HANDBOOK OF POLYPHASE ELECTRIC MOTORS

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PREFACE

Strictly speaking, the first requirement of a satisfactory motor installation is a good motor, properly selected for the application and correctly installed.

Second, the motor must be properly maintained over the period of its use to establish what is commonly referred to as "preventive maintenance."

The third requisite of a satisfactory motor installation is the ability to quickly troubleshoot any problem that might develop so that the machine may be repaired and promptly put back into service.

This book is designed to cover all three of these functions in a brief and concise form so that persons involved with polyphase motors may quickly find the answer to many problems that arise in the daily work routine.

All the material assembled in this book is designed to be of a general nature to cover all types of polyphase motors and their related components. This will naturally lead the reader to use this manual only as a guide for performing the various tasks of installing and maintaining polyphase motor systems, rather than as a complete instruction manual. For any specific piece of equipment, it is suggested that the manufacturer's recommendations be followed.

JOHN E. TRAISTER

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chapter 1

INTRODUCTION TO POLYPHASE MOTORS

In basic terms, electric motors convert electric energy into the productive power of rotary mechanical force. This capability finds application in unlimited ways, from explosion-proof, water-cooled motors for underground mining to induced-draft fan motors for power generation; from adjustable-frequency drives for waste and water treatment pumping to eddy-current clutches for automobile production; from direct-current drive systems for paper production to photographic film manufacturing; from rolled-shell shaftless motors for machine tools to large outdoor motors for crude-oil pipelines; from mechanical variable-speed drives for woodworking machines to complex adjustable-speed drive systems for textiles. All of these and more represent the scope of electric motor participation in powering and controlling the machines and processes of industries throughout the world.

POLYPHASE MOTORS

Three-phase motors offer extremely efficient and economical application and are usually the preferred type for commercial and industrial applications when three-phase service is available. In fact, the great bulk of motors sold are standard ac three-phase motors. These motors are available in ratings from fractional horsepower up to thousands of horsepower in practically every standard voltage and frequency. There are few applications for which the three-phase motor cannot be put to use.

Three-phase motors are noted for their relatively constant speed characteristic and are available in designs giving a variety of torque characteristics; that is, some have a high starting torque and others a low starting torque. Some are designed to draw a normal starting current; others, a high starting current.

A typical three-phase motor is shown in Fig. 1–1. Note that the three main parts are the *stator, rotor,* and *end plates.* It is very similar in construction to conventional split-phase motors except that the three-phase motor has no centrifugal switch.

The stator shown in Fig. 1–2 consists of a steel frame and a laminated iron core and winding formed of individual coils placed in slots. The rotor may be a squirrel-cage or wound-rotor type. Both types contain a laminated core pressed onto a shaft. The squirrel-cage rotor is shown in Fig. 1–3 and is similar to a split-phase motor. The wound rotor is shown in Fig. 1–4 and has a winding on the core that is connected to three slip rings mounted on the shaft.

The end plates or brackets are bolted to each side of the stator frame and contain the bearings in which the shaft revolves. Either ball bearings or sleeve bearings are used.

Induction motors, both single-phase and polyphase, get their name from the fact that they utilize the principle of electromagnetic induction. An induction motor has a stationary part, or stator, with windings connected to the AC supply, and a rotation part, or rotor, which contains coils or bars. There is no electrical connection between the stator and rotor. The magnetic

