wires, which protrude radially toward and away from the center of the machine, form the beginning and the end of each pole-phase group. The operation which has been performed between Fig. 271 and Fig. 272 can be described in this way:—Suppose, for example, that there are 96 total coils in the winding and that it is to be connected for three phases and four poles. There will then be $3 \times 4 = 12$ pole phase groups, and $96 \div 12 = 8$ coils in each group. Starting at any arbitrary point, the winder connects the first eight coils in series by connecting the end of coil 1 to the beginning of coil 2, and the end of coil 2 to the beginning of coil 3, etc., until eight coils are in series. The beginning of coil 1 is then bent outward and left long and the end of coil 8 is bent inward and left long. Between these two are seven short "stubs" or coil-to-coil connections, which are shown taped up in Fig. 272. The winder then proceeds to connect coils 9 to 16 in series in the same manner to form pole-phase group No. 2, and so on around the machine until he has completed 12 pole phase groups and used all the coils, and the winding looks as shown in Fig. 272.

In case the winding has certain coils provided with heavier insulation on the end turns to take the strain of the full voltage of the machine where different phases are adjacent, the operation is slightly different. Then, the number of coils per pole phase group must be checked before the windings are inserted in the slots, and specially insulated phase coils placed on both ends of each group. In this case the location of the pole phase groups is definitely determined by the winder before he starts connecting the coils together.

The next step is to mark the pole phase groups *A-B-C-A-B-C*, etc., around the machine and then to connect all the groups together in the proper manner to form a three-phase winding by means of a diagram of the same form as those shown in this chapter. The completed winding will then appear as shown in Fig. 273.

While it is intended to reproduce here only the standard diagrams over a wide range of speeds, it is useful to review the general theory of their construction and the simple methods by which any winding may be checked for phase polarity. This is shown in Figs. 274 to 277, inclusive. In Fig. 274 a winding chosen at random is shown "stubbed" into pole-phase groups for a two-phase connection, and in Fig. 276 stubbed for a three-phase connection. To determine the proper connections for the pole-phase groups in a two-phase winding, the rule is to mark on the groups arrows alternating in direction in pairs, *i.e.*, on two successive groups the arrows are clockwise and on the two immediately adjacent the arrows are counter-clockwise. Such arrows, for example, are shown in Fig. 274 just above the windings. If now one end of any group in a phase is chosen as a lead and all the groups are followed through and connected as indicated by the arrows, the connection will be correct. Such a

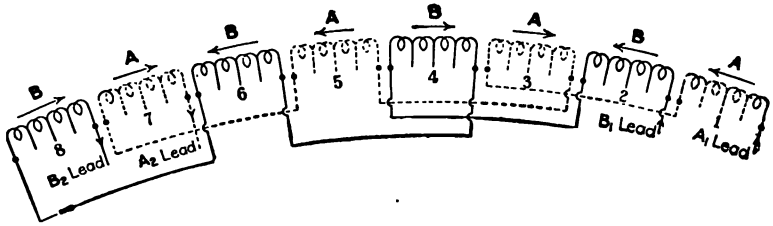


FIG. 274.—Checking a two-phase connection.

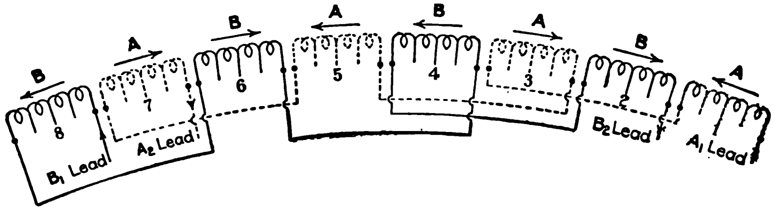


FIG. 275.—Similar to Fig. 274, but "B" phase reversed.

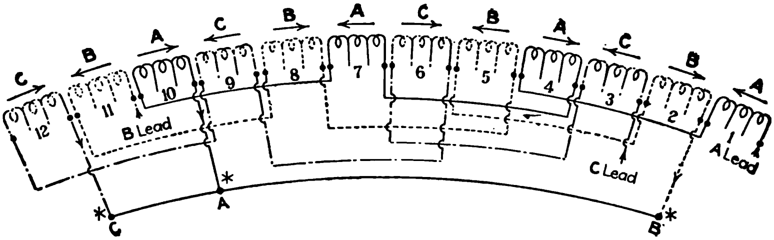


FIG. 276.—Checking a three-phase connection.

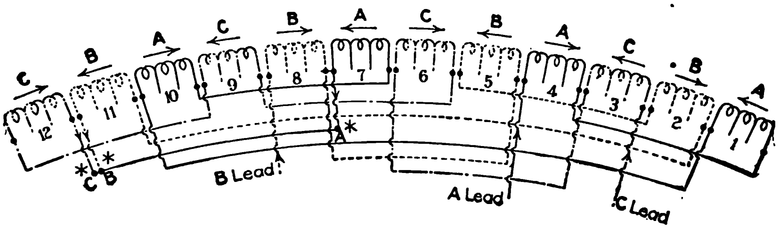


FIG. 277.—Similar to Fig. 276, but leads taken off different groups.

connection is shown in Fig. 274. However, suppose the arrows had alternated in pairs, but started with a different group, as shown just above the windings in Fig. 275. The result is shown in Fig. 275, which is just as correct as Fig. 274, except that the motor would run with the opposite direction of rotation. Since the rotation can be changed by reversing the two leads of either phase outside of the motor, it is evident that the rule using the arrows alternating in pairs is correct in all cases. It should also be noted that it makes no difference from what group the lead is taken, provided all the groups are followed through with the arrows.

In the three-phase machine it is even simpler. The rule in that case is to put arrows on the groups alternating in direction from group to group, as shown in Fig. 276. Any group may then be chosen as a "lead" group or a "star" group so long as the arrows are followed in passing *from the lead to the star* in each phase. Figure 276 shows one arrangement and Fig. 277 another equally correct, and there might be an indefinite number more, simply by choosing the lead from another group and following the arrows through to the star in each phase. Although shown for a developed four-pole winding only, these diagrams may be considered as strictly general, as additional groups may be added to make six, eight, or any other number of poles, and the current passed through them in any order, so long as the phases are kept in the correct rotation, and the current in the right direction, as indicated by the arrows.

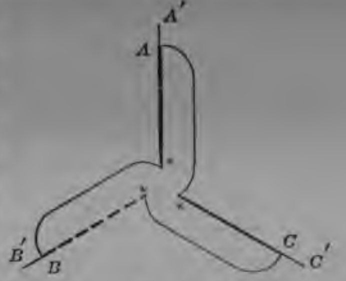


FIG. 278.—Changing from star to delta.

In case a delta connection is wanted instead of a star, check the connections through as for a star and then connect the *A* star to the *B* lead, the *B* star to the *C* lead, and the *C* star to the *A* lead, as shown in Fig. 278; or connect the *A* lead to the *B* neutral, the *B* lead to the *C* neutral, and the *C* lead to the *A* neutral. The three new leads will be taken from the corners of the delta so formed.

CHAPTER XIV

WAVE DIAGRAMS

With the exception of one or two diagrams briefly mentioned in Chapter III practically all the diagrams discussed in the book and those shown in Chapter XIII are of the type usually employed for the stator winding. These could be used for the rotor also so far as any electrical considerations are concerned. It will be noticed, however, when the cross connections are considered that they are not arranged with mechanical symmetry around the machine and, hence, if a diagram of this type were used on the rotor there would be a tendency toward mechanical unbalance which would set up mechanical vibration when the rotor was running at full speed. In addition to this objection, cross connections of this type are difficult to arrange and secure in place on the rotor on account of their irregular shape and the considerable space which they occupy. For this reason, so-called "wave" diagrams, as shown in Figs. 279 to 289 inclusive, are ordinarily employed on the rotor. They are of the old, well known D. C. armature type sometimes called "progressive" or "retrogressive" windings. On examination they will be found to be very regular mechanically and distributed with practically perfect symmetry around the machine. They have also the advantage of requiring a minimum of cross connections—these being reduced to the three leads to the collector rings, one jumper joining the two halves of each phase winding and in case of a star connection the additional "star ring" with 3 taps, one to each phase.

