E·M Synchronizer

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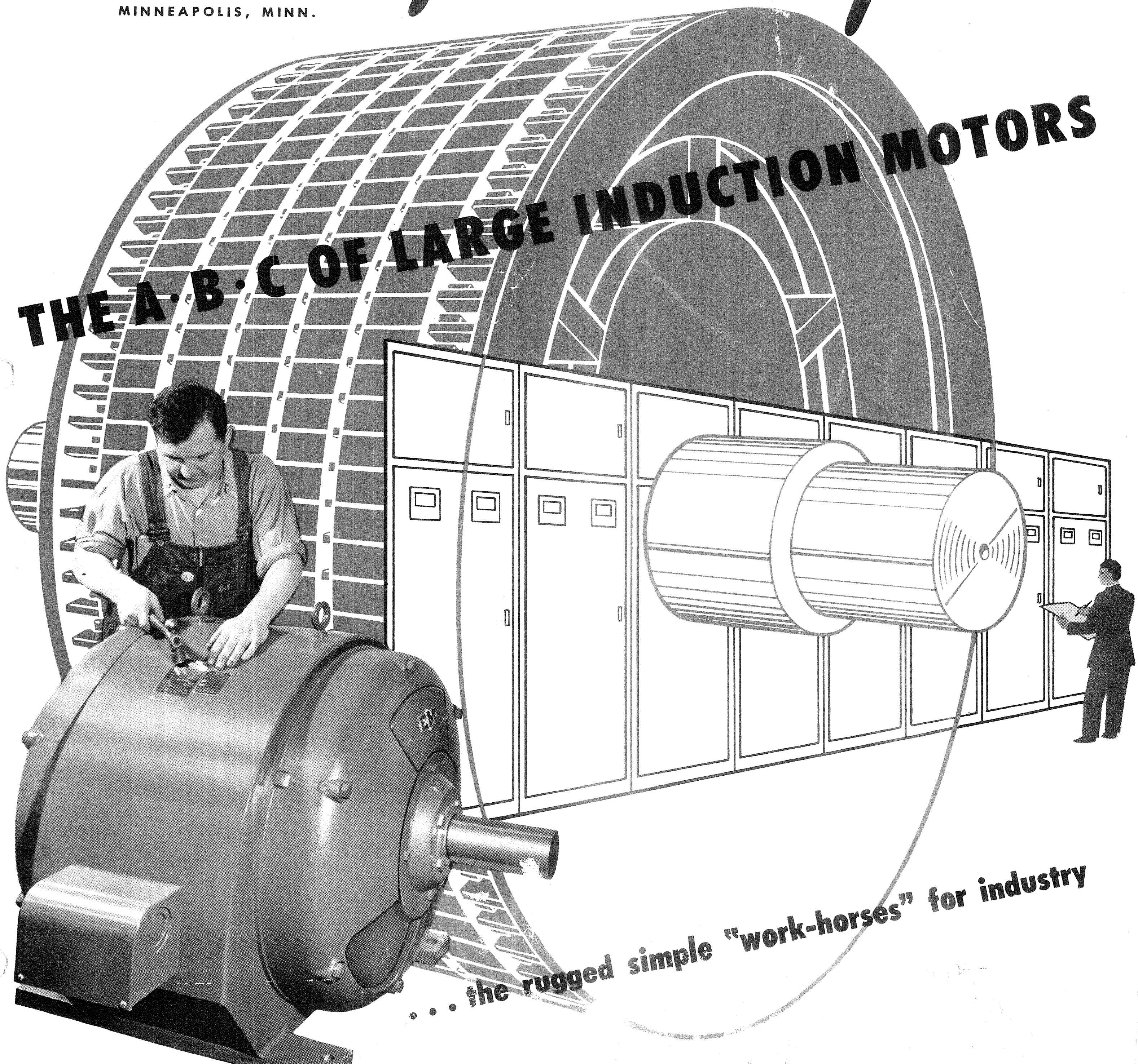
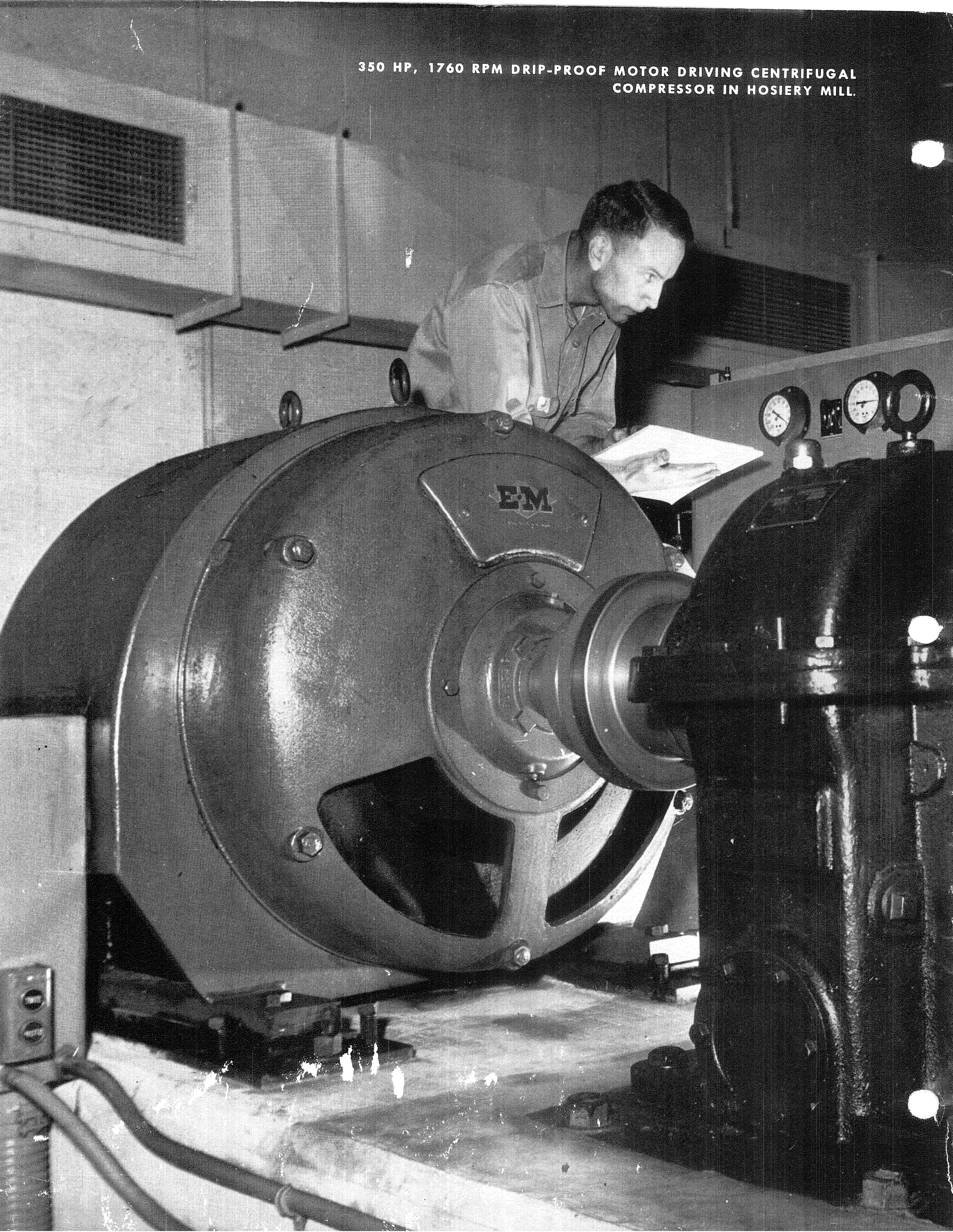
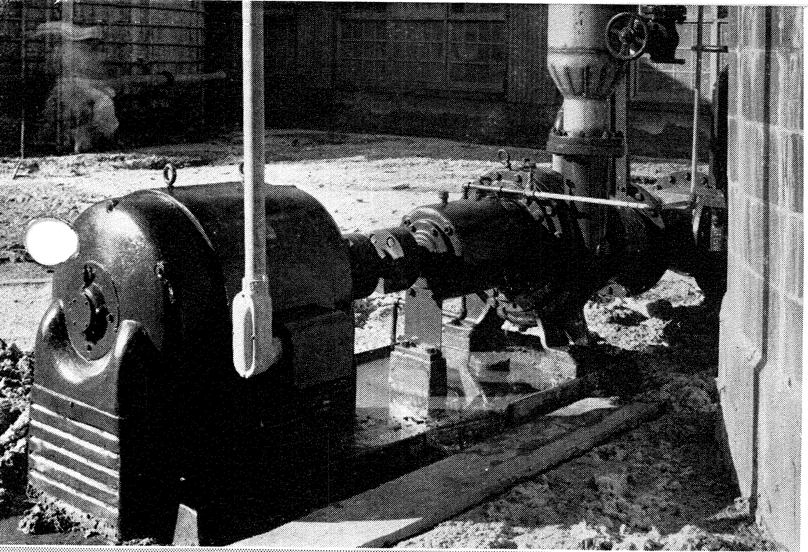
THE A·B·C OF LARGE INDUCTION MOTORS



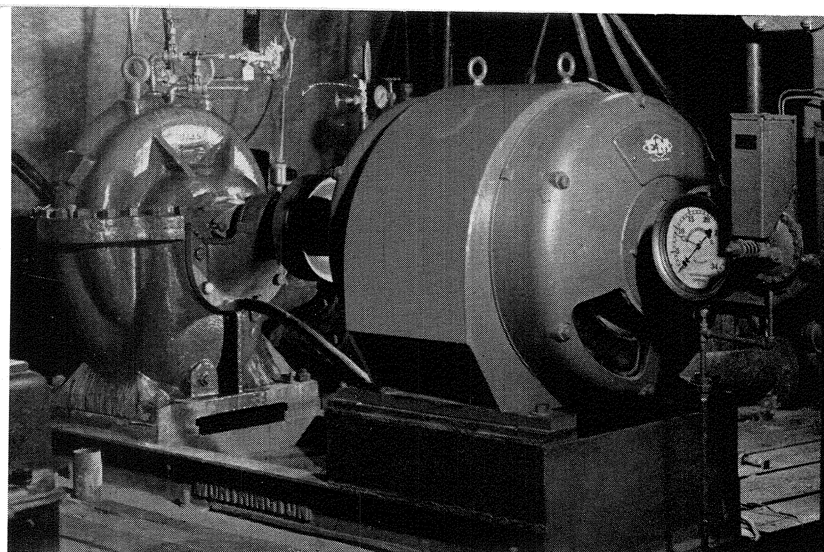
... the rugged simple "work-horses" for industry



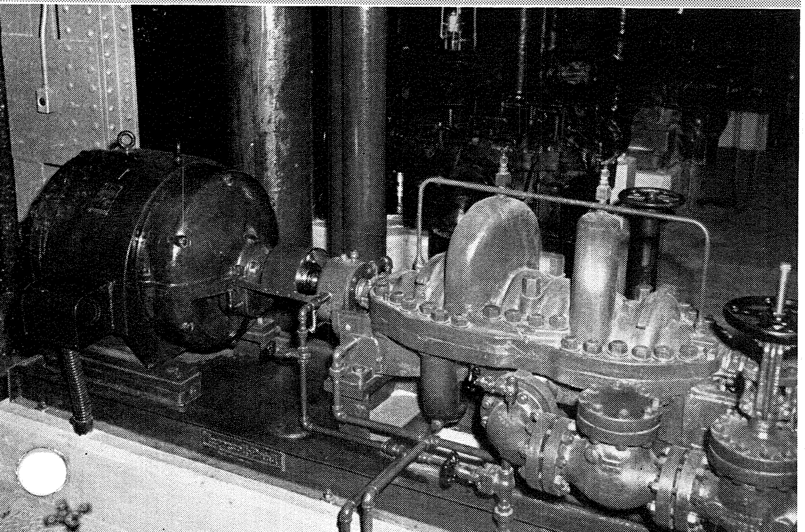
350 HP, 1760 RPM DRIP-PROOF MOTOR DRIVING CENTRIFUGAL COMPRESSOR IN HOSIERY MILL.



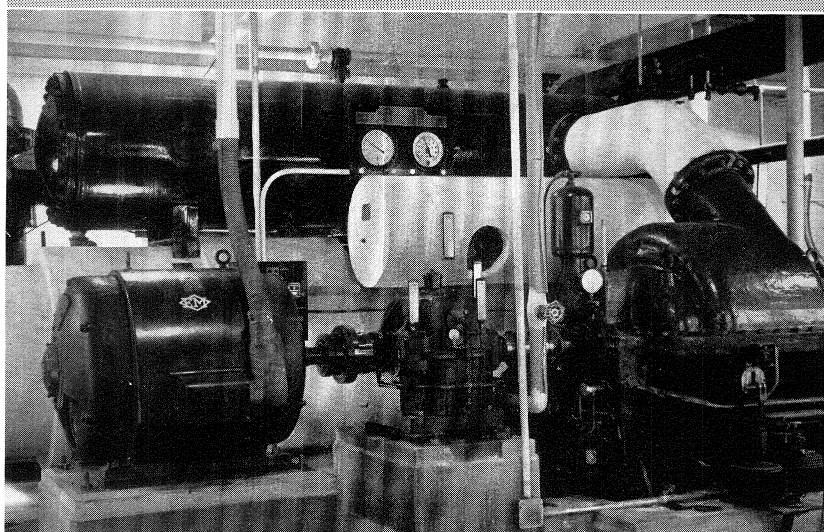
Outdoor Stock Pump at a Paper Mill Driven by 100 HP Motor



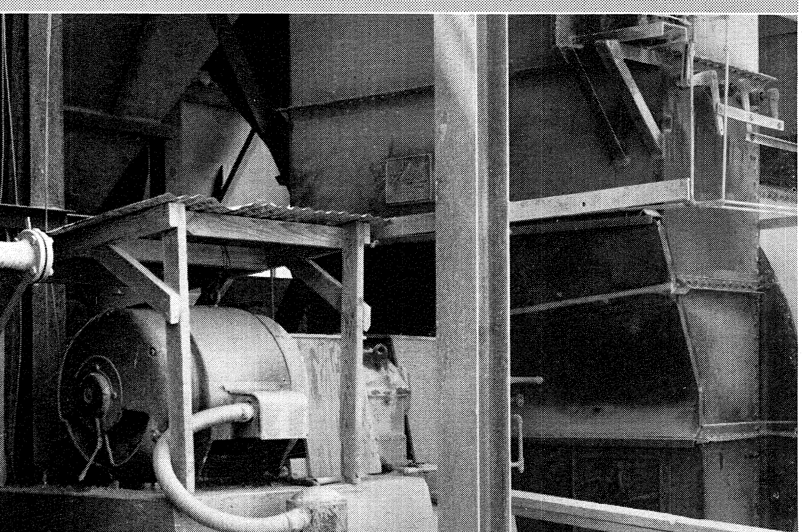
Underground Mine Pump with Drip-Proof Motor 350 HP, 1800 RPM



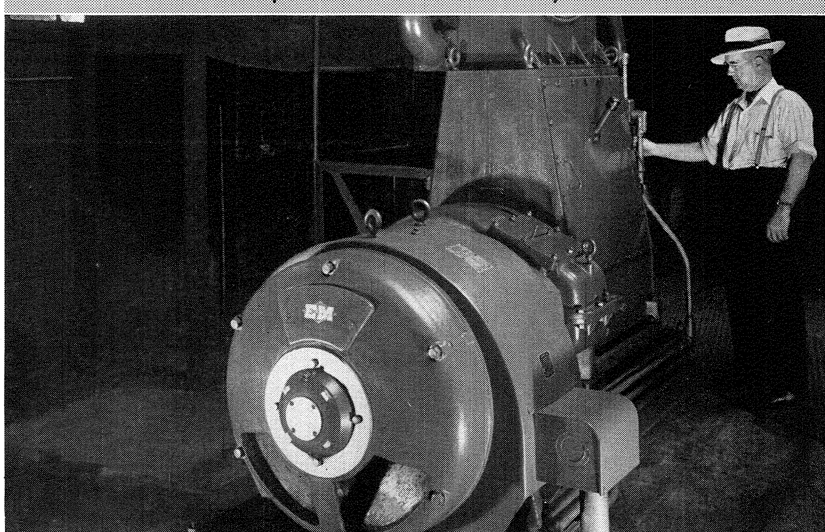
Two-Pole, 200 HP Motor on Feedwater Pump in a Boiler Plant



Chill Water Compressor in Textile Mill Driven by 350 HP Motor



Kiln Fans at Cement Plant Driven by 250 HP, 1800 RPM Motors



High-Pressure Pump in Boiler Works Powered by 150 HP Motor

Inductio[illegible] Motors [illegible] *provide reliable low-maintenance drive power*

THE ABC OF LARGE INDUCTION MOTORS

INDUCTION MOTORS are the "work-horses" of modern industry. This is particularly true in the medium and high speeds, because as shown in this article, the power factor and efficiency, above 500 rpm, are quite acceptable for most applications.