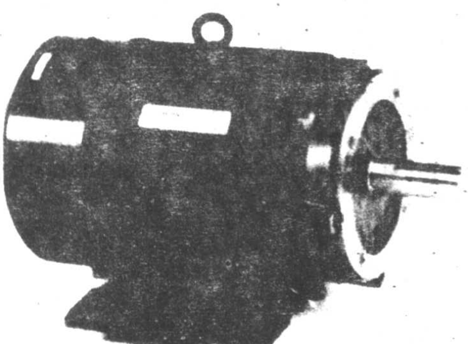

Figure 1–1 Typical three-phase motor

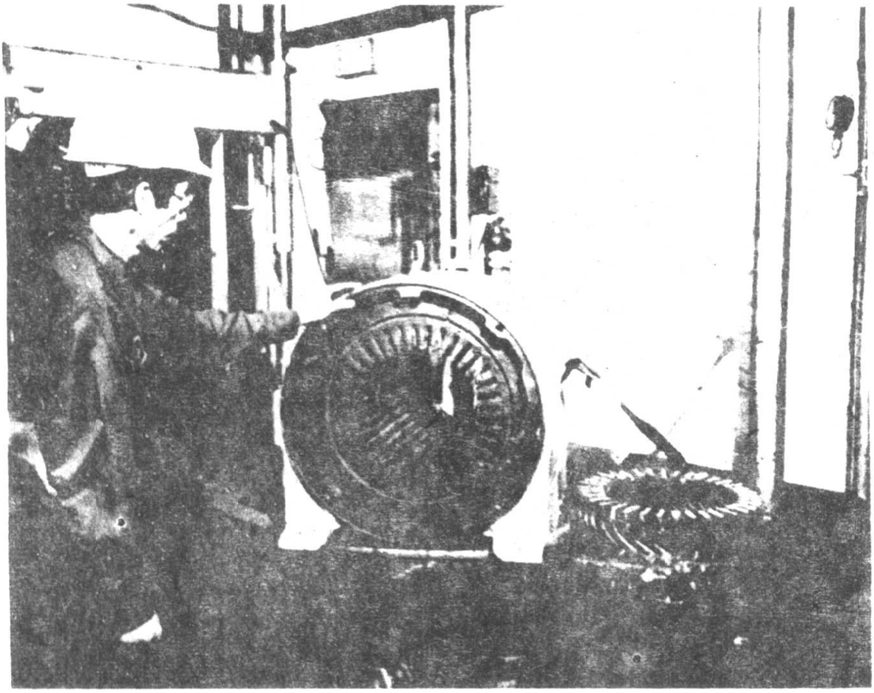

Figure 1-2 Stator consisting of steel frame, laminated iron core, and winding formed of individual coils placed in slots

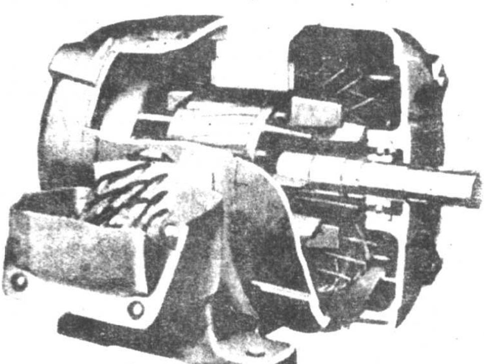

Figure 1-3 Squirrel cage rotor, similar to split-phase rotor (Courtesy Westinghouse)