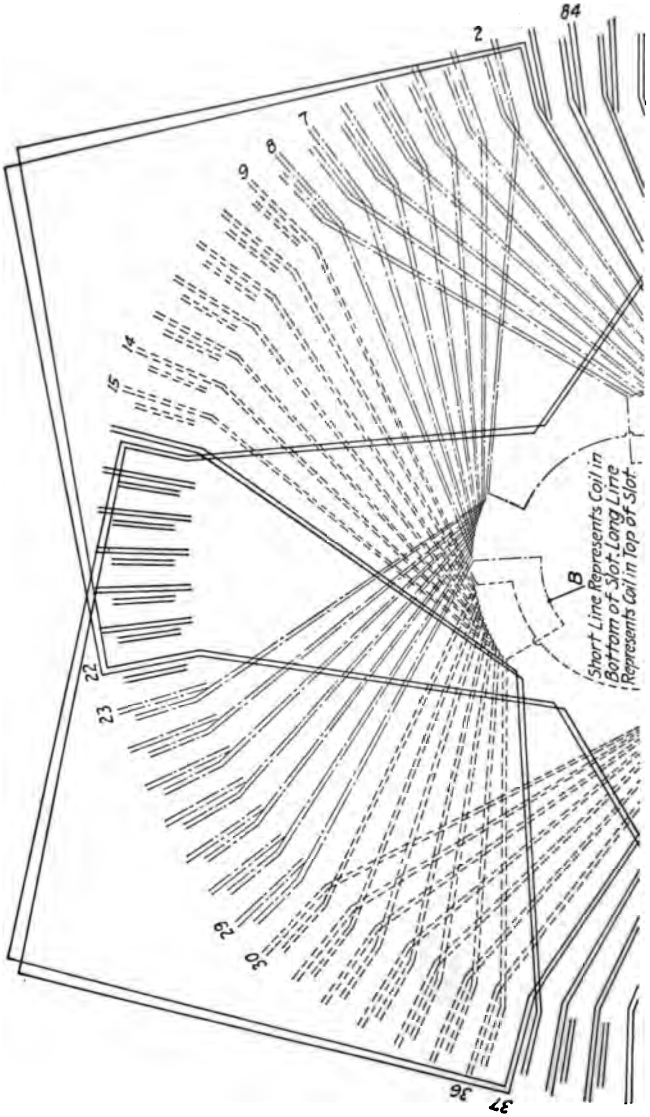
The rotor winding is practically always three phase and may be connected either star or delta depending on the voltage which is desired between the collector rings. A star connection would give 1.73 times the voltage between rings that would exist with a delta connection. This would mean a smaller current with consequently smaller rings and brushes but would, in turn, require insulation for the higher voltage throughout the winding and between collector rings.

A two phase winding is practically never used on the rotor as it would require four collector rings and an added set of brushes. When the rotating magnetic field is set up by the primary winding it is practically the same whether created by two phase or three phase current and is the same as if it were set up by D. C. as described in Chapter II. Hence, when the field is set up it can act on a three phase rotor as well as a two phase and advantage is taken of this fact to reduce the required number of collector rings and brush holders to a minimum.

In checking over these wave diagrams it will be noticed that the number of slots is always a multiple of the number of phases times the number of poles and hence an even figure whereas a true "progressive" or "retrogressive" winding as ordinarily used on direct current for a two coil per slot winding must satisfy the expression

$$\frac{\textit{Number of slots} \pm 1}{\textit{Pairs of poles}} = \text{an integral number}$$

in order that the conductor after passing around the machine may fall into the slot adjacent to the one in which it started. In the diagrams, Figs. 279 to 289, this is avoided mechanically in the following way: Since the total number of slots is a multiple of the number of poles and since the throw of the coil on a rotor is exactly pitch the natural result would be that after once passing around the rotor the conductor would fall again into slot No. 1 in which it started. For example assume a 72 slot rotor wound for 8 poles. Starting in the bottom of slot No. 1 the conductor passes successively through the top of slot 10, bottom of 19, top of 28, bottom of 37, top of 46, bottom of 54, top of 63 and would again fall into the bottom of slot No. 1. However, the winder at this point bends the coil to one slot shorter throw and arbitrarily places it in the bottom of slot 72 and again around the rotor when he throws it in slot 71 and winds a third time around the rotor and stops when he comes out of the top of slot No. 61. He then leaves the two ends of this section of winding, viz., bottom of slot No. 1 and top of slot No. 61. This completes one sixth of the winding and he proceeds to complete the other five sixths in the same manner. At the finish there are left six complete sections and twelve loose ends or leads. The winder then takes the lead from the top of slot No. 61 described above and looks for the section of the winding which lies in the tops of slots


84
2
7
8
9
14
15
22
23
29
30
36
37
B
Short Line Represents Coil in Bottom of Slot. Long Line Represents Coil in Top of Slot.

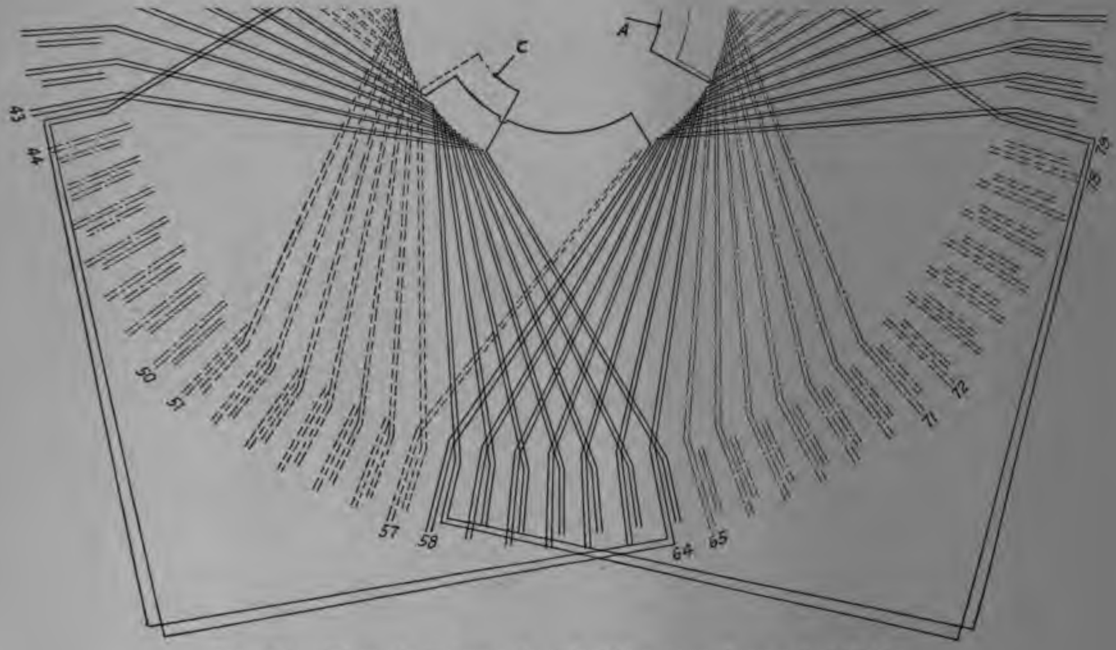
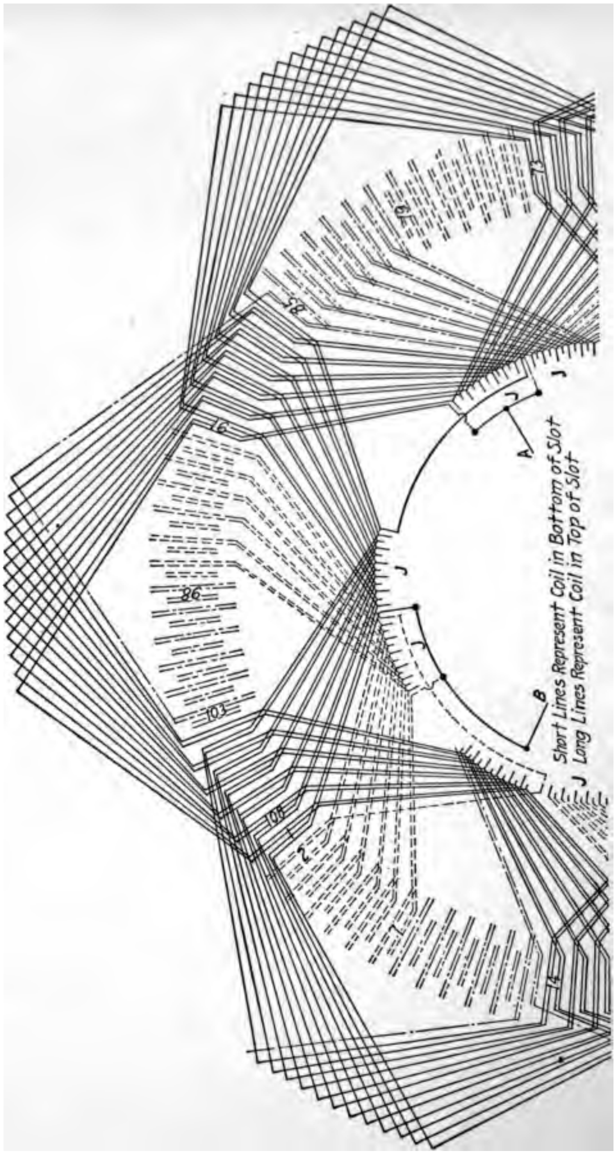


FIG. 279.—Three phase, four pole, series delta wave diagram for 84 slots.