The ruggedness and simplicity of *squirrel-cage motors* makes them a first choice where constant speed is acceptable. The every-day needs of industry find squirrel-cage motors filling almost every conceivable constant-speed drive requirement.

Where speed control or frequent reversing is desired, or where high controllable torque and extra-low starting current must be associated, *wound-rotor (slip-ring) induction motors* are used.

Many designs and types of induction motors, some of them extremely special, are required to supply all the needs of industry. The construction, operation, application and control of the more common ones are discussed in this article.

MR. G. L. OSCARSON, the author of this special issue of the E-M Synchronizer, is a graduate of the Institute of Technology, University of Minnesota. Specializing in electrical power apparatus, Mr. Oscarson was for seventeen years directly associated in the field with the industrial application of motors, generators and controls. Since 1940 he has been chief application engineer of the Electric Machinery Mfg. Company, responsible for the coordination of application requirements of large power apparatus. This paper is one of many Mr. Oscarson has prepared both for publication and for presentation to engineering groups.

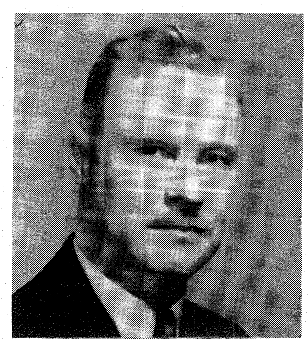


TABLE OF CONTENTS:

PART ONE

A BRIEF EXPLANATION of some alternating-current formulas and definitions; and a review of induction motor characteristics, insulations, and constructions.

Alternating current (AC)

A-C Voltage alternates regularly in value and in direction. A single-phase wave of a-c voltage is illustrated in Fig. 1. One complete alternation is one cycle or 360 electrical degrees.

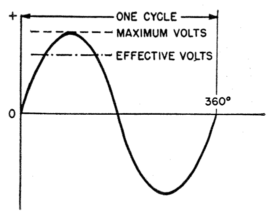


FIG. 1—*A-C single-phase service (sine wave).*

Frequency (f) is the number of such alternations per second. Perfect alternating current is a sine wave with no ripples or distortions.

Phase—If the electrical power is supplied over two circuits, in one of which the voltage reaches zero and other corresponding values 90 degrees later than in the other circuit, the service is *Two Phase* (Fig. 2). If the power is provided in what amounts to three circuits which reach corresponding values at 120 deg. intervals, the service is *Three Phase* (Fig. 3).

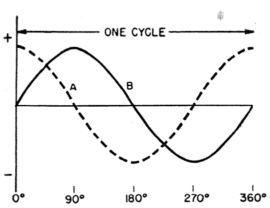


FIG. 2—*Two-phase service.*

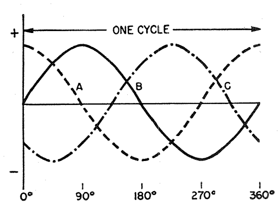


FIG. 3—*Three-phase service.*

Volts (E)—The Volt is the common measure of electrical pressure. *Effective Voltage,* also called RMS voltage (root-mean-square voltage), is .707 of the maximum value of the voltage wave as shown in Fig. 1. Effective voltage is the voltage measured by the usual a-c voltmeter.

Amperes (I)—The Ampere is the unit rate of flow of electric current. As commonly used it is the *effective* (*RMS*) *value* of alternating current and is the value indicated by a common a-c ammeter.

Resistance (R)—Resistance ... hindrance or impedance to current flow o... Resistance is measured in *ohms.* Fundam... law is:

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

Where I = current in amperes
E = voltage in volts
R = resistance in ohms

Inductance (L)—Any device with iron in the magnetic circuit has what amounts to magnetic inertia. *This inertia is effective on any change in current.* Since the voltage, and therefore the current, is always changing in value on alternating current, the inertia characteristic of opposing any change in current *causes the current change to lag behind the voltage change.* It also serves to limit the current value. This effect, known as *inductance,* is measured in *henries.*

Inductive Reactance (X_1)—The effect of inductance *varies with the frequency,* and the term Inductive Reactance is used to express this effect.

$$X_1 = 2\pi fL$$

where X_1 = inductive reactance in ohms
f = frequency in cycles per second
L = inductance in henries.

Impedance (Z)—On alternating-current circuits the flow of current is limited by *both resistance and inductive reactance.* The combination of these two elements is known as *impedance.* Mathematically, when resistance and inductive reactance are present:

$$Z = \sqrt{R^2 + X_1^2}$$

where Z = impedance in ohms
R = resistance in ohms
X_1 = inductive reactance in ohms

By ohms law then; $I = \frac{E}{Z}$

where I = effective value of a-c amperes
E = effective voltage
Z = impedance

Actually in most a-c circuits *the value of X_1 is so high compared to the value of R* that for a first approximation it is assumed:

$$Z = X_1$$

Power (W)—Electrical power is measured in watts (W), kilowatts (K... $\frac{W}{...0}$) or megawatts ($Mw = \frac{W}{1,000,000}$).

A wa... one ampere effective current flowing at a p... effective volt. In alternating current a furthe... on is that the voltage and current must be in phas... that is they must both reach zero, maximum positive and maximum negative values at the same instant.

Assuming that the voltage and current are *in phase,*

on Single-Phase service $W = EI;\ Kw = \frac{EI}{1000}$

on Two-Phase service $W = 2EI;\ Kw = \frac{2EI}{1000}$

on Three-Phase service $W = \sqrt{3}EI;\ Kw = \frac{\sqrt{3}EI}{1000}$

If the current and voltage are *not in phase,* that is, do not reach corresponding values at the same instant, the resultant product of current and voltage is *apparent power* instead of actual power. Apparent power is measured in volts-amperes (Va) or kilovolt amperes ($Kva = \frac{VA}{1000}$).

Apparent power is measured as follows:

on Single-Phase service $Va = EI;\ Kva = \frac{EI}{1000}$

on Two-Phase service $Va = 2EI;\ Kva = \frac{2EI}{1000}$

on Three-Phase service $Va = \sqrt{3}EI;\ Kva = \frac{\sqrt{3}EI}{1000}$

Power Factor is the factor by which apparent power (volt-amperes) is multiplied to obtain actual power (watts).

In most magnetic circuits as mentioned above, the current will lag behind the voltage. A typical case is represented in Fig. 4, where the current changes lag 60 degrees (1/6 cycle) behind corresponding voltage changes. In that part of the current wave and voltage wave *when both are positive or both negative,* the resulting power is positive (E x I = W, or –E x –I = W). This is represented by the cross hatched area *above* the zero line.

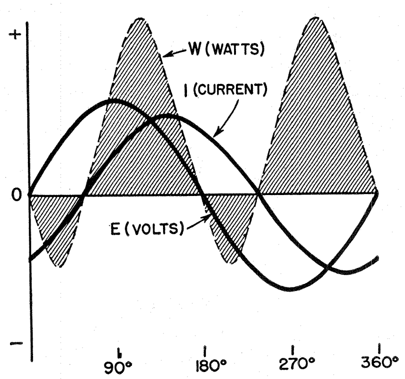


FIG. 4—*Volts, amperes and watts where current lags voltage by 60 degrees.*

When either the current wave or voltage wave is negative and the other is positive the resulting power is negative (–E x I = –W, or E x –I = –W). This is represented by the cross hatched area below the zero line. The *net power* is the positive area minus the negative area. The *apparent power* (volt-amperes) is the *sum* of the two areas. *The power factor is the net power divided by the apparent power.*

Thus power fact[illegible] *he factor by [illegible] we multiply apparent power to [illegible] power.*

Mathematic[illegible] power f[illegible] is equal to the *cosine of the angle* by which the current lags (or in rare cases leads) the vo tage. In Fig. 4, the angle of lag is 60 degrees. The cosine of this angle, and thus the corresponding power factor, for that amount of lag, is 0.50 corresponding to 0.5 (or 50.0%) lagging power factor.

Low power factor is undesirable. The capacity of generators, transformers, transmission lines and distribution lines is usually fixed by heating limits or by permissible voltage drop. In any case the current is usually the limiting factor. Since power factor = $\frac{Kw}{Kva}$ any *decrease* in power factor means an *increase* in Kva (and therefore amperes) for a given Kw load.

Approximate power factors of typical NEMA Class B motors are shown in the curves on the opposite page. Note that *decrease* in rated speed or in rated horsepower results in *lower* power factor at all loads.

Variation in line voltage *will affect the power factor of induction* motors. In general the following may be expected:

Induction Motor Load	EFFECT OF VOLTAGE ON POWER FACTOR		
	Normal Voltage	10% High	10% Low
Full Load	No Change	down 3 points	up 1 point
¾ Load	No Change	down 4 points	up 2 points
½ Load	No Change	down 5 points	up 4 points

Thus if the full-load power factor of a motor at normal voltage is 0.896, a 10% increase in voltage will lower the power factor to 0.866.

Magnetizing Current Transformers, motors and other apparatus with magnetic circuits containing iron must be magnetized in order to operate. It is often convenient to speak of the input current as having *two components:* one *a load component which is in phase* with the voltage, and the other a *magnetizing component* at right angles and lagging the voltage. This lag would be 90 electrical degrees.

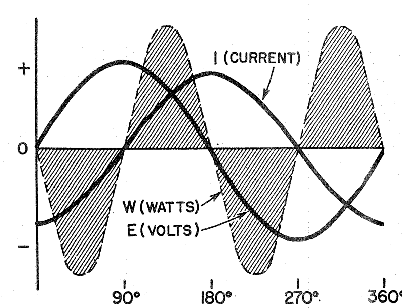


FIG. 5—*When voltage and current are 90 degrees out of phase the power is all reactive.*

The *load component* registers on the watthour meter *and does the actual work.* The *magnetizing component puts energy into the magnetic circuits* of the apparatus during ¼ cycle and returns it to the system the next quarter cycle. Th[illegible] trated in Fig. 5 where positive and negative [illegible]nting power are equal and cancel out. Except [illegible] et power interchange due to the magnetizin[illegible] is zero.

POWER FACTOR of INDUCTION MOTORS (Approx.)

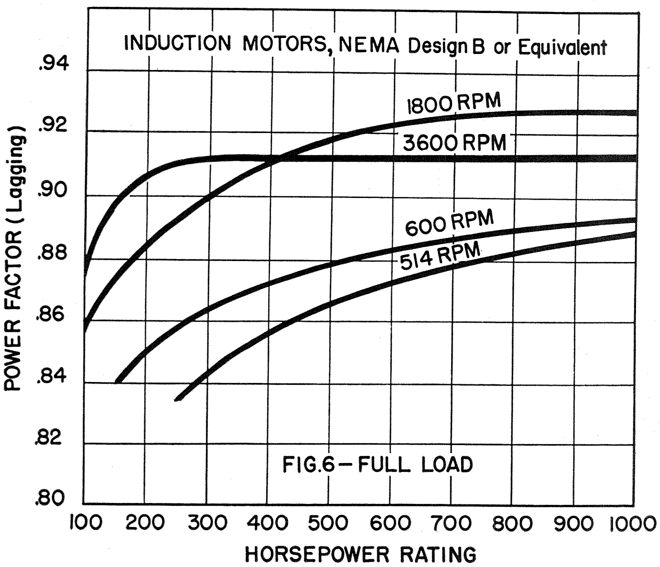


FIG.6 — FULL LOAD

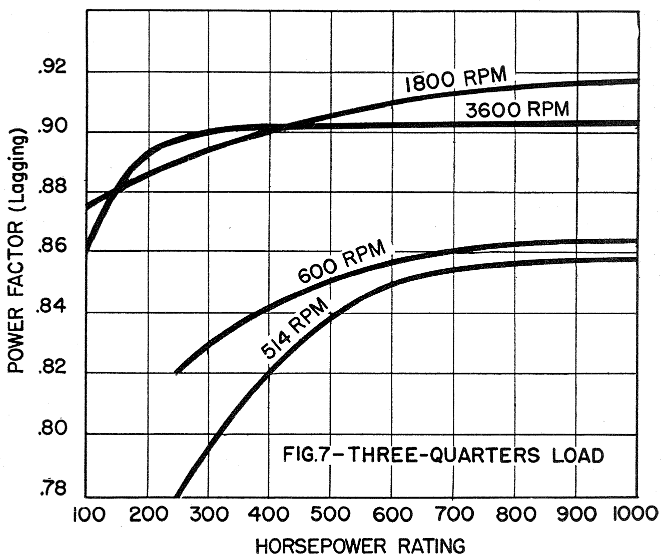


FIG.7 — THREE-QUARTERS LOAD

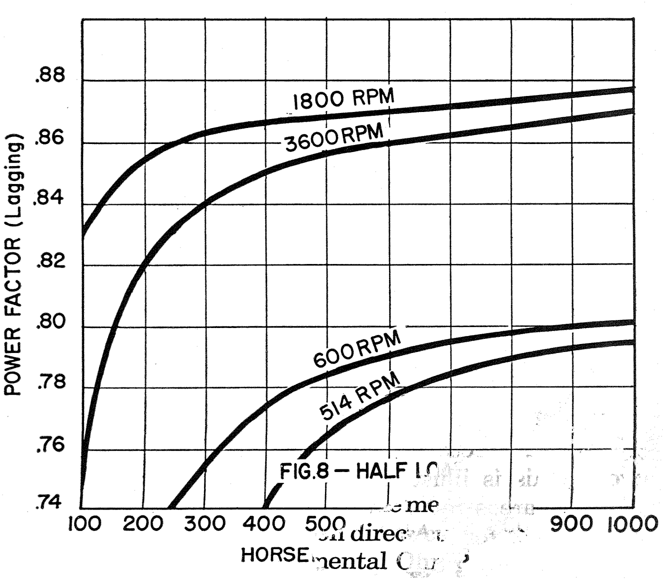


FIG.8 — HALF L

Mathematically:

$$I_t = \sqrt{I_r^2 + I_x^2}$$

where I_t = total line current

I_r = in-phase, (power) component

I_x = out-of-phase (magnetizing) component

also

$$Kva = \sqrt{Kw^2 + Kvar^2}$$

where Kva = total kva

Kw = load component

Kvar = reactive component (magnetizing kva)

Torque (T) is the turning effort at one foot radius expressed in pound-feet. It is a measure of the ability of a motor to develop power. National Electrical Manufacturers Association has defined the torques applying to induction motors in NEMA "Motor and Generator Standards". (NEMA-MG 50)

Locked-Rotor Torque *(also called breakaway torque or starting torque) is the minimum torque a motor will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency (NEMA-MG 50-67).*

Full-Load Torque *is the torque necessary to produce rated horsepower at full-load speed. In pounds at one foot radius it is equal to the horsepower times 5250 divided by the full-load speed (NEMA-MG 50-66.5).*

For example, a 500 hp, 1760 rpm motor will have the following full-load torque:

$$\frac{5250 \times 500}{1760} = 1493 \text{ pound feet}$$

Accelerating torque is the net difference, at any speed, between the *torque required by the external load* and the *torque developed by the motor*. This torque is available for acceleration of the motor and its connected load.

Breakdown Torque is the maximum torque a motor will develop, with rated voltage applied at rated frequency, without an abrupt drop in speed (NEMA-MG 50-69). This is sometimes incorrectly referred to as the maximum torque or pull-out torque.

Starting and breakdown torques will *vary as the square* of the applied voltage. For instance, if a motor has 125% starting torque on full voltage, and the voltage is reduced to 80% of normal, the resulting starting torque will be:

$$\frac{80^2}{100^2} \times 125\% = 80\% \text{ of full-load torque.}$$

In some cases the starting or accelerating torque available at reduced voltage may be insufficient to start or bring the connected load up to speed.

Synchronous Speed is the speed an induction motor would reach if there were no slip. It is the speed at which the magnetic field, in effect, rotates about the stator.

RPM = [illegible] / p

where RPM = synchronous speed

f = frequency in cycles per second

p = number of stator poles

Common induction motor *synchronous speeds* are:

Number of Stator Poles	SYNCHRONOUS RPM		
	60 Cycles	50 Cycles	25 Cycles
2	3600	3000	1500
4	1800	1500	750
6	1200	1000	500
8	900	750	
10	720	600	
12	600	500	
14	514		
16	450		

Full-Load Speed and Slip As explained later, the rotor of the induction motor can never run at quite synchronous speed. The difference between synchronous speed and operating speed is known as *slip*. This is usually expressed in *percent of synchronous speed.*

$$\text{Percent slip} = \frac{\text{(Synchronous speed} - \text{Operating speed)} \times 100}{\text{Synchronous Speed}}$$

For example, a 200 hp, 2-pole, 60 cycle motor may have a full-load speed of 3560 rpm. Synchronous speed would be 3600 rpm.

$$\text{Percent slip} = \frac{(3600 - 3560) \times 100}{3600} = 1.1\%$$

Full-load slip varies from 1% on large, high-speed induction motors to 3% on small, low-speed motors. For specific applications higher slip values may be built into a motor.