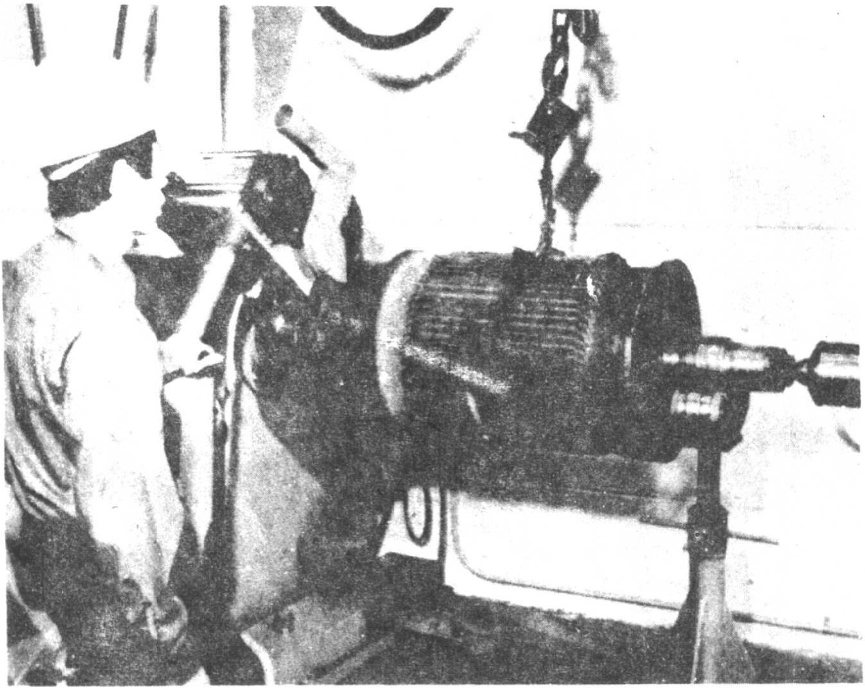

Figure 1–4 Typical wound rotor

field produced in the stator windings induces a voltage in the rotor coils or bars.

Since the stator windings act in the same way as the primary winding of a transformer, the stator of an induction motor is sometimes called the *primary*. Similarly, the rotor is called the *secondary* because it carries the induced voltage in the same way as the secondary of a transformer.

The magnetic field necessary for induction to take place is produced by the stator windings. Therefore, the induction-motor stator is often called the *field* and its windings are called *field windings*.

The terms primary and secondary relate to the electrical characteristics and the terms stator and rotor to the mechanical features of induction motors. The rotor transfers the rotating motion to its shaft, and the revolving shaft drives a mechanical load or a machine, such as a pump, spindle, or clock.

Commutator segments, which are essential parts of DC motors, are not needed on induction motors. This simplifies greatly the design and the maintenance of induction motors as compared to DC motors.

The turning of the rotor in an induction motor is due to induction. The rotor, or secondary, is not connected to any source of voltage. If the magnetic field of the stator, or primary, revolves, it will induce a voltage in the rotor, or secondary. The magnetic field produced by the induced voltage acts in such a way that it makes the secondary follow the movement of the primary field.

The stator, or primary, of the induction motor does not move physically. The movement of the primary magnetic field must thus be achieved electrically. A rotating magnetic field is made possible by a combination of two or more AC voltages that are out of phase with each other and applied to the stator coils. Direct current will not produce a rotating magnetic field. In three-phase induction motors, the rotating magnetic field is obtained by applying a three-phase system to the stator windings.

The direction of rotation of the rotor in an AC motor is the same as that of its rotating magnetic field. In a three-phase motor the direction can be reversed by interchanging the connections of any two supply leads. This interchange will reverse the sequence of phases in the stator, the direction of the field rotation, and therefore the direction of rotor rotation.

SYNCHRONOUS MOTORS

A synchronous polyphase motor has a stator constructed in the same way as the stator of a conventional induction motor. The iron core has slots into which coils are wound, which are also arranged and connected in the same way as the stator coils of the induction motor. These are in turn grouped to form a three-phase connection, and the three free leads are connected to a three-phase source. Frames are equipped with air ducts, which aid the cooling of the windings, and coil guards protect the winding from damage.

The rotor of a synchronous motor carries poles that project toward the armature; they are called *salient poles*. The coils are wound on laminated pole bodies and connected to slip rings on the shaft. A squirrel-cage winding for starting the motor is embedded in the pole faces.

The pole coils are energized by direct current, which is usually supplied by a small DC generator called the *exciter*. This exciter may be mounted directly on the shaft to generate DC voltage, which is applied through brushes to slip rings. On low-speed synchronous motors, the exciter is normally belted or of a separate high-speed motor-driven type.

The dimensions and construction of synchronous motors vary greatly depending on the rating of the motors. However, synchronous motors for industrial power applications are rarely built for less than 25 hp. In fact, most are 100 hp or more. All are polyphase motors when built in this size. Vertical and horizontal shafts with various bearing arrangements and various enclosures cause wide variations in the appearance of the synchronous motor.