73
79
85
91
86
103
108
1
2
7
14
J
J
J
J
J
A
B
Short Lines Represent Coil in Bottom of Slot
Long Lines Represent Coil in Top of Slot

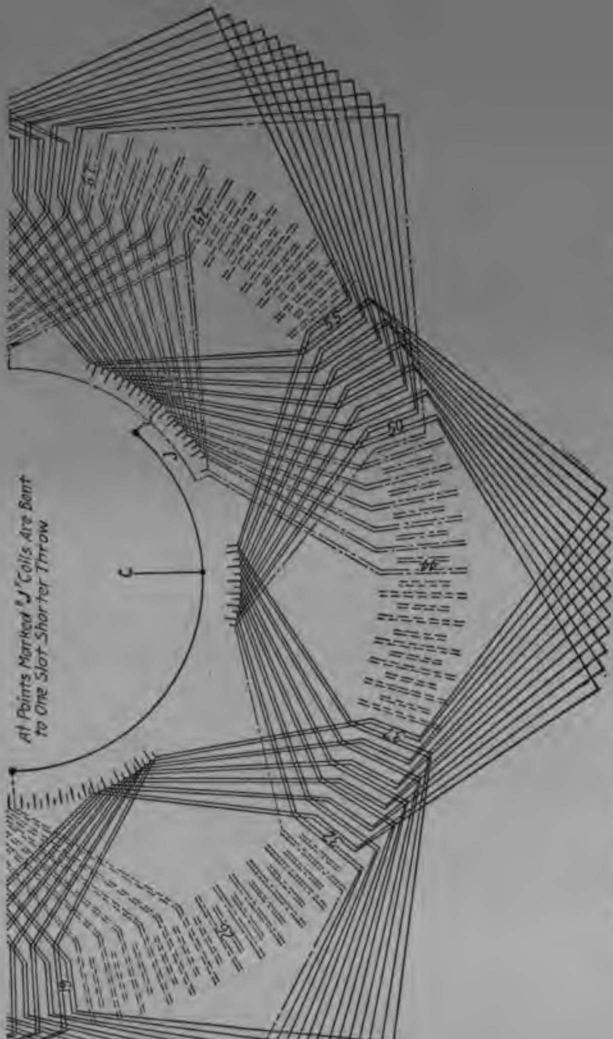
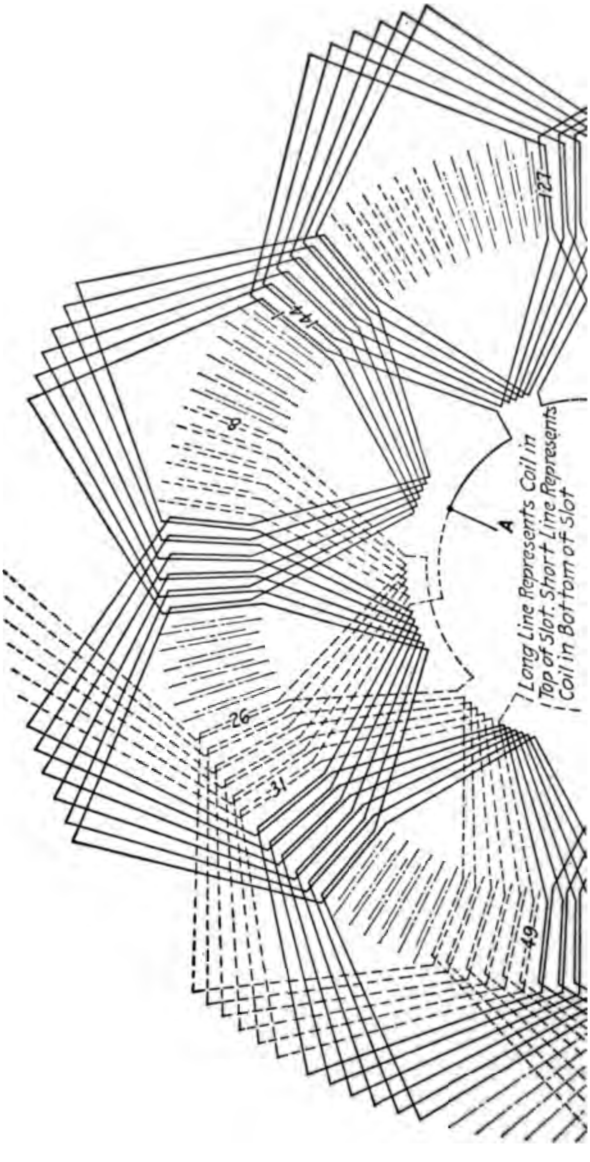


Fig. 280.—Three phase, six pole, series delta wave diagram for 108 slots.


127
144
8
A
26
31
49
Long Line Represents Coil in Top of Slot. Short Line Represents Coil in Bottom of Slot

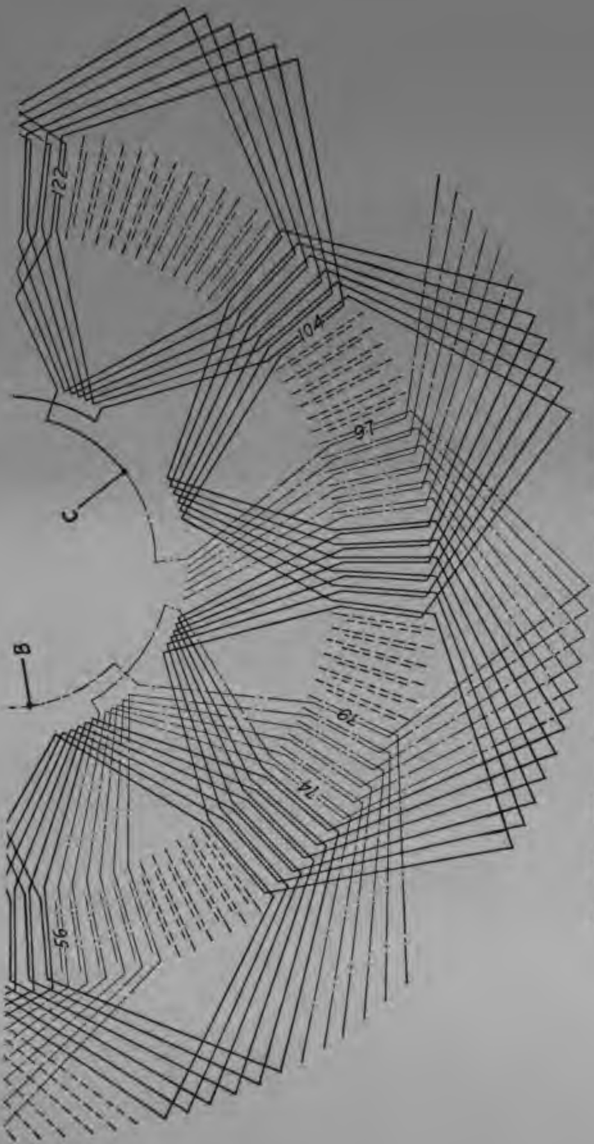
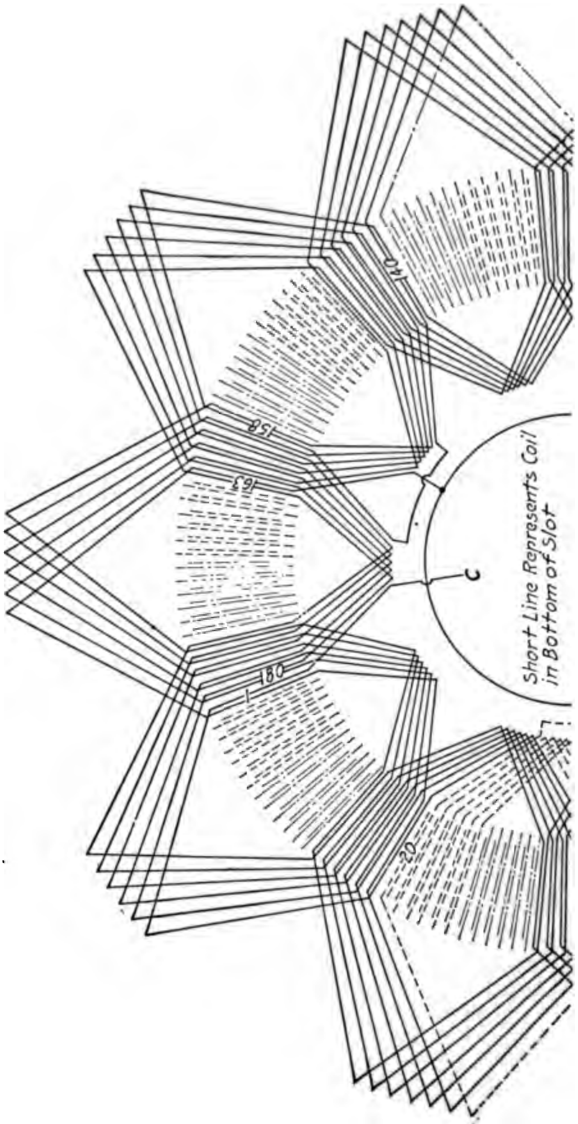