If the line voltage is 10% high, the slip will be reduced about 1 point. If the line voltage is 10% low the slip will be increased about 1.5 points.

Efficiency is the measure of the *ability of the motor to convert electrical input to mechanical output.*

The *kilowatt* is the common unit of *electrical input.* The *horsepower* is the common unit of *mechanical output.*

746 Watts = 1 Horsepower
1 Kw = 1.34 Horsepower

The recognized induction motor losses are:

- Stator no-load iron loss
- Stator copper loss (I^2R)
- Stray load loss
- Rotor copper loss (I^2R)
- Friction and windage

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}}$$

If a motor has an input of 94 kw and an output of 110 hp, efficiency will be as follows:

Input = 94 Kw
Output = 110 x .746 = 82.06 Kw

$$\text{Efficiency} = \frac{82.06}{94.00} = 87.3\%$$

The losses will be 94.00 − 82.06 = 11.94 Kw

The internal torque ˡeᵛ ped by the s ·l-cage induction motor is d ˈsses generᵃ ʰe rotor. In the case of a ..or induction ·e losses in the external . re also includeᵈ

A 1200 synchronᵘ rpm motor de· 96 hp at 1160 rpm, would have rotor losses as f

EFFICIENCY of INDUCTION MOTORS (Approx.)

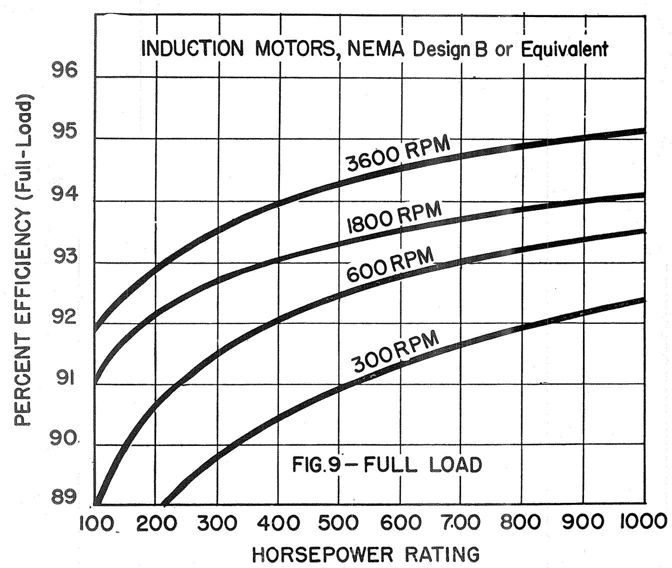


FIG.9 – FULL LOAD

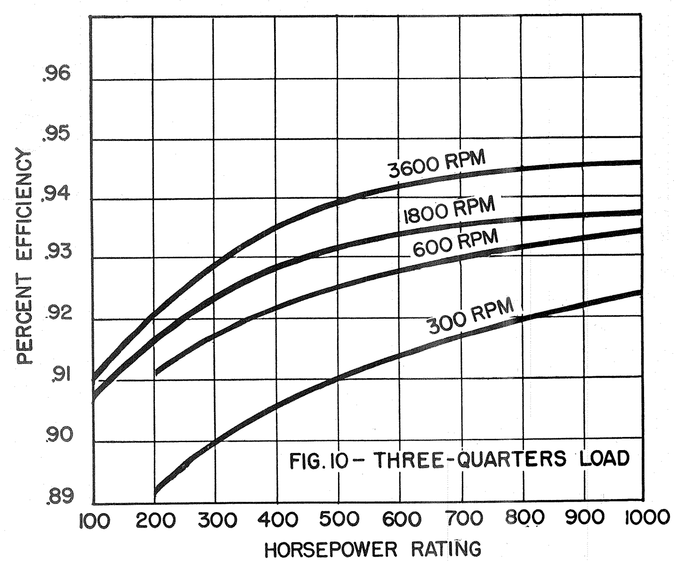


FIG. 10 – THREE-QUARTERS LOAD

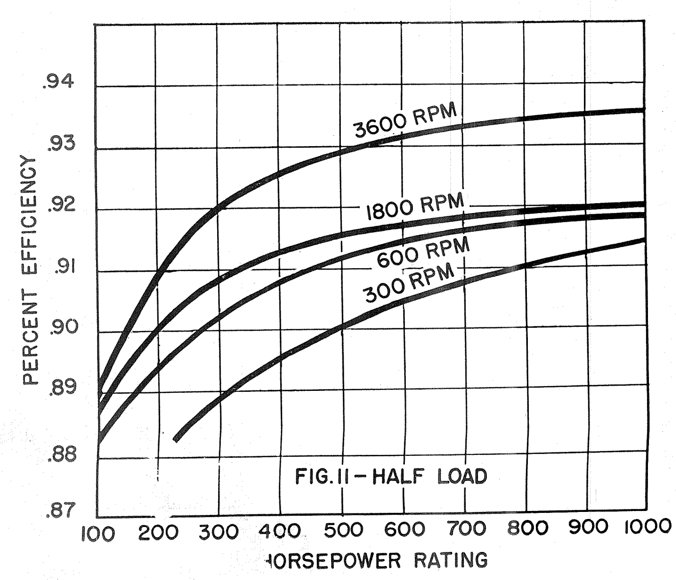


FIG. 11 – HALF LOAD

$$\text{Torque} = \frac{5250 \times \text{Hp}}{\text{RPM}} = \frac{5260 \times 96}{1160} = 435 \text{ Pound Feet}$$

$$\text{Slip} = 1200 \text{ RPM} - 1160 \text{ RPM} = 40 \text{ RPM}$$

$$\text{Slip loss} = \frac{2\pi \times \text{Torque} \times \text{RPM (Slip)}}{33000} = \frac{2\pi \times 435 \times 40}{33000}$$

$$= 3.3 \text{ Hp} \times .746 = 2.46 \text{ Kw}$$

Slip loss may also be determined by the following formula:

$$\text{Hp Slip loss} = \frac{\text{RPM slip}}{\text{RPM load}} \times \text{load Hp}$$

For the motor specified above:

$$\text{Hp Slip loss} = \frac{40}{1160} \times 96 = 3.3 \text{ Hp}$$

Curves on opposite page show approximate efficiencies of NEMA Class B Motors.

Variation in line voltage *will affect the efficiency of induction motors.* In general the following may be expected.

Induction Motor Load	EFFECT OF VOLTAGE ON EFFICIENCY		
	Normal	10% High	10% Low
Full Load	No Change	Up .5 to 1 point	Down 2 points
¾ Load	No Change	Unchanged	Unchanged
½ Load	No Change	Down 1 to 2 points	Up 1 to 2 points

Horsepower Determination—In some cases it will be desirable to determine approximate horsepower loading by measuring motor input with a voltmeter and ammeter or with a wattmeter.

Ammeter readings alone are not too accurate. However, if line voltage is at the nameplate value and if the ammeter reading is between ¾ of full-load amperes and 1¼ full-load amperes, it may be assumed that the load is very nearly proportional to the ammeter reading.

A 250 hp motor has a nameplate full-load current rating of 298 amperes at 440 volts and is drawing 260 amperes at that voltage. It can be assumed that the load is very nearly proportional: That is:

$$\frac{260}{298} \times 250 \text{ Hp} = 218 \text{ Hp}$$

If the voltage is appreciably high or low a correction may be made on the following basis:

	LINE VOLTAGE		
	Normal	10% High	10% Low
Full-Load Amperes	No Change	−7%	11%

At current values below ¾ of rated amperes it will be necessary to cut and try. First assume efficiency and power factor values, based on an estimate of the load, correcting for voltage if necessary, and substituting in the following formula:

$$\text{Hp} = \frac{1.73 \times E \times I \times \%\ \text{Efficiency} \times \%\ \text{Power Factor}}{10{,}000{,}000 \times .746}$$

Assume a 250 hp, 1800 rpm m[illegible] with a nameplate rating of 296 amperes at 440 volts, operating at 160 amperes and at 445 volts. Apparently this will be close to half load so we assume efficiency and power factor values from the curves (assume 90.5 and 85.5 respectively) for that load. The voltage is close enough to rated value so no correction need be made for that. Then:

$$\text{Hp} = \frac{1.73 \times 445 \times 160 \times 90.5 \times 85.5}{10{,}000{,}000 \times .746} = 128$$

which is sufficiently close to half load so that the assumed values of efficiency and power factor, as used, will suffice.

If the calculated load is not close to the load value, on which assumed efficiency and power factor values were based, it may be necessary to use new values corresponding to the estimated load and try again.

If a wattmeter is available, one variable, viz; power factor, is eliminated. Then:

$$\text{Hp} = \frac{\text{Kw} \times \%\ \text{Efficiency}}{.746 \times 100}$$

It is then necessary to assume an efficiency value, taking into account horsepower, speed, approximate load and voltage variation from normal.

Assume that the 250 hp, 1800 rpm motor previously mentioned was checked by wattmeter and had an input of 90 kw. For a first approximation assume an efficiency of 90%. Then:

$$\text{Hp} = \frac{90 \times 90}{.746 \times 100} = 109 \times 43.5\% \text{ of full load}$$

By referring to the efficiency curves we find that the value at half load is 90.5% and the assumed value of 90% which was used is nearly enough accurate. If the efficiency at the load as determined above is not close to the assumed value it will be necessary to make a correction. The efficiency value at the load as determined should be used and the horsepower recalculated. One such trial should make it possible to arrive at a sufficiently close approximation of the actual horsepower.

Insulation and Temperature Rise

Ambient Conditions—It is assumed that the temperature of the air surrounding a motor is not over 40 degrees C (104 degrees F) and that the altitude does not exceed 3300 feet. The lower density of the cooling air at high altitude results in reduced cooling. In general however, any increase in altitude results in a lowering of ambient temperature, offsetting the decreased cooling effect. The *total* temperature based on lower ambient but a higher temperature rise, is usually about the same regardless of altitude.

Total temperature is important *in that it directly influences* [illegible] *f the insulatio*[illegible] *the motor.* It is generally accepte[illegible] ach 10 degr[illegible] in temperature will approx[illegible] alve the eff[illegible] Class A or Class B insu[illegible] tual failure of t[illegible] tion is generally mechan[illegible] lting from redu[illegible] rength of the insulation [illegible] ontinual or repeated exposure to high temperat[illegible]

Class A Insulation consists of cotton, silk, paper, or other organic materials impregnated with insulating varnish; molded or laminated phenolic resin (bakelite) with cellulose filler; films and sheets of cellulose acetate (cellophane); and enamels as applied to conductors.

Class A insulation is based on a total allowable temperature of 105 degrees C as being suitable for reasonable insulation life. This is based on:

40 degrees C ambient temperature
40 degrees C temperature rise by thermometer
15 degrees C hot spot temperature allowance
10 degrees C service factor
105 degrees C Total temperature

The 15 degree C hot spot allowance is based on the assumption that the hottest spot within the motor is 15 degrees C hotter than the maximum temperature observable by an external thermometer. The 10 degrees C service factor is always used on general-purpose induction motors to permit flexibility of operation. This allows a 40 degrees C rise motor, open or drip-proof construction, to carry 15% overload continuously without a temperature rise which would be unduly damaging to insulation.

Class A insulation is considered standard and will withstand the conditions found on the majority of applications. It is mildly resistant to moderate amounts of moisture, weak acids or alkalies, non-conducting abrasive material, dust, oil, and other similar materials.

Special Class A Insulation consists of organic materials, processed to a greater degree than standard Class A insulation. It should be used where Dyehouse or Packinghouse insulation is specified. It is highly resistant but not "proof" against severe conditions of moisture, dampness, conductive or abrasive dust, acid or alkali dusts or vapors.

Class B Insulation consists of mica, asbestos, fiber glass and other inorganic materials. Organic materials are commonly used as binders but may be used for structural purposes only.

Permissible total temperature of Class B insulation is 130 degrees C. Class B insulation is frequently used where extremely high ambient temperatures may prevail. Class B temperature is based on:

40 degrees C ambient temperature
70 degrees C temperature rise by thermometer
20 degrees C hot spot temperature allowance
130 degrees C Total Temperature

Class H Insulation—Newly developed high temperature insulations, such as silicones, permit total temperatures of 170 degrees C. However, full advantage of this permissible temperature in reduction of motor size is usually not possible. Other factors, such as torques, bearing temperature, etc., limit frame reduction and possible temperature rise.

Tropical Insulation—Motors operating in the tropics may encounter any or all of the following conditions:

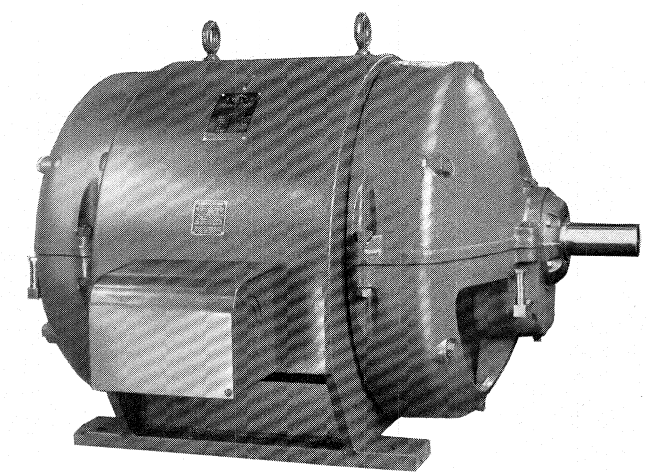
1. **Excessive moisture**
2. **Excessively high ambient temperature**
3. **Corrosion**
4. **Fungus**
5. **Insects, Termites, etc.**
6. **Vermin, lizards, rats, etc.**

Such units will require special tropical insulation.

Protective Constructions

Open type Motor—(NEMA-MG 50-40) is a self-ventilated motor having no restriction to ventilation other than that necessitated by mechanical construction.

Drip-proof Motors—(NEMA-MG 50-14), Fig. 12, have ventilating openings so constructed that drops of liquid or falling particles reaching the motor at an angle not greater than 15 degrees from the vertical cannot enter the motor either directly or by striking and running along a horizontally or inwardly inclined surface. *This is the recommended minimum protection for the great majority of induction motor applications.*



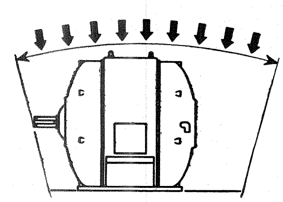
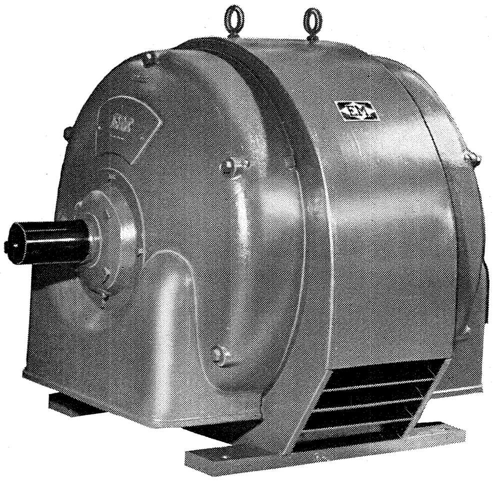


FIG. 12—*DRIP-PROOF MOTOR has protective enclosure preventing entrance of water dropping not more than 15 degrees from vertical.*

Splash-proof Motors,—(NEMA-MG 50-16), Fig. 13, have ventilating openings so constructed that drops of liquid or solid particles falling on the motor or coming straight toward it at an angle not greater than 100 degrees from the vertical cannot enter the motor directly or by running along the surface.

Splash-proof motors are frequently used in ice plants, dairies, creameries, paper mills, chemical plants, and other places where floors may be hosed down. They are also suitable for installation outdoors except where drifting snow may enter the machine. Temperature rise of standard splash-proof motors is 50 degrees C.



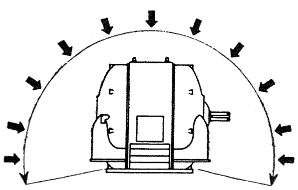


FIG. 13—SPLASH-PROOF MOTOR has protective enclosures and baffles preventing water entering at not more than 100 degrees from vertical.

Special Protections—The drip-proof and splash-proof construction suffice for the great majority of applications. Occasionally special conditions call for quite special constructions, such as explosion-proof, water-proof, submersible and dust tight. Totally enclosed, fan-cooled, open or enclosed separately ventilated, and explosion-proof motors are examples of constructions used for special applications.

Totally-enclosed fan-cooled and fan-cooled explosion-resisting motors are quite expensive. In the sizes under discussion in this article totally-enclosed fan-cooled motors will cost 180% to 230% as much as standard open-type motors. Fan-cooled explosion-resisting motors will cost 200% to 250% as much as standard open motors.