Synchronous motors are used in electrical systems where there is need for improvement in power factor or where low power factor is not desirable. This type of motor is especially adapted to heavy loads that operate for long periods of time without stopping, such as for air compressors, pumps, ship propulsion, and the like.

The construction of the synchronous motor is welll adapted for high voltages, as it permits good insulation. Synchronous motors are frequently used at 2300 volts or more. Its efficient slow-running speed is another advantage.

DIRECT-CURRENT MOTORS

A direct-current motor is a machine for converting DC electrical energy into rotating mechanical energy. The principle underlying the operation of a DC motor is called *motor action* and is based on the fact that when a wire carrying current is placed in a magnetic field, a force is exerted on the wire, moving it through the magnetic field. There are three elements of motor action as it takes place in a DC motor:

1. Many coils of wire are wound on a cylindrical rotor or armature on the shaft of the motor.
2. A magnetic field necessary for motor action is created by placing fixed electromagnetic poles around the inside of the cylindrical motor housing. When current is passed through the fixed coils, a magnetic field is set up without the housing. Then, when the armature is placed inside the motor housing, the wires of the armature coils will be situated in the field of magnetic lines of force set up by the electromagnetic poles arranged around the stator. The stator is the stationary cylindrical part of the motor.
3. The shaft of the armature is free to rotate because it is supported at both ends by bearing brackets. Freedom of rotation is assured by providing clearance between the rotor and the faces of the magnetic poles.

Shunt-wound DC motors. In this type of motor, the strength of the field is not affected appreciably by a change in the load, so a relatively constant speed is obtainable. This type of motor may be used for the operation of machines that require an approximate constant speed and that impose low starting torque and light overload on the motor.

Series-wound DC motors. In motors of this type, any increase in load results in more current passing through the armature and the field windings. As the field is strengthened by this increased current, the motor speed decreases. Conversely, as the load is decreased, the field is weakened and the speed increases, and at very light loads speed may become excessive. For this reason, series-wound motors are usually directly connected or geared to the load to prevent runaway. The increase in armature current with an increasing load produces increased torque, so the series-wound motor is particularly suited to heavy starting duty and where severe overloads may be expected. Its speed may be adjusted by means of a variable resistance placed in series with the motor, but due to variation with load, the speed cannot be held at any constant value. This variation of speed with load becomes greater as the speed is reduced. Use of this motor is normally limited to traction and lifting service.

Compound-wound motors. In this type of motor, the speed variation due to the load changes is much less than in the series-wound motor, but greater than in the shunt-wound motor. It also has a greater starting torque than the shunt-wound motor and is able to withstand heavier overloads. However, it has a narrower adjustable-speed range. Standard motors of this type have a cumulative-compound winding, the differential-compound winding being limited to special applications. They are used where the starting load is very heavy or where the load changes suddenly and violently, as with reciprocating pumps, printing presses, and punch presses.

Brushless DC motors. The brushless DC motor was developed to eliminate commutator problems in missiles and spacecraft in operation above the earth's atmosphere. Two general types of brushless motors are in use, the inverter-induction motor and a DC motor with an electronic commutator.

The inverter-induction motor uses an inverter that uses the motor windings as the usual filter. The operation is square-wave, and the combined efficiencies of the inverter and induction motor are at least as high as for a DC motor alone. In all cases, the motors must be designed to saturate so that starting current is limited; otherwise, the transistors or silicon-controlled rectifiers in the inverted will be overloaded.

MOTOR ENCLOSURES

Electric motors differ in construction and appearance depending on the type of service for which they are to be used. Open and closed frames are quite common. In an open enclosure, the motor's parts are covered for protection, but air can freely enter the enclosure. Further designations for this type of enclosure include drip proof, weather-protected, and splash proof.

Totally enclosed motors have airtight enclosures. They may be fan-cooled or self-ventilated. An enclosed motor equipped with a fan has the fan as an integral part of the machine, but external to the enclosed parts. In the self-ventilated enclosure, no external means of cooling is provided.