FIG. 281.—Three phase, eight pole, series delta, wave diagram for 144 slots.


140
158
163
180
1
20
C
Short Line Represents Coil in Bottom of Slot

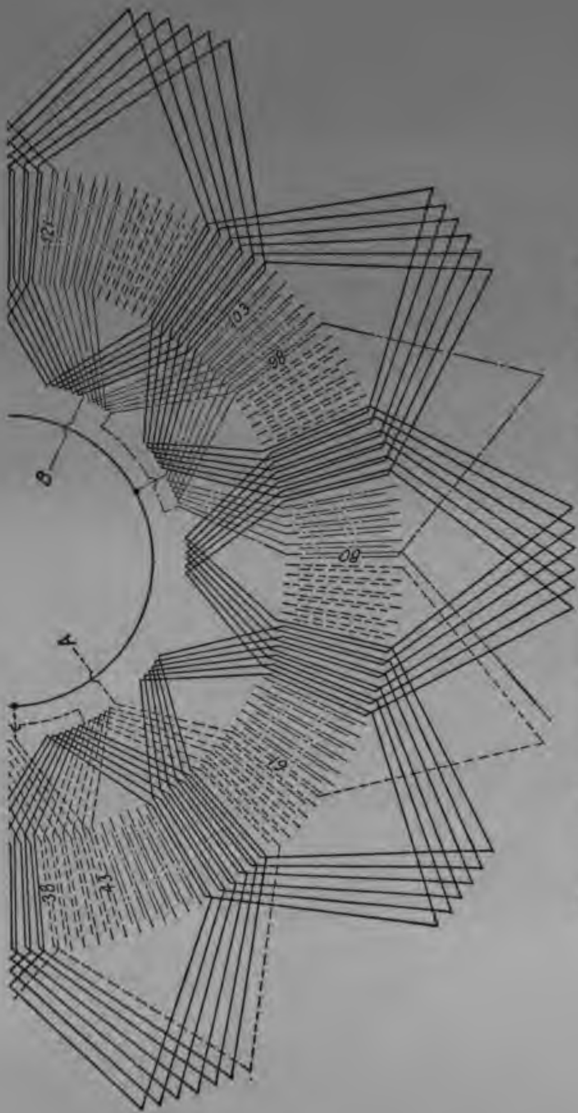
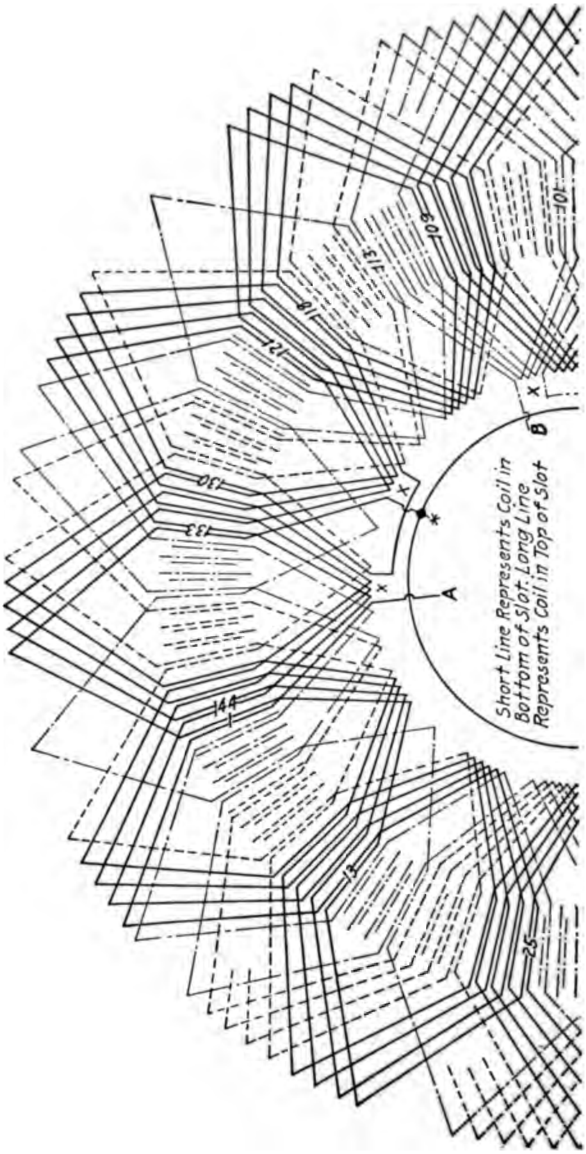


FIG. 282.—Three phase, ten pole, series star wave diagram for 180 slots.


101
109
113
118
121
130
133
144
1
13
25
x
x
x
B
A
*
Short Line Represents Coil in
Bottom of Slot; Long Line
Represents Coil in Top of Slot