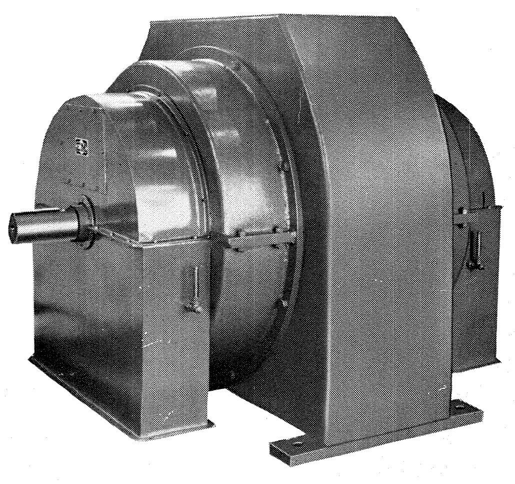


FIG. 14—TOTALLY-ENCLOSED motor with inlet and outlet duct openings for forced ventilation.

In some cases it is not possible to avoid these types of constructions. However it is often possible to arrange motor location so standard motors may be used. This should be done whenever possible.

Mechanical Constructions

Coupled type (Bracket Bearing)—Most induction motors are of the coupled bracket type as illustrated on these pages. These motors may be open, drip-proof, splash-proof, or of various other protective constructions. The bearings are supported by end brackets and rigid or flexible couplings are used to connect the motor to the load. The motor feet are usually mounted on a sub-base extending under the driven machine.

Coupled Type (Pedestal Bearing)—Large or slow-speed induction motors generally use pedestal-type bearings. The motor is complete with base and pedestals. Flexible couplings are generally used to connect the motor shaft extension to the load. The motor base may either be mounted on extension of sub-base under the driven machine, or may be set in concrete.

Belted Type Motors are also of the same general construction as coupled type units. Belt tightening rails are usually provided to maintain proper belt tension. In extreme cases, where belt tension is very high, an outboard bearing is required.

Flanged-Mounted (Overhung) Type is used for direct connection to air compressors. The stator of the motors is bolted to a flange on the compressor frame, hence the name. The rotor is mounted on an extension of the compressor shaft.

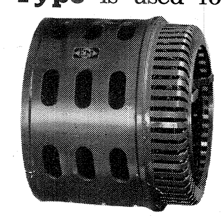


FIG. 15—FLANGE-MOUNTED MOTOR.

Vertical Motors are commonly used to drive deep well vertical shaft turbine-type pumps. To facilitate adjustment of clearances between the impellers and the pump housing the motor is sometimes provided with a hollow shaft. The pump shaft extends upwards through the hollow space and it is supported by the motor shaft. Vertical adjustment is readily made by means of a nut on the upper end of the pump shaft.

In some cases the pump thrust is carried in a pump thrust bearing. Then a flexible coupling is used between the motor and the pump shaft. In other cases the motor shaft carries the pump shaft but no vertical adjustment is provided. A rigid coupling connects the pump and motor shaft together.

Special Constructions of induction motors are required for various special requirements. Possible variations of mechanical construction are almost limitless.

PART TWO

HOW THE INDUCTION MOTOR OPERATES; *Torque Characteristics of the Rotor Winding.*

Magnetic Lines of Force (commonly called flux) surround any conductor carrying current. This results in a *magnetic field* of definite strength depending on the amount of current flowing in the conductor and the nature of the magnetic circuit, that is the iron path available for flux adjacent to the conductor. The magnetic field has a *definite polarity* depending on the direction of current. Thus the magnetic field surrounding a conductor carrying alternating current varies both in strength and direction. *It pulsates, at line frequency, from maximum in one direction to maximum in the opposite direction.* For explanatory purpose consider a two-pole motor with 6 stator slots as shown on the opposite page.

If twelve conductors, properly connected, are placed in the six equally spaced slots on the inner periphery of a laminated steel ring (called a stator) and are connected to a 3-phase supply, they will produce, in effect, *a rotating magnetic field.* The magnetic field will be substantially uniform in total strength, but will rotate in space as described later.

The seven diagrams on page 13 show the disposition of electric currents and magnetic fields in the stator of a 3-phase squirrel-cage motor, for regular intervals numbered 0 to 6, and comprising one-half cycle of a full alternating current wave.

As the alternating currents change in value and direction the magnetic field, in effect, rotates clockwise about the stator; the lines of force thus cutting across the squirrel-cage bars in the rotating element (called a rotor). These bars are all electrical conductors and are connected by short-circuiting rings. The magnetic lines of force represented by the colored dash lines may be assumed to pass through the air-gap at right angles to the face of the rotor.

As long as the rotor remains stationary the motor is, for all practical purposes, a transformer with a short-circuited secondary winding. The rotor bars constitute the secondary. Currents of considerable magnitude, alternating at line frequency, flow in these bars. They are induced by the magnetic lines of force cutting across the bars. As is well known, a conductor in a magnetic field and carrying current will have exerted on it a force tending to move it at right angles to the magnetic field. *A tangential force, or torque, is thus exerted on the rotor periphery.*

The direction of this torque causes the rotor to attempt to turn in the same direction as the magnetic field in the stator is rotating; in this case clockwise. The amount of torque developed depends on the power consumed as resistance losses in the cage bars of the rotor, that is it depends on the I^2R losses.

If the torque developed causes the rotor to turn, *it will accelerate to some definite speed at which the turning effort is equal to the retarding effort or load.*

If very little load is imposed, say only friction and windage of the rotor, only a slight amount of current need flow in the squirrel-cage bars to develop that torque. Only a very slight amount of relative motion (slip) between the rotating magnetic field and the rotor is required to induce this amount of current. *The rotor will therefore turn at nearly synchronous speed at no load.*

However, even to overcome only friction and windage some definite torque is required. To develop this there must be some current inducted in the rotor bars, however slight. *This necessitates some slip even at no load and therefore synchronous speed cannot quite ever be reached.*

By reversing any two of the leads of a 3-phase motor, the phase rotation will be reversed. Instead of A, B, C, as in Fig. 3, page 5 it would become A, C, B. This would cause the magnetic field to build up to reverse order and to rotate counter-clockwise.

Synchronous Speed, as stated previously, *varies inversely as the number of stator poles.* The stator represented on the opposite page is that of a *two-pole* motor. The winding is so arranged that the resultant flux leaves the stator at one point (a North Pole) and re-enters the stator at a directly opposite point (a South Pole). If the windings would be arranged for *four poles*, the flux would leave the stator at two points and re-enter at two points. The flux paths for a 4 pole motor are shown in Fig. 16. *Stator windings can be arranged to have 2, 4, 6, or any other practicable number of poles in multiples of two.*

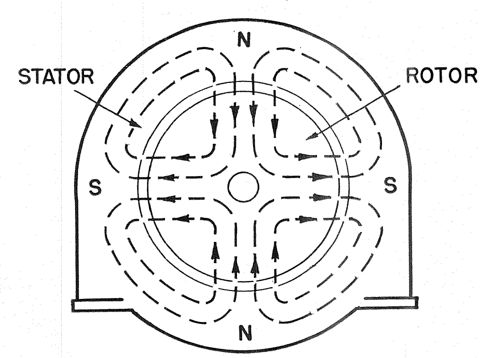
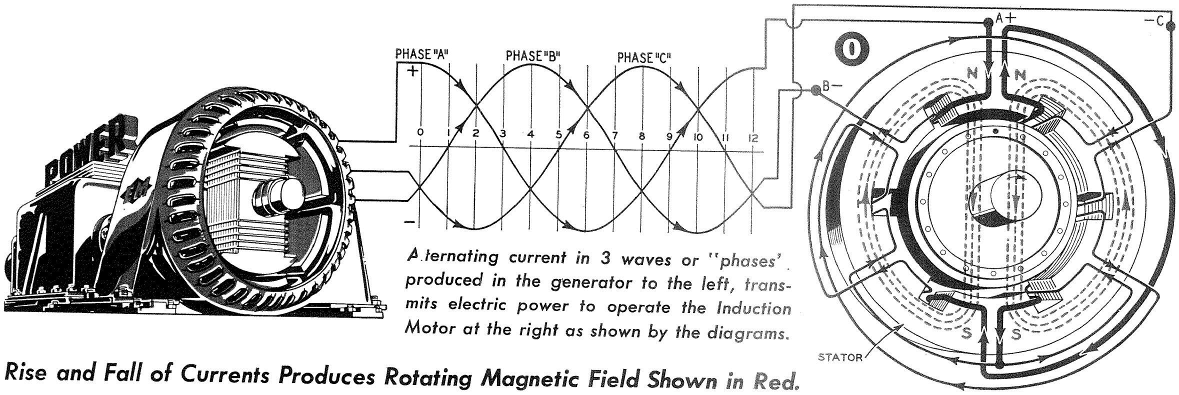


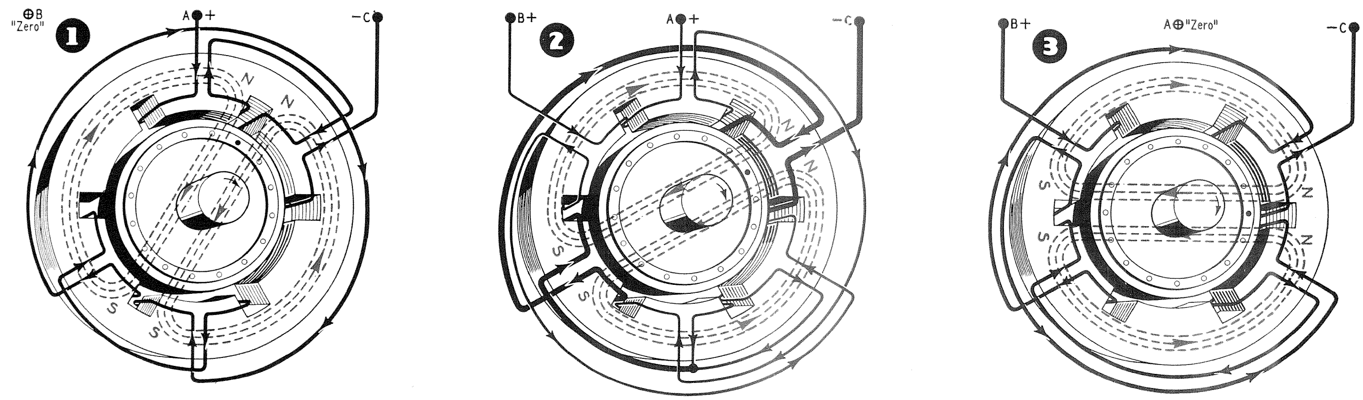
FIG. 16—*Diagram of paths of magnetic flux (dashed lines) for four pole motor. Induction motors can be built with any practical number of pairs of poles.*



Alternating current in 3 waves or "phases" produced in the generator to the left, transmits electric power to operate the Induction Motor at the right as shown by the diagrams.

Current is maximum in phase A, dividing equally and leaving motor through B and C.

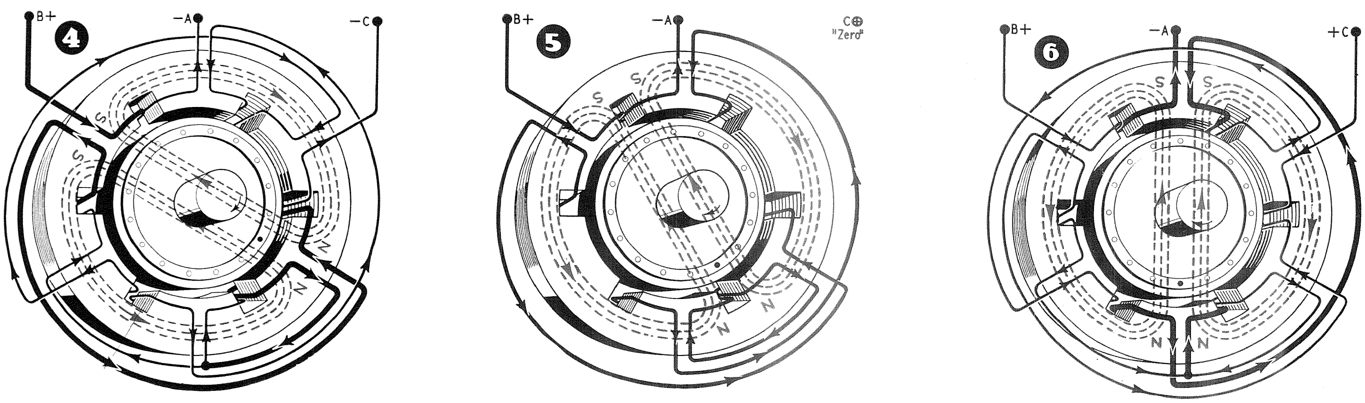
Rise and Fall of Currents Produces Rotating Magnetic Field Shown in Red.



Current in phase B is now zero, and that entering phase A leaves the motor through C.

Phase C is now maximum in reverse direction. Stator field and rotor have rotated 1/6th turn.

This drawing, and 4, 5 and 6 below, show additional successive shifts in rotation of rotor.



HOW 3-PHASE ALTERNATING CURRENT

PRODUCES THE ROTATING MAGNETISM THAT SPINS THE ROTOR

FIG. 17—*The seven diagrams above show the disposition of electric currents and magnetic field of the stator of a two-pole induction motor for regular intervals numbered 0 to 6, comprising ½ cycle of the alternating-current waves. As the a-c current changes in strength and direction the magnetic field rotates around the stator. The poles of the rotor, induced by lines of flux cutting across the squirrel-cage bars, are forced, by magnetic attraction, to follow the rotation of the stator poles.*

Torque—A typical induction motor torque curve is represented in Fig. 18. Torque, in percent of full-load torque, is plotted against speed.

In this case, the locked-rotor torque is 125% of full-load torque. It rises to 225% at approximately 85% speed, and drops to 100% at 98% speed (2% slip). At synchronous speed, zero torque is developed, as has previously been mentioned. *If the rotor is driven above synchronous speed* it will continue to draw a magnetizing current component from the line but will deliver a power component. It will therefore operate as *an induction generator,* delivering full load at normal full-load slip (in this case a negative slip).

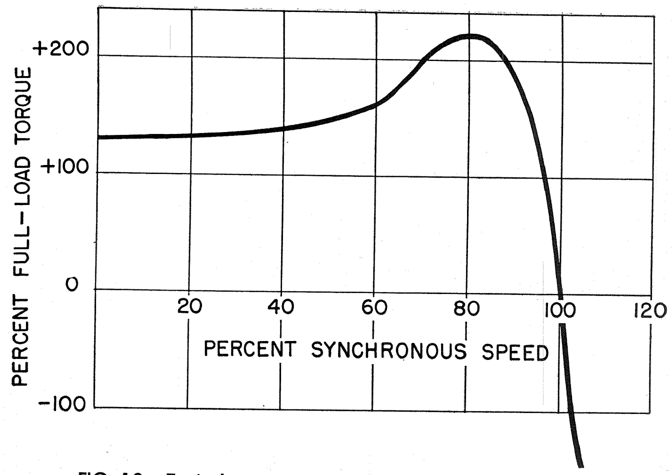


FIG. 18—*Typical torque curve showing operation both as induction motor and as an induction generator.*

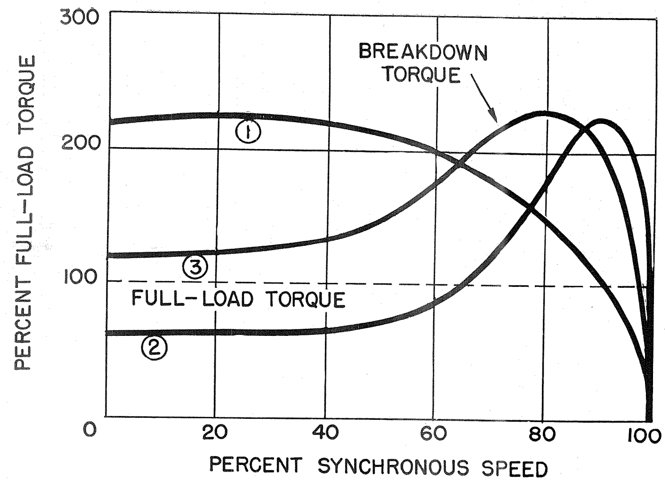


FIG. 19—*Torque of induction motor varies with resistance and reactance of cage bars, shown by 1, 2, 3 above.*

The locked-rotor torque, *full-load slip and locked-rotor kva of any squirrel-cage motor will vary widely with changes of resistance* in the rotor winding. The breakdown torque will however remain substantially the same. As stated previously, a squirrel-cage motor has many of the characteristics of a transformer. A high-resistance secondary (rotor winding) results in a relatively low locked-rotor kva. A low-resistance rotor results in a high locked-rotor kva.

Torque is maximum *when the resistance and inductive reactance are equal.* But inductive reactance increases with frequency and will be high with locked-rotor conditions. To develop high starting torques the rotor resistance must therefore also be high and locked rotor kva will be relatively low. This is illustrated by *Curve 1,* Fig. 19. Such a motor would have a high slip, a high slip loss and consequently a low efficiency, and would not be suitable for continuous full-load operation, except in very rare cases.