The type of enclosure to use depends on the ambient and surrounding conditions. In a drip-proof machine, for example, all ventilating openings are constructed so that drops of liquid or solid particles falling on the machine at an angle of not greater than 15 degrees from the vertical cannot enter the machine, directly or by striking and running along a horizontal or inclined surface of the machine. The application of this machine lends itself to areas where liquids are processed.

An open motor having all air openings that give direct access to live or rotating parts, other than the shaft, limited in size by the design of the parts or guarded by screen to prevent accidental contact with such parts is classified as a *drip-proof, fully guarded* machine. In such enclosures, openings shall not permit the passage of a cylindrical rod $\frac{1}{2}$ inch in diameter. Where the distance from the guard to the live rotating parts is more than 4 inches, the openings shall not permit the passage of a cylindrical rod $\frac{3}{4}$ inch in diameter.

There are other types of drip-proof machines for special applications, such as externally ventilated and pipe ventilated, which as the names imply are either ventilated by a separate motor-driven blower or cooled by ventilating air from inlet ducts or pipes.

An enclosed motor whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor within the motor and to prevent the ignition of this gas or vapor surrounding the machine is designated as an *explosion-proof* (XP) motor.

Hazardous atmospheres (requiring XP enclosures) of both a gaseous and dusty nature are classified by the NE Code as follows:

- **Class I, Group A:** atmospheres containing acetylene.
- **Class I, Group B:** atmospheres containing hydrogen gases or vapors or equivalent hazards such as manufactured gas.
- **Class I, Group C:** atmospheres containing ethyl ether vapor.
- **Class I, Group D:** atmospheres containing gasoline, petroleum, naptha, alcohols, acetone, lacquer-solvent vapors, and natural gas.
- **Class II, Group E:** atmospheres containing metal dust.
- **Class II, Group F:** atmospheres containing carbon-black, coal, or coke dust.
- **Class II, Group G:** atmospheres containing grain dust.

The proper motor enclosure must be selected to fit the particular atmosphere. However, explosion-proof equipment is not generally available for Class I, Groups A and B, and it is therefore necessary to isolate motors from areas containing those hazards.

SELECTION OF ELECTRIC MOTORS

Each type of motor has its particular field of usefulness. Because of its simplicity, economy, and durability, the induction motor is more widely used for industrial purposes than any other type of AC motor, especially if a high-speed drive is desired.

If AC power is available, all drives requiring constant speed should use squirrel-cage induction or synchronous motors because of their ruggedness and lower cost. Drives requiring varying speeds, such as fans, blowers, or pumps, may be driven by wound-rotor induction motors. However, if there are machine tools or other machines requiring adjustable speed or a wide range of speed control, it is probably desirable to install DC motors on such machines and supply them from the AC system by motor-generator sets or electronic rectifiers.

Practically all constant-speed machines may be driven by AC squirrel-cage motors because they are made with a variety of speed and torque characteristics. When large motors are required or when power supply is limited, the wound-rotor motor is used even for driving constant-speed machines. A wound-rotor motor, with its controller and resistance, can develop full-load torque at starting with not more than full-load torque at starting, depending on the type of motor and the starter used.

For varying-speed service, wound-rotor motors with resistance control are used for fans, blowers, and other apparatus for continuous duty, and for cranes, hoists, and other installations for intermittent duty. The controller and resistors must be properly chosen for the particular application.

Synchronous motors may be used for practically any constant-speed drive requiring about 100 hp or over.

Cost is an important consideration where more than one type of AC motor is applicable. The squirrel-cage motor is the least expensive AC motor of the three types considered and requires very little control equipment. The wound-rotor is more expensive and requires additional secondary control. The synchronous motor is even more expensive and requires a source of DC excitation, as well as special synchronizing control, to apply the DC power at the correct instant. When very large machines are involved, as, for example, 1000 hp or over, the cost picture may change considerably and should be checked on an individual basis.