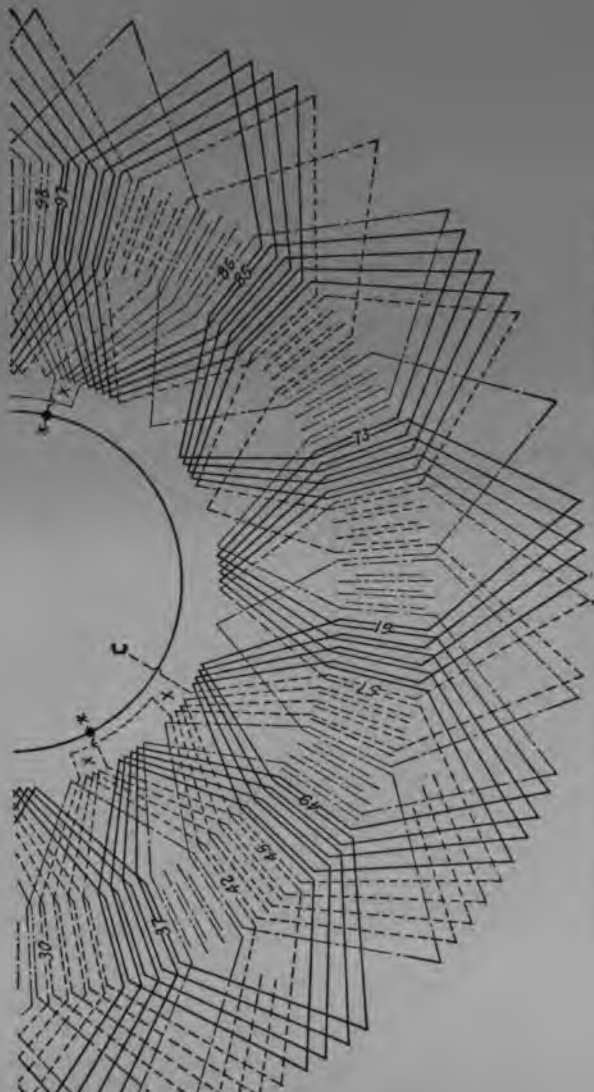
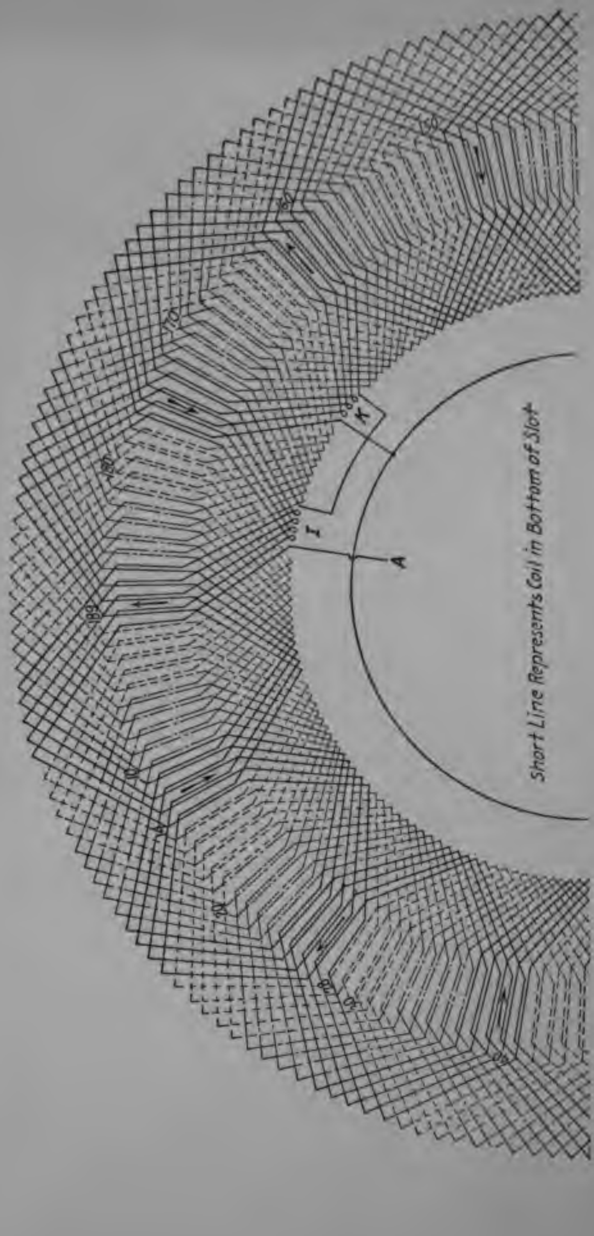


FIG. 283.—Three phase, twelve pole, series star, wave diagram for 144 slots.



Short Line Represents Coil in Bottom of Slot

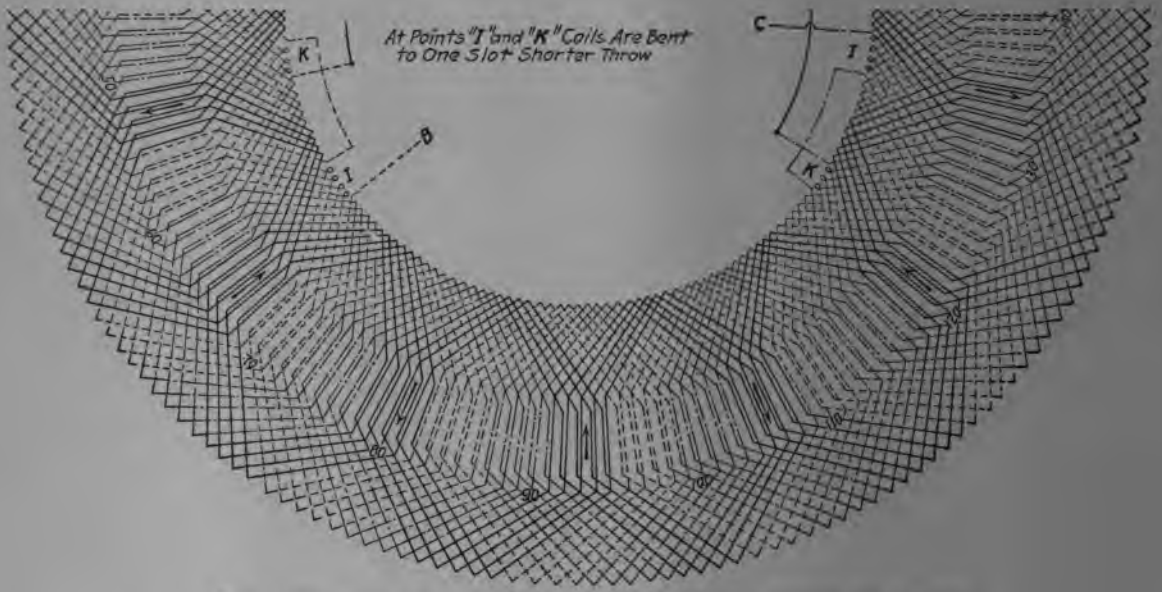
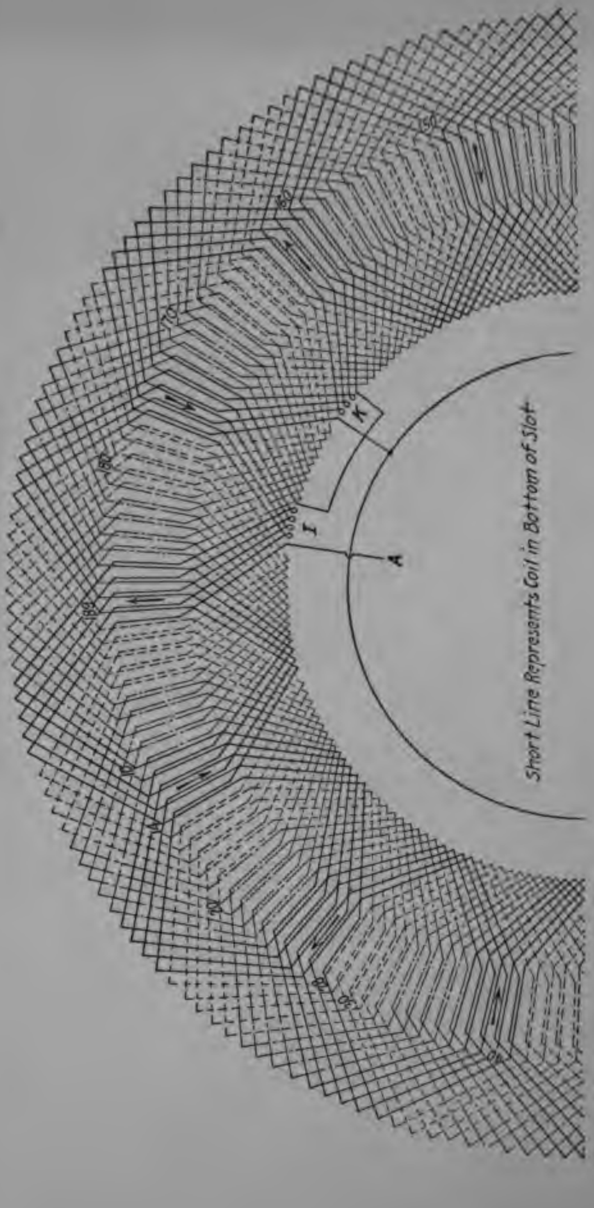


FIG. 284.—Three phase, fourteen pole, series star, wave diagram for 189 slots.