If this rotor is replaced by one with a *very low resistance winding,* the maximum torque must be obtained at a point where inductive reactance is also low, possibly at 10% slip. This is illustrated by *Curve 2,* Fig. 19. Due to the low resistance winding, the locked-rotor kva will be high. The efficiency and full load speed will be high.

Starting torque *will be extremely low* due to the fact that rotor currents will be relatively low at standstill, being limited by inductive reactance in spite of the low resistance. But torque is equal to I^2R and since the resistance is low the torque will be low.

However, at operating speed (2% slip or 1.2 cycles per second on a 60 cycle system) the inductive reactance is low and the low stator resistance permits such a large current to flow that full-load torque is developed at very low slip. *Due to the low starting torque this design motor is not universally acceptable.*

A suitable compromise is a motor with a cage of normal design having characteristics as in *Curve 3,* Fig. 19. *This has adequate locked rotor torque for most applications, low starting kva and still has low slip and high efficiency.*

Double-Cage and Deep-Bar Rotors—Where good locked-rotor torque, low slip characteristics and low locked-rotor current are desired, a double-cage rotor, Figs. 20 and 23, is frequently used. The current in the low resistance lower cage bars is effectively limited by high inductive reactance at standstill. The inductive reactance is high on account of the large amount of iron in the magnetic circuit adjacent to these bars. The low-resistance lower cage winding is therefore quite ineffective. The upper cage, however, has low reactance and high resistance and this results in high locked-rotor torque and moderate starting current.

At operating speed the inductive reactance of the low-resistance winding is low due to the low slip frequency Most of the induced current then flows in the low resistance winding resulting in low slip and high efficiency.

Frequently, deep rectangular bars, Figs. 21, 22 and 24, are used. This approximates the performance of a double-cage rotor. It has the distinct advantage that the full area of the bar is effective for heat dissipation during starting and acceleration. The shallow, upper-cage, high-resistance bars of a double-cage winding are susceptible to damage on loads having a long accelerating time. This is due to concentration of the current in only the shallow upper cage windings at relatively low speeds.

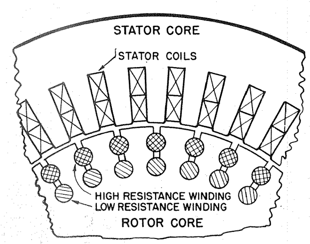


FIG. 20—*Double-cage rotor. Shallow high-resistance upper bars provide high starting torque. Deep, low-resistance bars give high efficiency low slip running torque.*

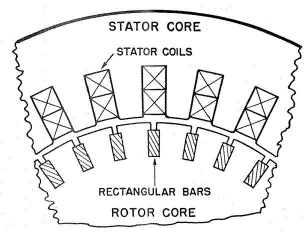


FIG. 21—*Deep-bar rotor. Approximates the performance of the double-cage rotor and has distinct advantage that large area is available for heat dissipation when starting.*

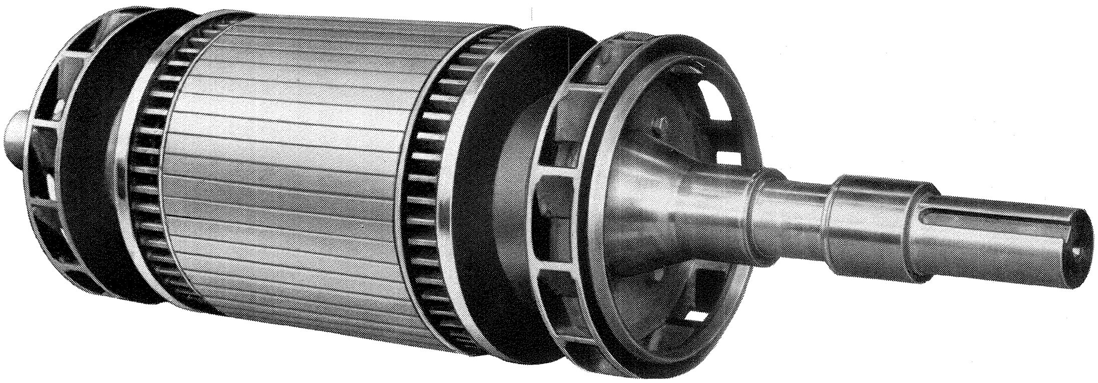


FIG. 22—*Rotor for medium-size, two-pole, 3600 rpm pump motor. Deep bars provide required starting torque with low starting current.*

ROTORS FOR SQUIRREL-CAGE MOTORS

The Arrangement of the Bars Is Varied To Provide Required Torques

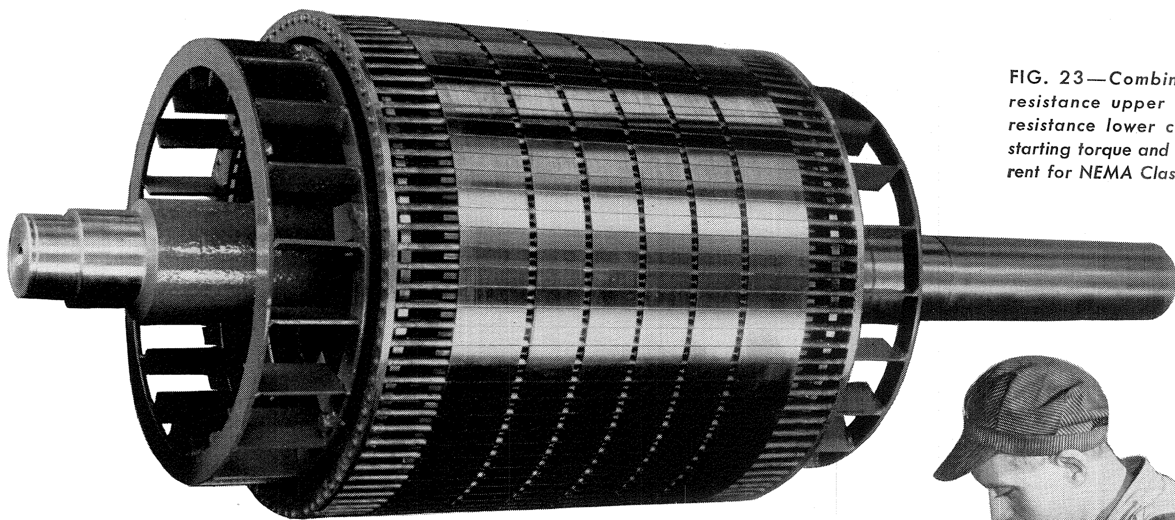


FIG. 23—*Combination of high-resistance upper cage and low-resistance lower cage gives high starting torque and low starting current for NEMA Class C motor.*

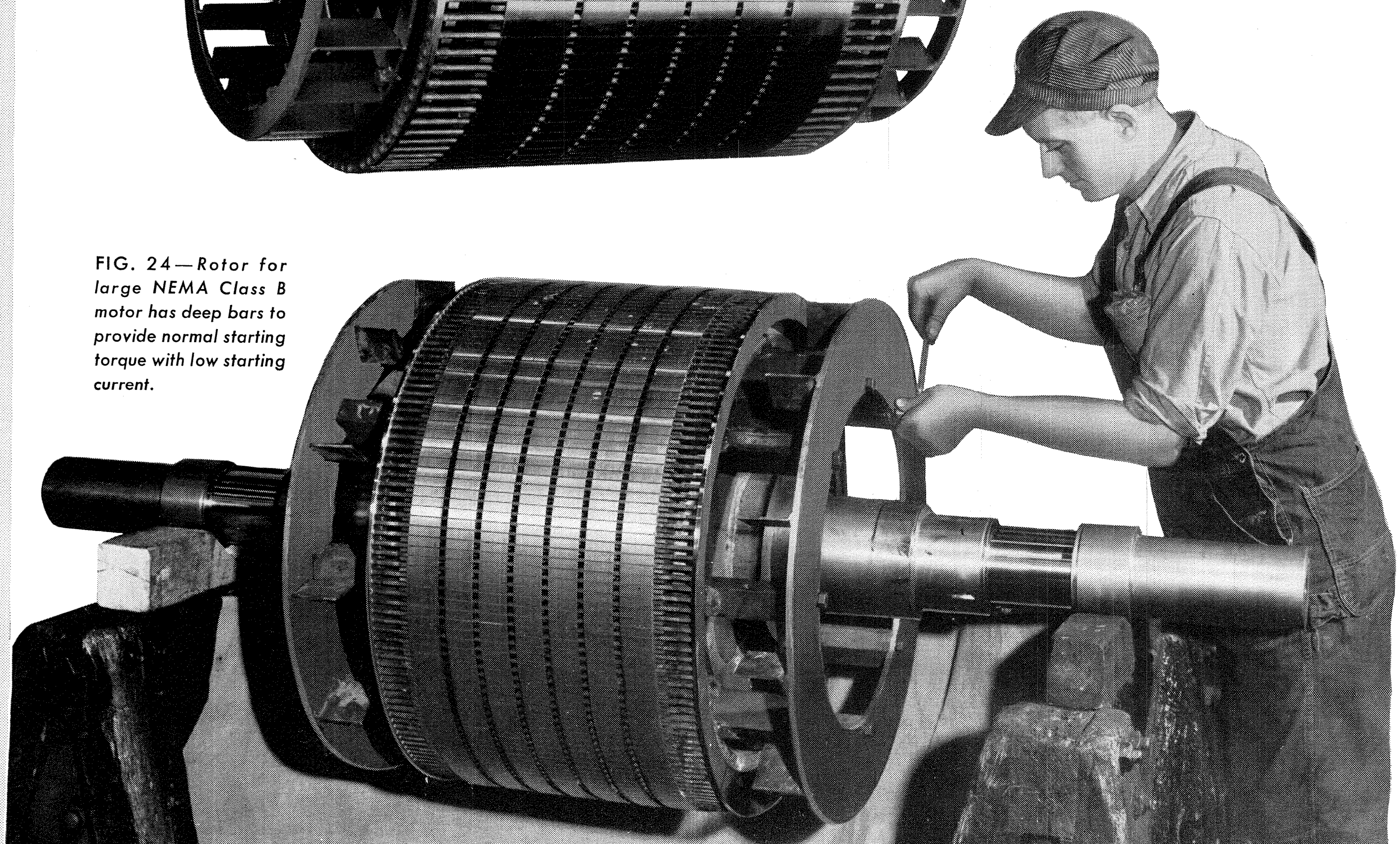
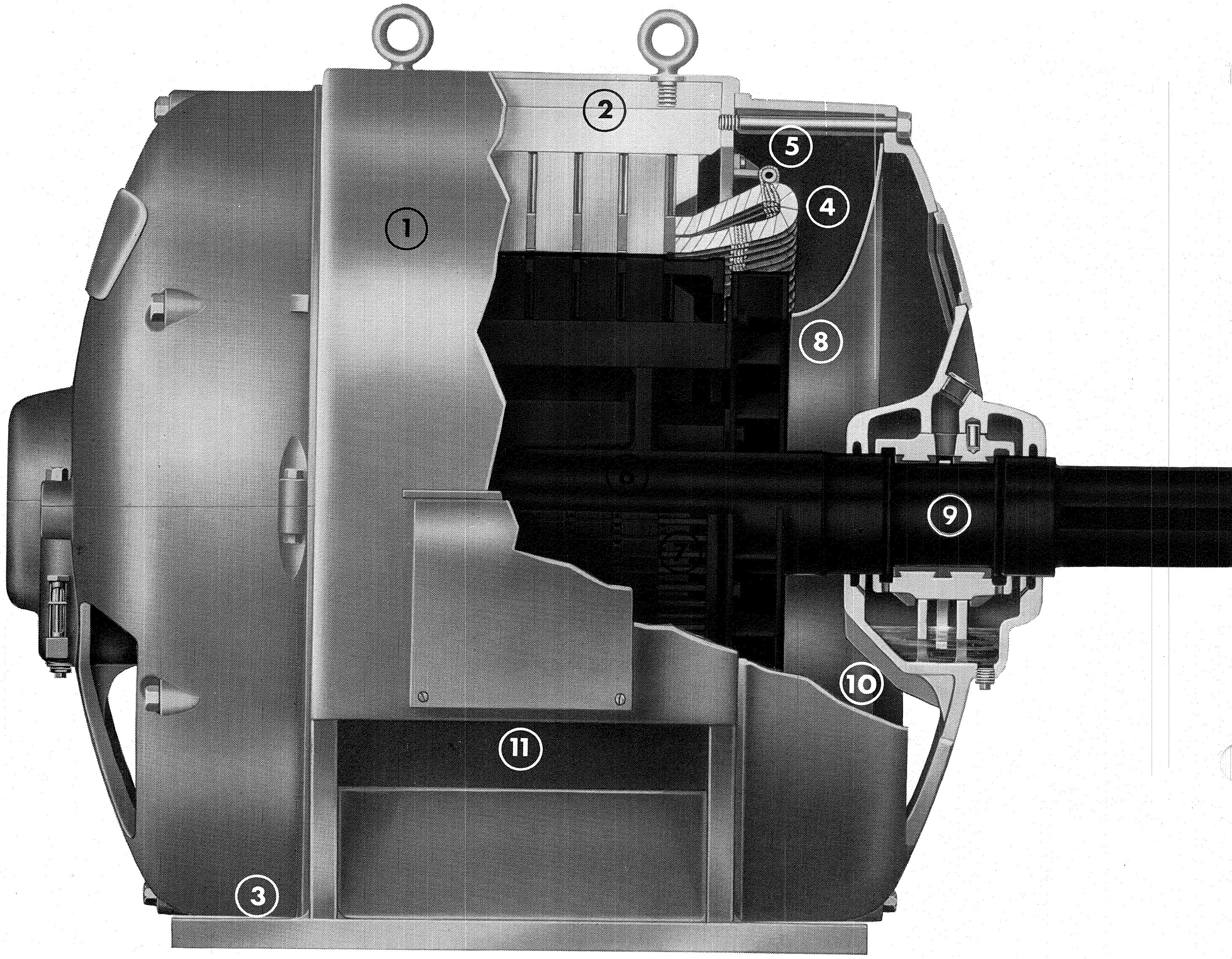


FIG. 24—*Rotor for large NEMA Class B motor has deep bars to provide normal starting torque with low starting current.*

CUTAWAY ILLUSTRATIONS SHOW CONSTRUCTION



Extra Protection and Durability Are Built Into Heavy Duty Induction Motors

FIG. 25—*The construction shown above is for drip-proof, sleeve bearing motors with four or more magnetic poles. Heavy-Duty Induction Motors are designed to meet the needs of drive service where continuous dependable trouble-free operation is a top requirement.*

The frame of the motor provides a high degree of physical protection to the working parts, and the smooth contours make cleaning easy. The electrical and magnetic components adequately and efficiently supply the required starting and running characteristics.

Large volume of air at low velocity ventilates all parts of the motor. This air is guided at the intake by curved baffles. The volute shape of the opening back of the stator core insures proper area for air discharge. Thorough ventilation means full utilization of the motor capacity and long life of the insulation.

Bearings are of modern one-to-one ratio length to diameter, insuring full seating over the length of the bearing journal. Anti-friction bearings are also standard or optional on these motors.

(Numbers refer to figure above)

1. External protection—Drip-proof construction (above) and splash-proof construction shield the motor from liquids and dirt.

2. Steel frame provides high impact strength and rigidity without excessive weight. Smooth contour makes cleaning easy.

3. Steel-Bar feet cannot crack with rough handling or when feet are being bolted down.

4. Stator Coils are insulated with many layers of tape, impregnated between layers, and sealed to minimize entrance of moisture.

5. Coil-Ends are firmly braced to minimize coil vibration and prevent coil distortion.

6. Rotor is made strong and stiff. The structure which supports the rotor core is welded directly to the motor shaft.

7. Cage-Winding durability and permanent torque characteristics are secured by silver soldering or phos-copper brazing the cage bars to the end-rings.

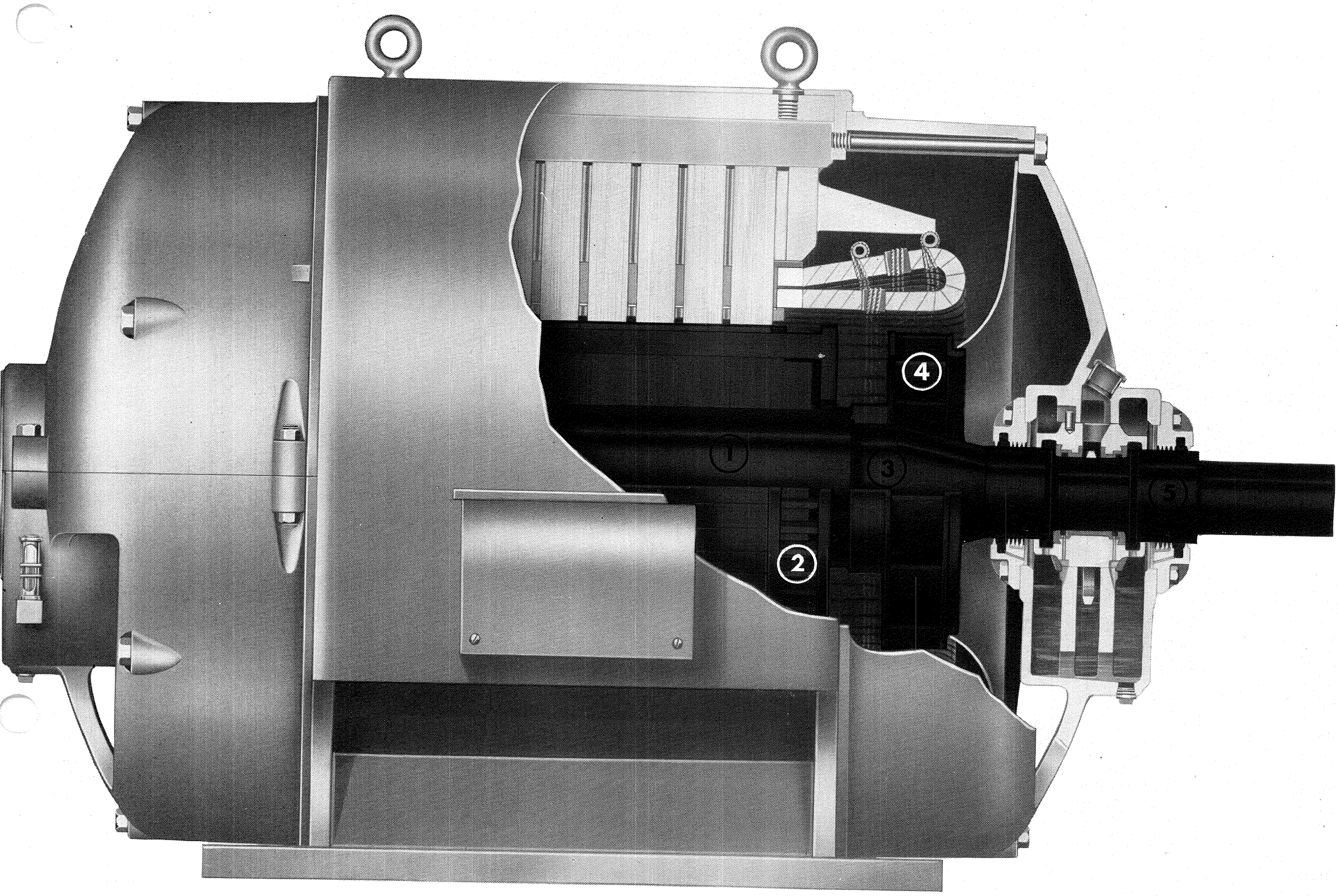
8. Ventilation is engineered to provide adequate volume of air to all working parts of the motor.

9. Bearings are designed to run cool and to minimize oil leakage or entrance of dust.

10. Large air intake—Relatively low air velocity minimizes dirt particles being drawn into the motor.

11. Air is discharged at the feet and a baffle directs it away from the motor.

FEATURES OF SQUIRREL-CAGE INDUCTION MOTORS



Two-Pole Motors Are Engineered for Exacting Needs of High-Speed Service

FIG. 26—*The requirements of two-pole motors put a high premium on motor reliability. Sound design, durable construction, proper protection and minimum vibration are major factors in assuring this dependability.*

(Numbers refer to figure above)

1. Strong, stiff rotor—Core laminations are single-piece punchings stacked and keyed directly on the shaft. Shaft diameter at rotor core is extra large to keep critical speed well above operating speed.

2. Phos-copper brazed cage windings—Cage bars are oxygen-free copper, brazed to the end rings. Cage structure designed so expansion and contraction are well within elastic limits of the metal.

3. Rotor is dynamically balanced for smooth running.

4. Minimum noise—Windage noise minimized by (1) Centrifugal fans designed to move air at relatively low velocity, (2) Ventilating fan blades inclined to produce low degree of shock on entering air, (3) Solid rotor core—no jets of air impinging on the stator teeth.

5. Cool-running bearings—Shaft Journals are ground to smoothness readings of 5 to 10 micro-inches. Bearing is 1 to 1 ratio diameter to length, with surface velocity and unit seating pressure designed for low temperature rise.

Kolene-Process centrifugally-cast bearing sleeve linings insure dense, uniform babbitt, free from blow-holes.

PRESSURE LUBRICATION. FIG. 27—*500 hp, 3600 rpm squirrel-cage motor for oil pipe-line pumping. Lubrication is furnished by pump worm-geared to motor shaft. High-pressure side is by-passed to reservoir with pre-set orifice to control proper flow of oil. Oil rings provide oil when motor is starting up.*

PART THREE

CHARACTERISTICS AND APPLICATION *of squirrel-cage and wound-rotor motors; the methods and limitations of reduced kva starting.*

Squirrel-Cage Motors

The great majority of squirrel-cage induction motors are used for a relatively few applications. To obtain some uniformity in application, the National Electrical Manufacturers Association (NEMA) has designated specific designs or classes of motors, *having specified locked-rotor torque, breakdown torque, slip, starting current, or other values.* The more common ones are NEMA Class B, NEMA Class C and NEMA Class D. These are described below.

NEMA Class B (Normal Starting Torque, Low Starting Current)—These are the most widely used of all types of squirrel-cage motors. They have locked rotor torques adequate for starting a wide variety of industrial machines and drives and a starting current, on full voltage, usually acceptable to power systems. A typical torque curve for a Class B motor is shown in Fig. 28.

Some of the general-purpose applications are:

Machine Tools	**Line Shafting**
Fans and Blowers	**Centrifugal Pumps**
Compressors (starting unloaded)	**Various Types of Mills**
	Generators
Chippers	**Crushers**
Hogs and Hammermills	**Jordans and Refiners**

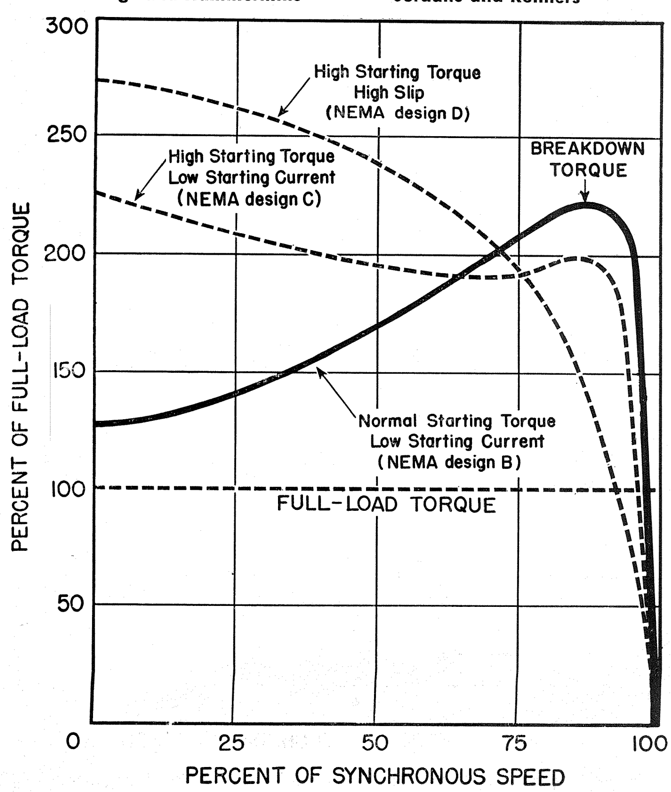


FIG. 28—*Typical torque curves for NEMA Class B, C and D induction motors.*

Locked rotor torques for NEMA Class B motors will be not less than the following;

Motors 200 HP and Smaller		Motors 250 HP and Larger	
Poles	**Locked Rotor Torque**	**Poles**	**Locked Rotor Torque**
2	100% full-load torque	2	40 to 75% full-load torque
4	100% full-load torque	4	50 to 125% full-load torque
6	125% full-load torque	6	50 to 115% full-load torque
8	125% full-load torque	8	50 to 110% full-load torque
10	120% full-load torque	10	50 to 110% full-load torque
12	115% full-load torque	12	50 to 110% full-load torque
14	110% full-load torque	14	50 to 95% full-load torque
16	105% full-load torque	16	50 to 90% full-load torque

Full-load slip will be between 1½% and 3% on Class B motors for the usual range of horsepower ratings. Very large motors may have a slip of less than 1%.

NEMA Class C (High Starting Torque, Low Starting Current)—These motors have high locked-rotor torques, low starting current and relatively high full-load slip. A typical torque curve for a Class C motor is shown in Fig. 28. Class C motors are especially suited for driving:

Reciprocating Compressors—starting under load

Material Conveyors and Elevators—having high break-away friction

Stokers, Crushers and Pulverizers—which encounter material at start

Positive Displacement Pumps—handling high viscosity liquids at start

Class C motors are usually designed with a locked-rotor torque of over 200% and a breakdown torque of not less than 195%. The slip at full load in the usual range of horsepower ratings will be 1½% to 3%. Class C motors have double-cage rotors as shown in Fig. 23, page 15.

NEMA Class D (High Starting Torque—Low Starting Current—High Slip)—These motors use a high-resistance rotor and are commonly used on loads having high intermittent peaks. The driven machines are usually provided with a flywheel having considerable Wk^2. At no-load the motor operates with very little slip. When the peak load is applied the motor slip increases appreciably, permitting the unit to absorb energy from the flywheel. This reduces the power peaks supplied by the electrical system, resulting in a more uniform power requirement.

Class D motors may be used with Punch Presses, Reciprocating Pumps, Chippers, etc. A typical torque curve is shown in Fig. 28.

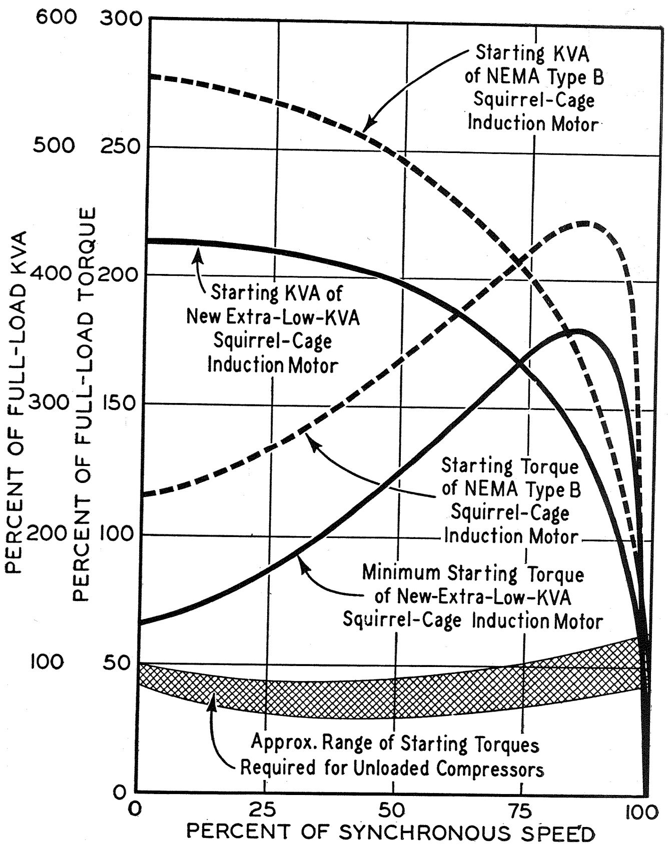


FIG. 29—*Comparison of typical torque and kva characteristics of NEMA Design B and E-M Design "X" extra-low kva induction motors*

E-M Design "X" (Low Starting Torque—Extra-Low Starting Current)—To supplement a line of low starting current, low starting torque synchronous motors, E-M has brought out a special line of squirrel-cage motors known as Design "X" (Across-the-line starting). Comparative torque and starting current characteristics are shown in Fig. 29.

The following ratings at 60 cycle speeds are now available in the flange-mounted (overhung) type and coupled type:

Horsepower	60 CYCLE SPEEDS		
	720	600	514
60		x	
75	x	x	
100	x	x	
125		x	
150		x	x
200		x	x
250			x

These motors have power factors and efficiencies no lower than standard NEMA Class B motors. The motors are especially adapted to machines which start unloaded such as air compressors and pumps.

The starting current is approximately 80% of that of equivalent Class B motors, thus in practically all cases permitting full-voltage starting.

2-Pole Motors (3600 synchronous rpm at 60 cycles, 3000 synchronous rpm at 50 cycles.)—To obtain low starting current, 3600 rpm and 3000 rpm Class B motors usually have low locked-rotor torque and low accelerating torque. A typical torque curve for such a motor is shown in Fig. 30.

The lower dotted curve illustrates the torques required by centrifugal pumps or centrifugal compressors with *closed discharge*. The upper dotted curve illustrates torque requirement with *open discharge*. These curves show that such units must always be started unloaded, and full line voltage must be maintained. If during a period of low voltage the motor should drop down to about 60% speed, it might not be able to accelerate to full speed on full voltage unless again unloaded.

Starting Current of Squirrel-Cage Motors—NEMA has established Code Letters representing starting conditions in *Kva per HP* when started on full voltage. The code letter is stamped on the motor nameplate. A knowledge of this motor starting current permits proper selection of wire size, fuses, breakers, etc., during installation of the motor. Code values are as follows:

Code Letter	Kva/HP at Locked Rotor Full Voltage	Code Letter	Kva/HP at Locked Rotor Full Voltage
A	.1 —3.14	J	7.1 — 7.99
B	3.15—3.54	K	8.0 — 8.99
C	3.55—3.99	L	9.0 — 9.99
D	4.00—4.49	M	10.0 —11.19
E	4.50—4.99	N	11.20—12.49
F	5.0 —5.59	P	12.50—13.99
G	5.6 —6.29	R	14.0 —and up
H	6.3 —7.09		

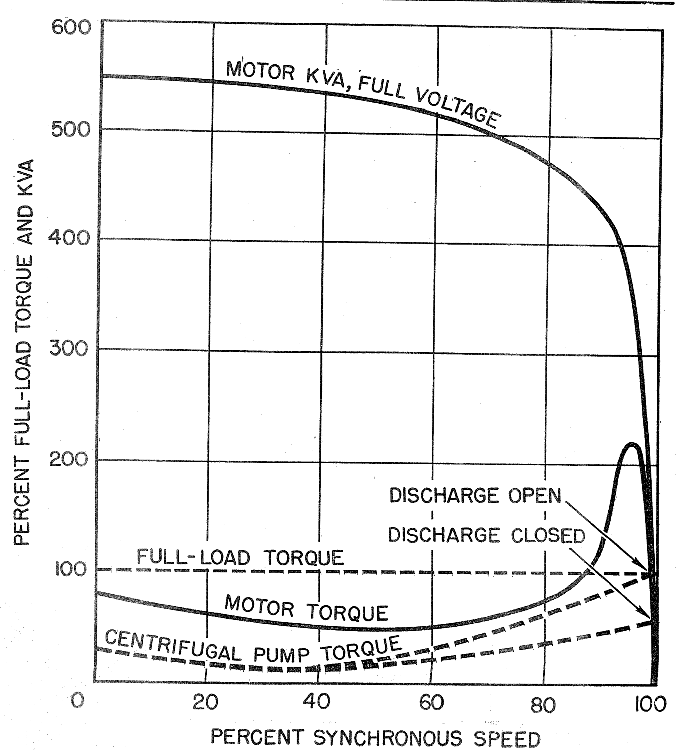


FIG. 30—*Typical speed-torque curve for NEMA Class B, 3600 rpm squirrel-cage motor. Dotted lines show torque requirements of centrifugal pump.*

Reduced-Kva Starting

It must be borne in mind that *any reduction in starting kva will be accompanied by at least an equal reduction in locked rotor torque and accelerating torque.* There is no advantage in specifying a high-torque motor to meet a difficult starting situation and then limiting the starting kva to a value such that reduced voltage starting must be used.

Each design of motor will have a quite definite ratio of torque to kva on starting, and for any given motor design a reduction in kva must be accompanied by a reduction in torque. Thus a Class C motor provides more starting torque per kva than a Class B motor.

Most power companies have quite definite restrictions on permissible starting kva. Common permissible starting methods are the following:

1. *Full voltage starting regardless of rating or type.*
2. *Full voltage starting up to a specified horsepower limit*—reduced voltage starting above that value.
3. *Starting current limited to fixed percentage of full load current.* The method of starting may be full voltage, reduced voltage or other method as long as this stipulation is met.
4. *Increment starting.* This consists of permitting certain increases in starting current at fixed intervals of time using closed transition between steps; that is there may be no interruption in current during transfer from one step to the next. This method is commonly used on 120-208 volt network systems and either resistance or reactor starters, part winding starters, or wound-rotor motors are used.