Short Line Represents Coil in Bottom of Slot

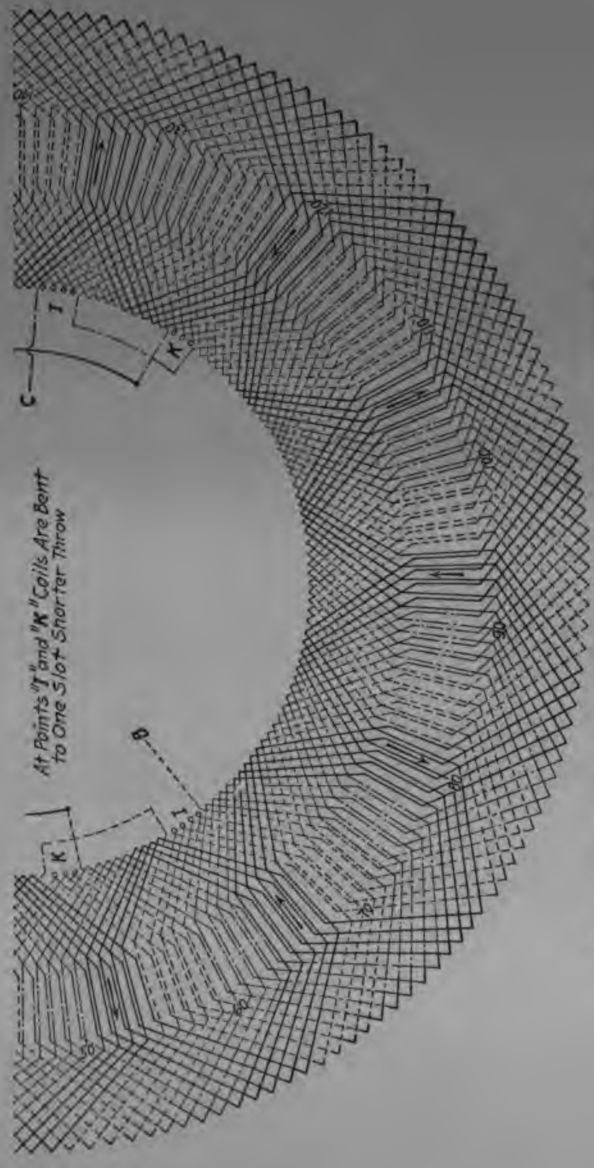
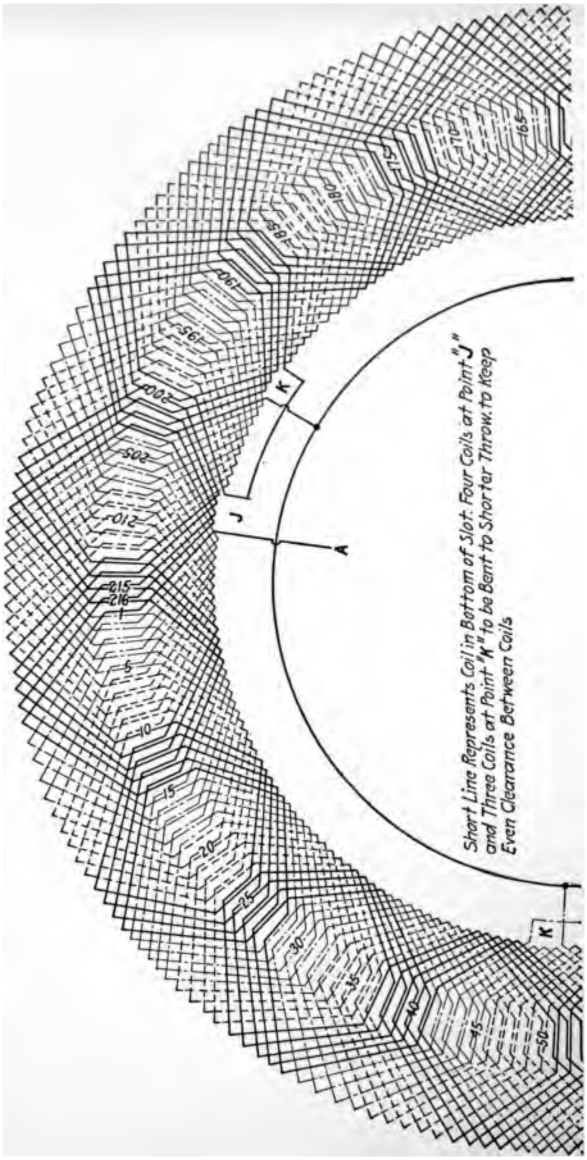


Fig. 284.—Three phase, fourteen pole, series star, wave diagram for 189 slots.



Short Line Represents Coil in Bottom of Slot. Four Coils at Point "J" and Three Coils at Point "K" to be Bent to Shorter Throw to Keep Even Clearance Between Coils

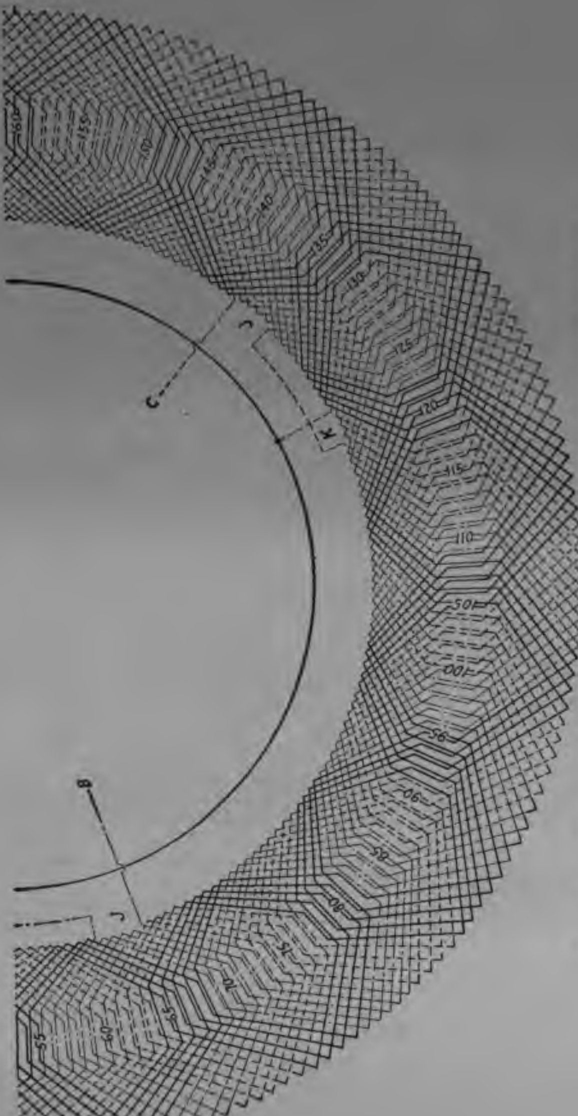
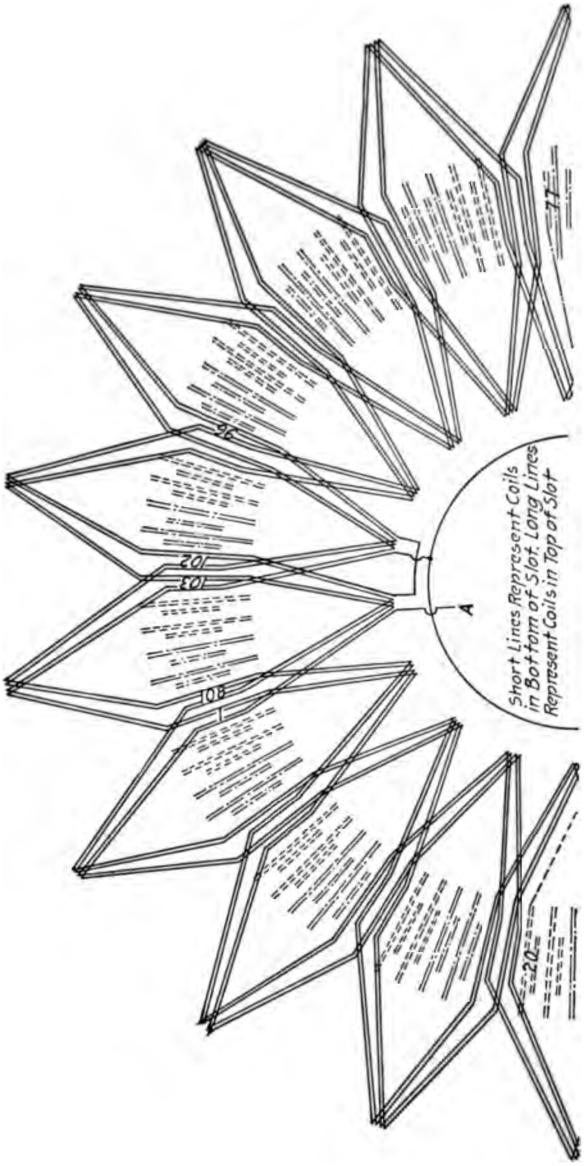


FIG. 285.—Three phase, sixteen pole, series star, wave diagram for 216 dots.