Circuit Connections for various types of starters are illustrated on the opposite page. Other connections may be possible in many cases but the diagrams used illustrate the principles involved.

The following tabulation illustrates the *line current, motor current,* and *locked-rotor torque* developed for various values of voltage applied to the stator of the motor for reduced voltage, (auto-transformer) and series resistor, or reactor, starting.

	AUTO-TRANSFORMER STARTING			SERIES RESISTOR STARTING		
Voltage Applied to Motor in Percent of Rated Voltage	Line Current in Percent of Motor Locked Rotor Current	Motor Current in Percent of Locked Rotor Current	Locked Rotor Torque in Percent of full Voltage Value	Line Current in Percent of Motor Locked Rotor Current	Motor Current in Percent of Locked Rotor Current	Locked Rotor Torque in Percent of Full Voltage Value
100	100	100	100	100	100	100
90	81	90	81	90	90	81
80	64	80	64	80	80	64
70	49	70	49	70	70	49
60	36	60	36	60	60	36
50	25	50	25	50	50	25

From the foregoing table it will be seen that the ratio of torque to kva is lower on series-resistor starting than on auto-transformer starting. With *series-resistor starting* the kva varies *directly* as the voltage applied to the motor terminals, and the torque varies as the square of that voltage. With conventional *reduced-voltage (auto-transformer) starting* both kva and torque vary as the *square* of the voltage. Also there is an opening of the circuit in the transition from reduced voltage to full voltage.

The great advantage of resistor starting is that the starting current can be increased in relatively small increments and with no interruption to the circuit. The series resistance may be short-circuited by means of contactors, or in the case of carbon-pile resistors, it may be reduced in large part by the application of pressure.

The terms starting kva and starting current *are commonly used interchangeably.* With respect to the combination of motor and starter this is satisfactory. Since kva is the product of voltage and current, any change of current, at fixed voltage, means a corresponding change in kva. Since kva per horsepower is used in setting up the NEMA code letters for motors starting characteristics the term kva is commonly used in all cases. This is true whether kva is expressed as a percentage of full load kva or as a fixed amount.

Figures on the opposite page show connections, torque and kva characteristics for various methods of starting.

1. **Full-Voltage Starting.**

2. **Reduced-Voltage (Auto-transformer) Starting,** transferring to full voltage at 75% speed. Dotted line shows torque available on full voltage. Note that current and torque drop to zero at transfer and that there is a transient current at that point which causes the current to exceed the full-voltage value for that speed.

3. **Closed-Transition (Korndorfer) Starting**—Circuit is not interrupted during starting and positive torque is always applied to motor. On second step, part of auto-transformer reactance remains in series with the stator winding.

4. **Series-Resistance Starting**—Provides closed transition but has low ratio of torque to kva. Compression type carbon pile disc is sometimes used as resistor element. Series reactor may be used instead of resistor.

5. **Part-Winding Starting**—Stator is wound with two, or more, parallel circuits, which are successively connected to the line. Provides closed transition and has good ratio of torque to kva. Not suitable for small or high speed motors.

6. **Star-Delta Starting**—In considerable vogue in Europe but has found little favor in this country, probably due to antipathy of American designers and operators to delta-connected motors. Only necessary starting equipment consists of switches. The motor starts as a star-connected motor and runs delta. This is equivalent to starting on the 57% tap of an auto-transformer.

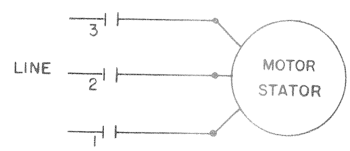
METHODS OF STARTING

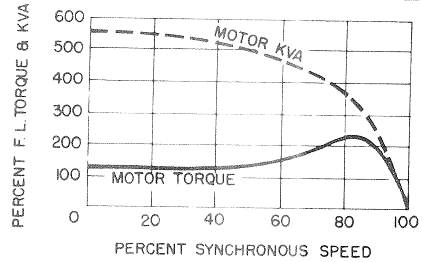
FOR SQUIRREL-CAGE INDUCTION MOTORS

1. FULL-VOLTAGE STARTING

Start: Close 1-2-3

Run: No change

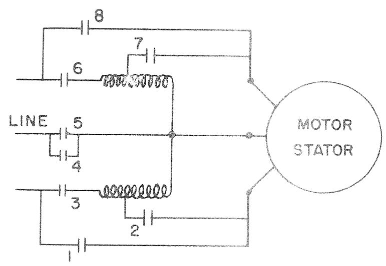


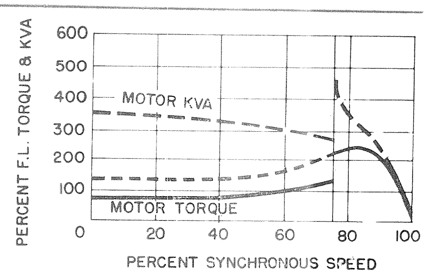


2. REDUCED-VOLTAGE (Auto-transformer) STARTING

Start: Close 2-3-5-6-7

Run: Open 2-3-5-6-7
Close 1-4-8



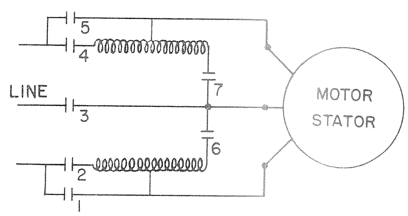


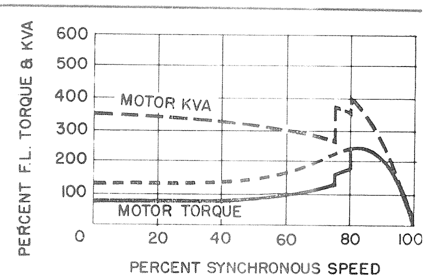
3. CLOSED-TRANSITION (Korndorfer) AUTO-TRANSFORMER STARTING

Start: Close 6-7-2-3-4

Transfer: Open 6-7

Run: Close 1-5



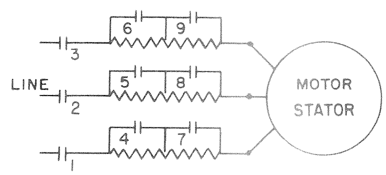


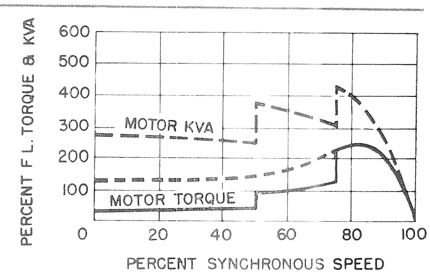
4. SERIES-RESISTANCE STARTING

Start: Close 1-2-3

Second Step: Close 4-5-6

Third Step: Close 7-8-9

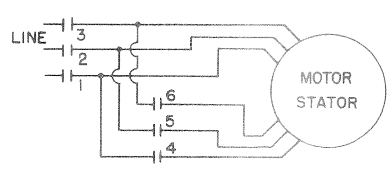


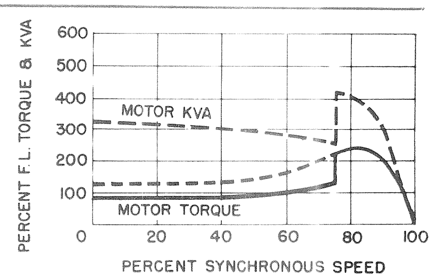


5. PART-WINDING STARTING

Start: Close 1-2-3

Run: Close 4-5-6

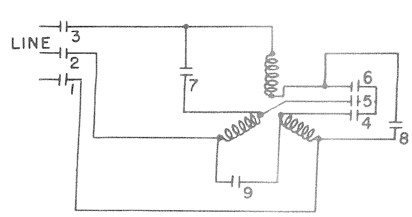


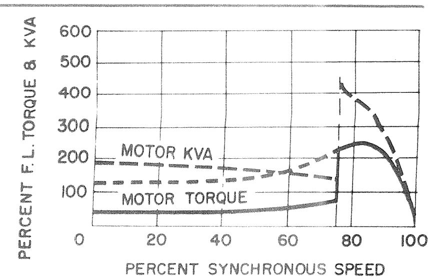


6. STAR-DELTA STARTING

Start: Close 1-2-3-4-5-6

Run: Open 4-5-6
Close 7-8-9





Multi-Speed Squirrel-Cage Motors—Squirrel-cage motors are essentially fixed speed motors. Variable speed is obtained, however, on group steel-mill roll-out motors by altering the frequency of the power supply. This is done by means of variable frequency generators.

Speed may also be varied over a small range by varying the primary voltage. This can be done for small motors only. It is not practicable for normal industrial applications due to difficulty in dissipating the heat generated by the rotor slip loss.

However, it is readily possible to arrange, squirrel-cage motors for two speeds per winding. As mentioned on page 12, the number of magnetic paths determines the number of poles and thus the synchronous speed. The number of magnetic paths depends on the direction of current flow through the coil groups.

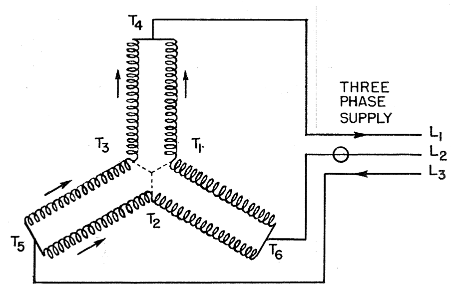


FIG. 31—*Parallel-star (high-speed) coil connection for two-speed induction motor. Ends T_1, T_2, T_3 are connected together; T_4, T_5 and T_6 are connected to power supply.*

Fig. 31 illustrates a typical parallel-star coil grouping. At a given instant, the direction of current in the coil groups would be as indicated by the arrows. The coils would be grouped and connected as shown in Fig. 32.

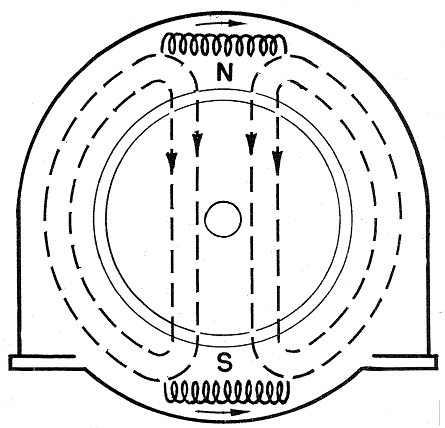


FIG. 32—*Parallel-star connection of Fig. 31 provides 3600-srpm speed for a 3600srpm/1800srpm two-speed motor.*

This would result in one North pole and one South pole per phase group. The magnetic lines of force would be as shown by the dash line. On 60-cycle service this motor would have a synchronous speed of 3600 rpm.

Now if the internal and external connections are changed to those shown in Fig. 33, this becomes a series-delta

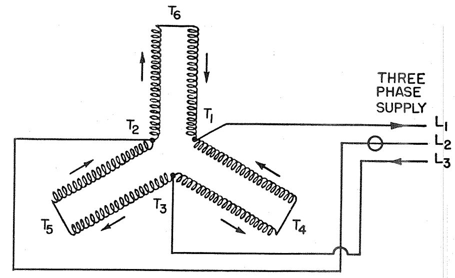


FIG. 33—*Series-delta (low-speed) coil connection for two-speed induction motor. T_1, T_2 and T_3 are connected to the power supply.*

connection, probably better represented by Fig. 34. The direction of flow of current causes both coil groups in that phase, to establish South magnetic poles.

However, for magnetic lines of force to flow from the rotor into the stator (South poles) at both coil groups they must flow from the stator into the rotor at corresponding points (North poles). North poles formed in this way are called "consequent" poles.

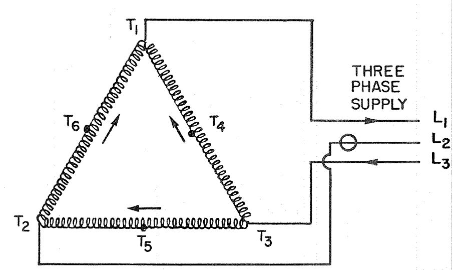


FIG. 34—*This diagram is supplementary to Fig. 33 above to show the series-delta arrangement of the windings for the low speed.*

The arrangement is shown as it actually occurs, in Fig. 35. As will be noted, there now exists four poles and the synchronous speed on 60 cycles would be 1800 rpm—half the previous value.

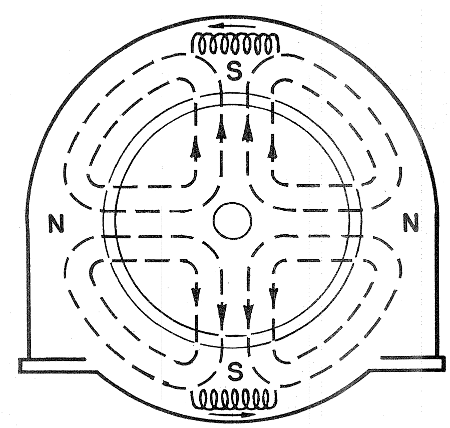


FIG. 35—*Series-delta connection of Figs. 33 and 34 provides "consequent" poles to give 1800 srpm for a 3600 srpm/1800 srpm two-speed motor.*

By choice of winding and circuit arrangements a motor may be designed for two-to-one ratio for either variable torques, constant torques or constant horsepower operation.

By building a motor with two separate windings, each suitable for two-to-one connection, a squirrel-cage motor can be built for *four speeds.*

Variable-Torque, Multi-Speed Motors are used for loads such as fans and centrifugal pumps.

Constant-Torque, Multi-Speed Motors are used on reciprocating compressors and loads of similar nature.

The following table lists two-speed, *constant-torque speeds and ratings* available with a 100 hp, high-speed motor.

High Speed		HP Continuous 40°C at Low Speed of						
HP 40°C.	Syn. RPM 60 Cycle	1800	1200	900	720	600	450	No. of Windings
100	3600	50						1
	1800			50				1
	1800		66	50	40	33 or 25		2
	1200					50		1
	1200			75	60	50 or 37		2
	900						50	1
	900				80 or 66			2
	720					83 or 62		2
	600						75	2

Constant-Horsepower, Multi-Speed Motors are used for machine tools. The connections used in Figs. 31 and 33 are for constant horsepower.

NOTE that a two-to-one speed and horsepower is possible with a single winding. Any two-speed combination is available with two windings; also a two-to-one horsepower and speed combination is possible on *each* of two separate windings.

Wound-Rotor (Slip-Ring) Induction Motors

As discussed on page 14 the resistance of the rotor winding has a marked effect on the torque developed at any speed. To develop high starting torque at low starting current requires a *high-resistance rotor.* To develop low slip at full load, high operating efficiency and moderate rotor heating requires a *low-resistance rotor. The wound rotor (slip-ring) motor is a means of approximating both of these conditions.*

The wound-rotor motor has a *phase-wound* secondary (rotor), having as many poles as the stator winding, connected to slip rings. These slip rings are, in turn, connected to an external resistor. By means of a controller, or a series of magnetic contactors, varying amounts of this external resistance may be shorted out. Torque vs. speed curves for various resistance steps are illustrated in Fig. 37.

With all secondary resistance inserted (R_1), approximately full-load starting torque is developed at less than 150% of full-load current. By successively shorting out resistor steps, at standstill, up to about 225% of full-load torque can usually be developed on the 4th step. Cutting out additional resistance will then reduce the torque at standstill.

Speed Control with Wound-Rotor Motors

If the motor in Fig. 39 should be left with only two steps of resistance shorted out it would continue to operate indefinitely at approximately 65% speed, as the torque developed by the motor equals the load torque at that speed. The heat resulting from the slip loss would be dissipated in the external secondary resistor which, in that case, would have to be designed for continuous duty.