Short Lines Represent Coils in Bottom of Slot, Long Lines Represent Coils in Top of Slot
A
96
102
103
108
1
77
20

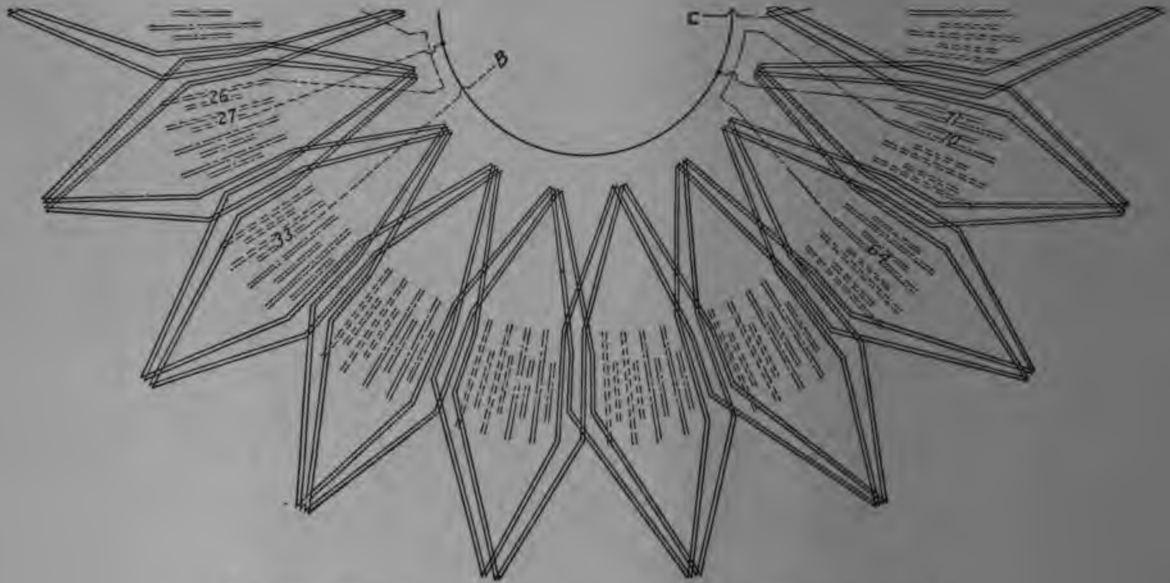
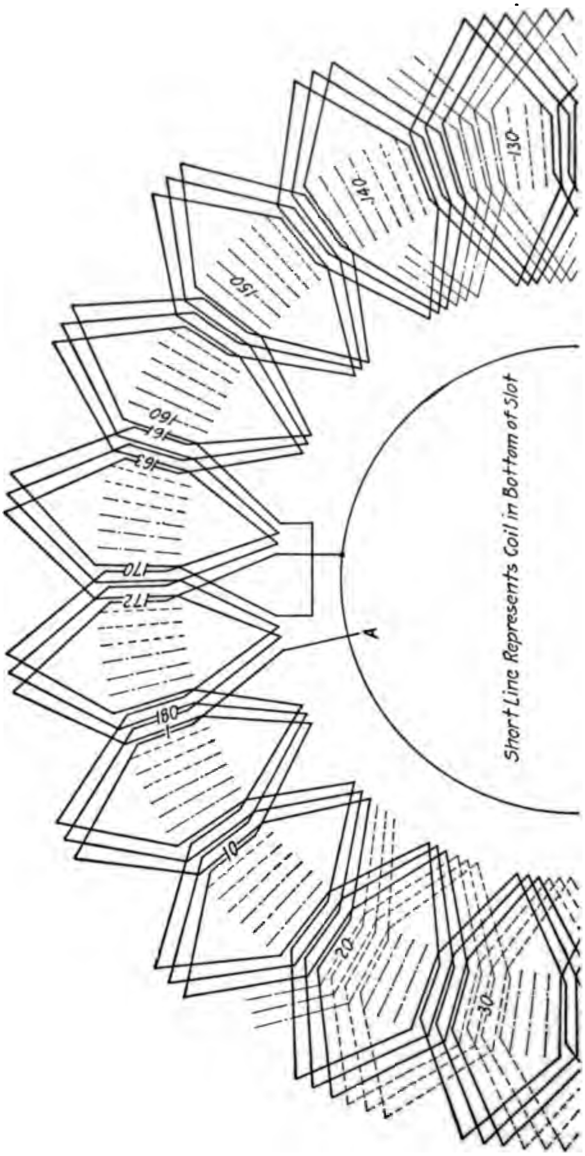


FIG. 286.—Three phase, eighteen pole, series star, wave diagram for 108 slots.


130
140
150
160
161
163
170
172
A
180
1
10
20
30
Short Line Represents Coil in Bottom of Slot

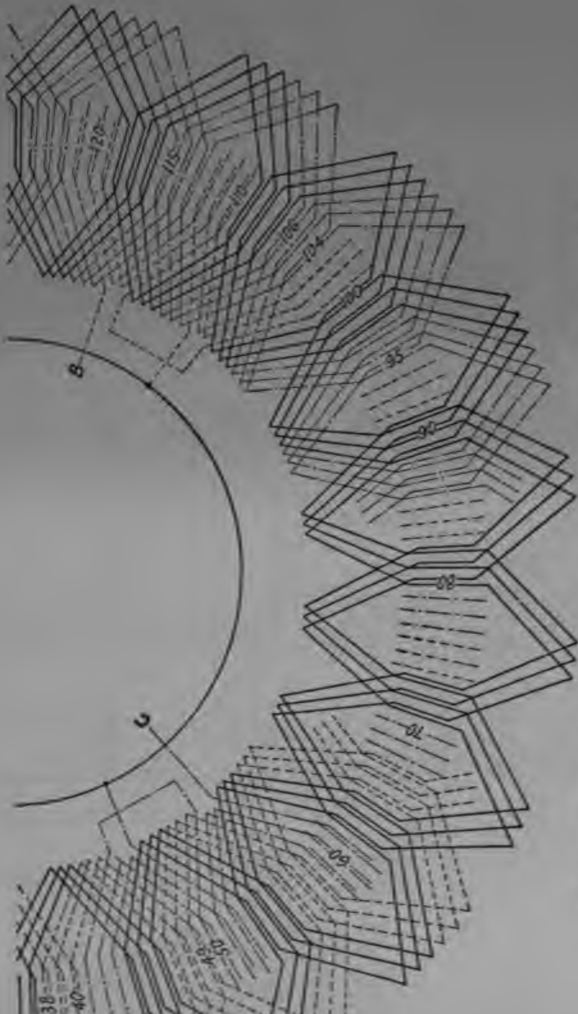
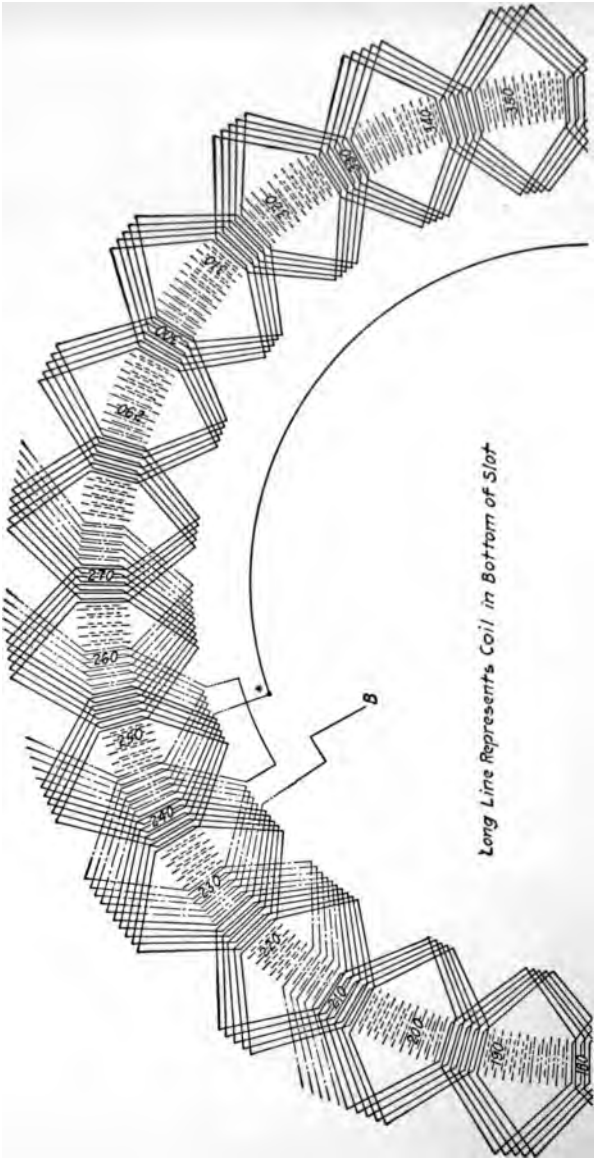


Fig. 287.—Three phase, twenty pole, series star, wave diagram for 180 slots.


350
340
330
320
310
300
290
270
260
250
240
230
220
210
200
190
180
B
Long Line Represents Coil in Bottom of Slot

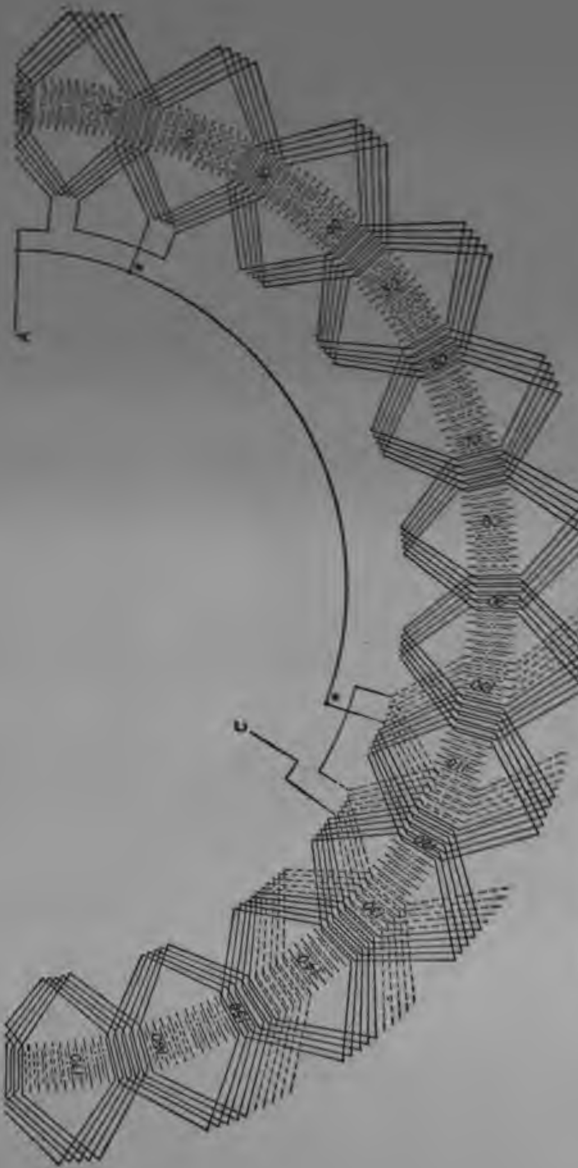
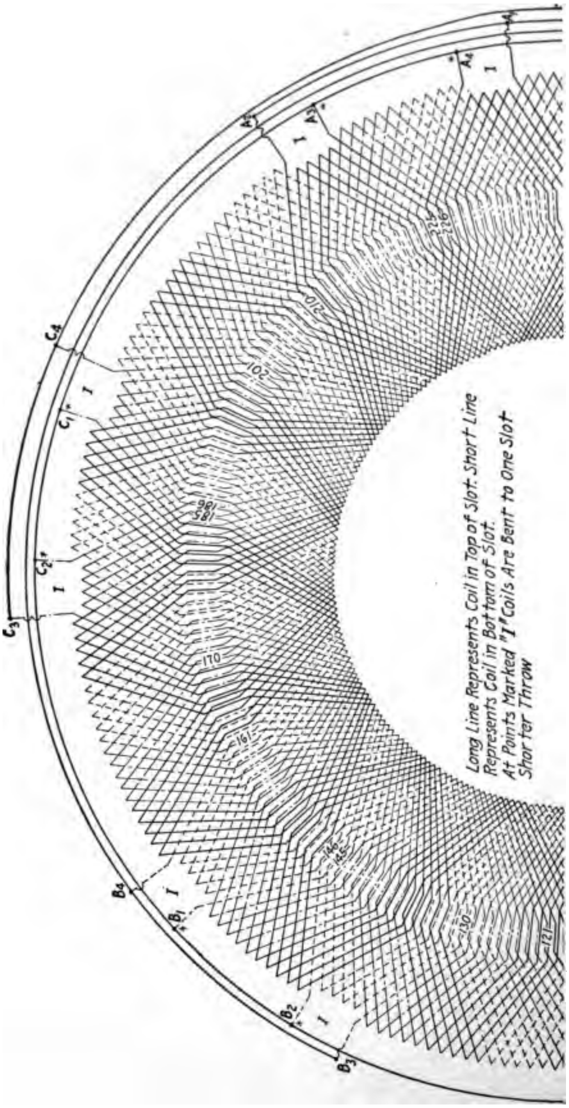


FIG. 288.—Three phase, twenty-four pole, series star, wave diagram for 360 slots.



Long Line Represents Coil in Top of Slot. Short Line Represents Coil in Bottom of Slot. At Points Marked "I" Coils Are Bent to One Slot Shorter Throw

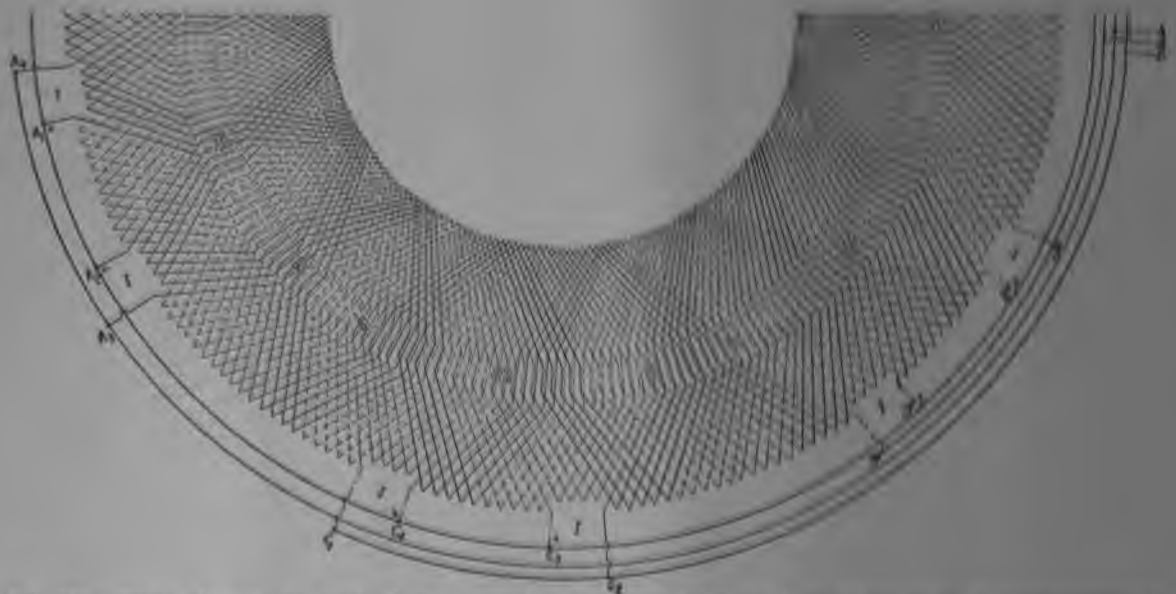


FIG. 289.—Special diagram illustrating how a wave winding is paralleled three phase, sixteen poles, 240 slots connected four parallel star.

1–72–71, etc. Having located this section which may be called section No. 4, the end of section No. 1 is connected to the end of No. 4 so that the completed phase will have passed three times around the armature clockwise and three times counter-clockwise. This is very similar to the case explained by Figs. 45, 46, and 47 in Chapter III. A little study of the diagrams, Figures 279 and 289, will show how this is done. After the three separate phases are complete they are connected in star or delta and the leads brought out as shown in the diagrams.

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