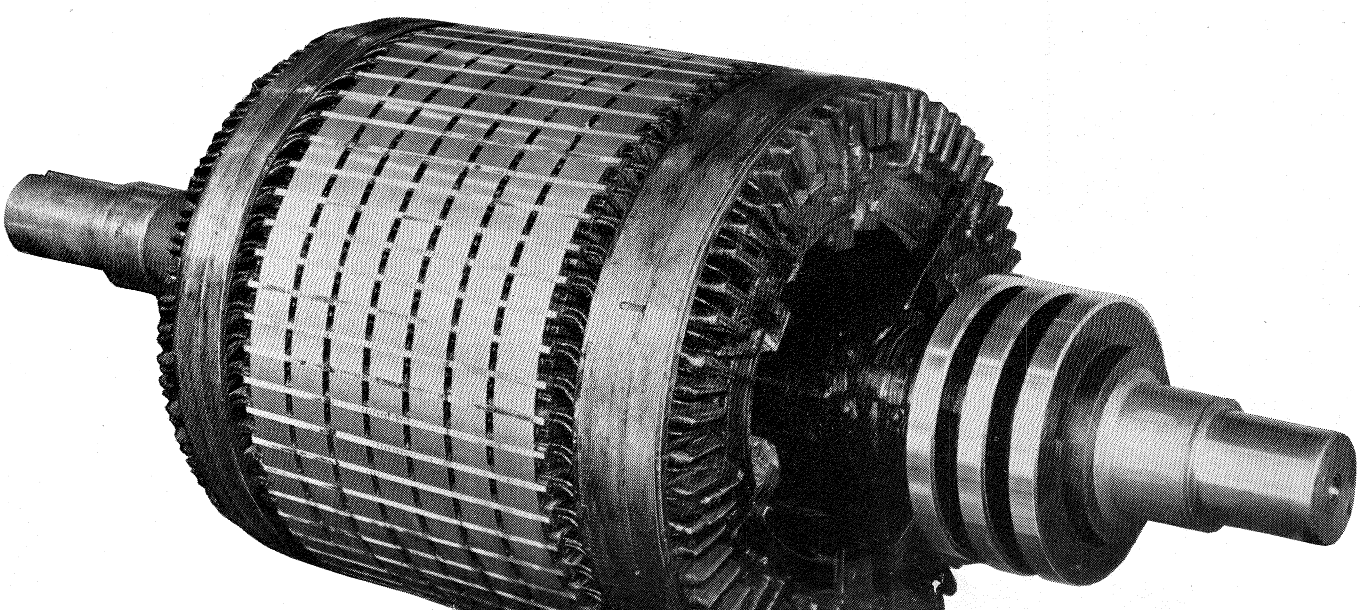


FIG. 36—Rotor of 600 hp, 1750 rpm wound-rotor induction motor for driving centrifugal refrigeration compressor.

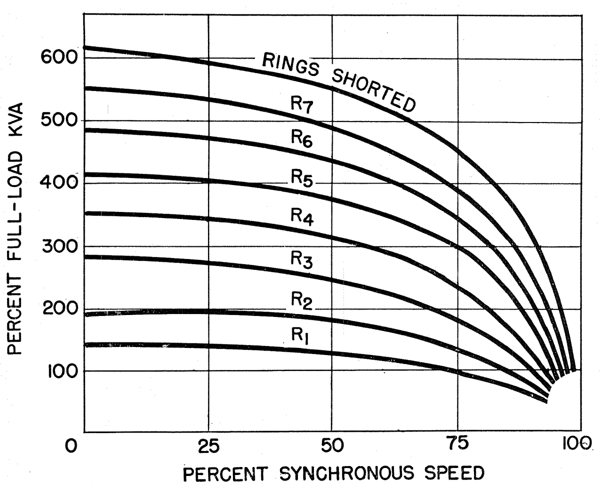


FIG. 37—*Starting currents of wound-rotor motor with various steps of external resistance in secondary circuit.*

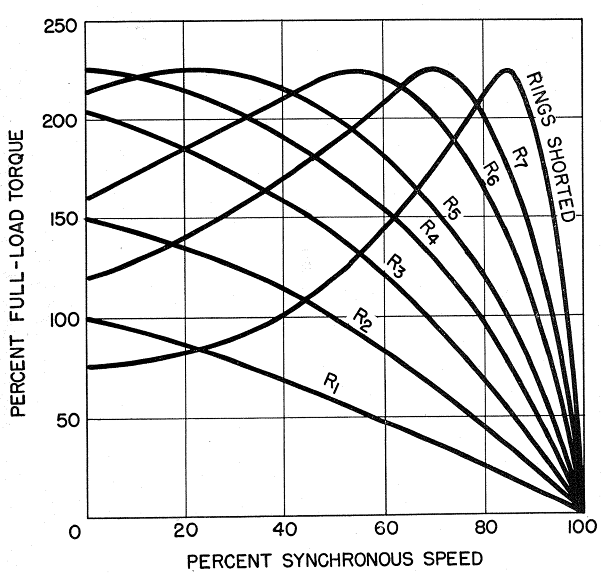


FIG. 38—*Torque curves of wound-rotor motor with various steps of external resistance in secondary circuit.*

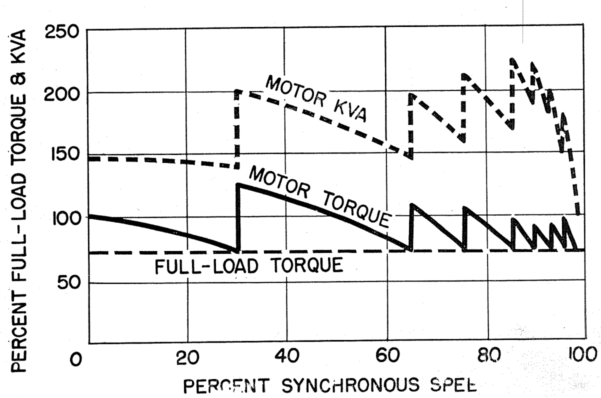


FIG. 39—*Showing how secondary resistance of wound-rotor motor can be controlled to provide required torque at various speeds with minimum current.*

However, if, for some reason, the torque should drop to 50% of full-load torque, *the speed would immediately increase to approximately 75% of synchronous speed* (following the R_2 torque curve, see Figure 38, until it crosses the 50% torque line).

The wound rotor motor, therefore, *is not an exact means of speed control under varying load conditions.* That is a given point on the controller will not necessarily assure a given speed. Torque characteristics of the load will be a factor since *the intersection of load and motor* torque curves will determine the speed. *For a given resistor value the speed can vary widely if load torque, voltage or other conditions vary.*

For applications where the wound-rotor motor is used for starting purposes, the collector rings are short-circuited, by the contactors of the secondary control, during normal motor operation. The motor then operates like a squirrel-cage motor with resulting maximum operating efficiency.

However on some loads having high intermittent peaks of short duration the motor will be operated with a step or two of resistance cut in. Then at light load the motor operates at nearly synchronous speed. When peak loads are encountered they will cause an appreciable drop in speed. The flywheel effect in the motor and the load will deliver energy during the decelerating period, serving as a cushion between the load and the power supply. Large chipper motors are often operated in this way when their rating is an appreciable part of the power system capacity.

Application of Wound-Rotor Motors

Wound-rotor motors are especially adaptable to *compressors, plunger pumps,* or other applications started loaded, where high values of starting torque and low starting currents may be required; also where the inertia of the driven machine is high and extremely high slip losses would have to be dissipated in a squirrel-cage rotor in getting up to speed.

Wound-rotor motors are also used on *cranes, hoists, elevators,* and other similar types of load where frequent starting, stopping and reversing, as well as speed control may be required.

In some cases wound-rotor motors are used where continuous operation at reduced speed is required. *Pumps and boiler draft fans* are typical applications. In general, speed stability is unsatisfactory below 50% speed. At that speed a wound-rotor motor will develop 40% of full rated horsepower continuously.

Wound-rotor motors have been used in large numbers for operating boiler draft fans. Automatic combustion control is used to actuate the steps of external resistance in the rotor circuit to secure the proper speeds, and dampering is used to regulate air flow between speed steps and belo[illegible] speed.

Wound-rotor motors are also used with either manual or automatic control, to vary the speed of centrifugal pumps and centrifugal refrigerating compressors.

STARTING TORQUE and KVA

OF WOUND-ROTOR INDUCTION MOTORS FOR VARIOUS TYPICAL LOADS

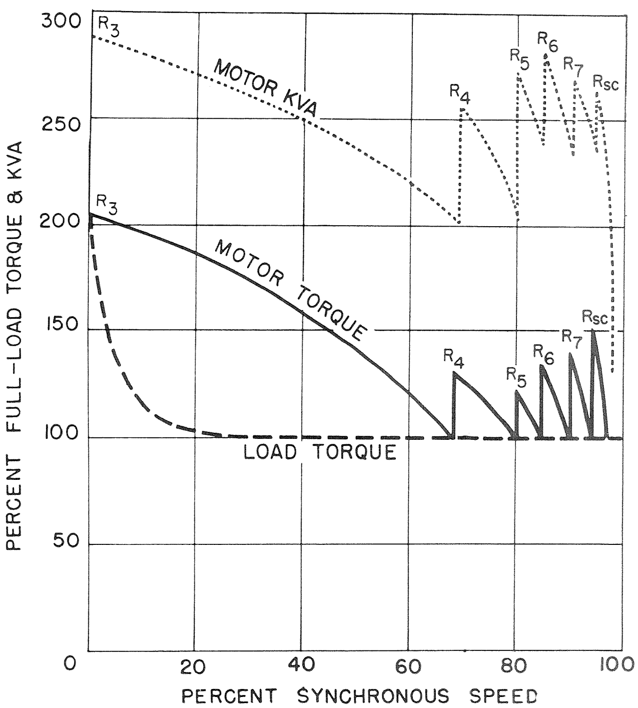


FIG. 40—*Starting Loaded Reciprocating Compressor.*

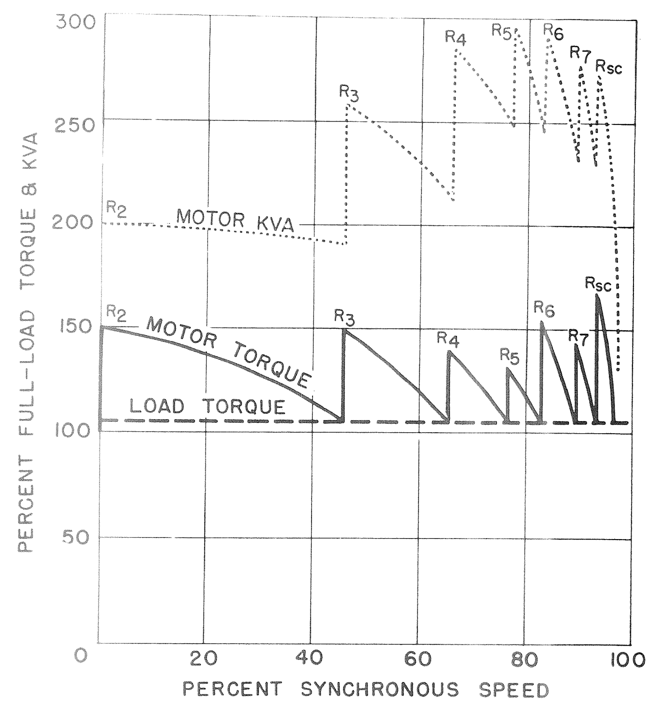


FIG. 42—*Starting Constant-Torque Load.*

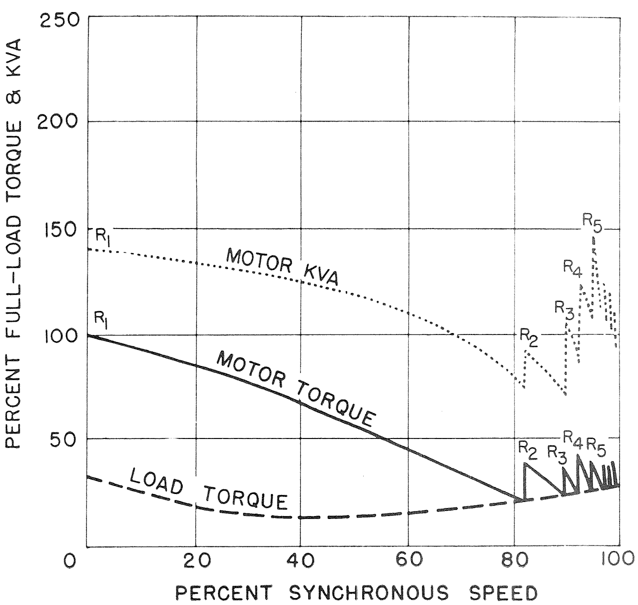


FIG. 41—*Starting Unloaded Reciprocating Compressor.*

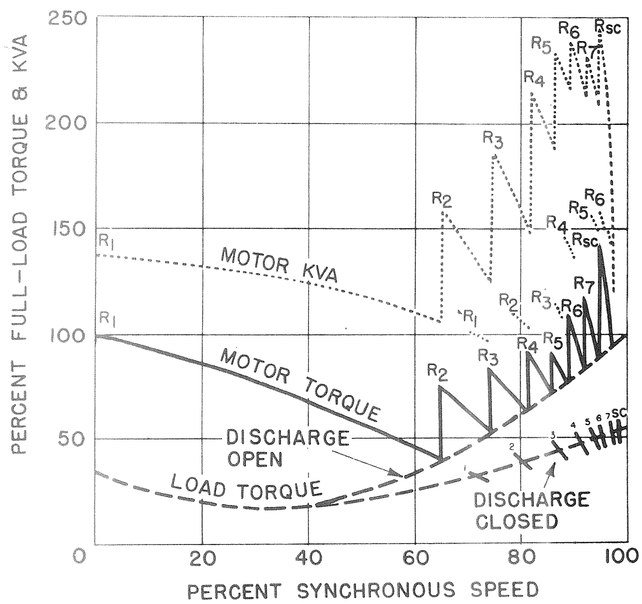


FIG. 43—*Starting Centrifugal Pump or Compressor.*

● **The four curve- ... ,w the torque of the wound-rotor induction mɯtor ɩan be controlled to mat-- the starting and accelerating requirements of the load. This torque control is obtained by successively short-circuiting sections of the external resistor in the rotor circui' so that the minimum motor torque necessary to accelerate the load will be maintained. Starting torque control as above keeps starting current at a minimum.**

PART FOUR INDUCTION MOTOR CONTROL... *The Adjustable-Speed Magnetic Drive*

Squirrel-Cage Motor Controls

The chart on page 21 illustrates the various methods of starting squirrel-cage motors. The decision as to the type of starting depends on the conditions of the installation from the standpoints of permissible current inrush from the power system, torque requirements of the load, and whether or not high torque acceleration is objectionable to the driven machine.

For large induction motors *Magnetic Control* has largely outmoded manually-operated control. The remote control feature permits mounting the starter near the motor, using short motor leads, with small control wires running to the pushbutton station or to pressure switch, float switch or other pilot device.

Full Voltage (Across-the-Line or "X") Starters are universally used wherever the line capacity or generating capacity will permit, and where full-voltage torque and acceleration is not objectionable. Full-voltage starting equipment is easiest to install, operate and maintain, and has lowest first cost.

For Low-Voltage Motors. Fig. 44 shows a typical across-the-line starter. The starter is provided with undervoltage protection and thermal overload relays. The combination starter provides a disconnect switch, which is obtainable in the fusible or non-fusible type, in combination with the starter.

For Voltages above 600, oil-immersed contactor type control, such as shown in Fig. 45, is commonly used.

A control-circuit transformer supplies the low voltage for the pushbutton circuit and the closing circuit of the contactor. In many cases a time-delay undervoltage release type of pushbutton station is used to keep the control energized during momentary voltage dips.

Short-Circuit Protection—In many locations the energy available from the power system in case of a ground or short-circuit is more than can be interrupted by the motor starter. Provision must then be made for interrupting the circuit, in case of a fault, without danger to personnel or excessive damage to apparatus. This requirement is met for high voltage motors, with the "Hi-Fuse" (*high-interrupting-capacity, current-limiting fuse control*), shown in Fig. 46, or *high-interrupting-capacity oil or air circuit breaker control.*

In the "Hi-Fuse" Control, Fig. 46, current-limiting power fuses are used between the motor switch and the power circuit. These fuses limit short-circuit current to a value that can successfully be interrupted by the fuses. The fault current is interrupted in ½ cycle or less, thus disconnecting the motor and control so quickly as to minimize damage to the motor, and minimize the stresses on the control and the power system. The fuses serve also as disconnects.

Reversing, Across-the-Line Starting for squirrel-cage motors is accomplished by t magnetic contactors or switches, one for forward rotatio , the other for reverse rotation. A mechanical interlock is provided to prevent both switches from closing at the same time.

Multispeed, Across-the-Line Starters consist of one or more magnetic contactors or switches for each speed, which respond to pressing the pushbutton corresponding to the motor speed desired. Overload protection is provided for each speed and the switches are mechanically interlocked to prevent their closing for one speed until they have opened for the other.

Reduced Kva Starting—A popular, current-limiting starting device for squirrel-cage motors up to approximately 200 horsepower has been the well-known manually operated *Compensator,* such as shown in Fig. 47.

The Compensator consists of an auto-transformer, providing a reduced voltage for starting, and a switching means by which the operator connects the motor first to the auto-transformer for starting, and then to full line voltage for running. These operations are performed manually by throwing the lever to "start" and then to "run". An interlock prevents throwing the lever directly to "run" so the motor must be started on reduced voltage.

On *network systems,* typically 120-208 volts, the starting current is usually limited to increments of so many amperes per second. Also, opening the circuit during starting is not permitted. In such cases the *resistor type* starter is commonly used. This starter uses a resistance in series with the motor windings which limits the current to an acceptable value. At suitable time intervals successive amounts of series resistance are short-circuited until sufficient voltage is applied to permit the motor to start and accelerate. Compression type starters utilizing graphite discs are also used for this purpose. Resistance type starters may be either manually or magnetically operated.

For high-voltage reduced kva starting, magnetically operated control is generally used. "Hi-Fuse" Control of the type shown in Fig. 46 provides short-circuit protection.

Wound-Rotor Motor Control

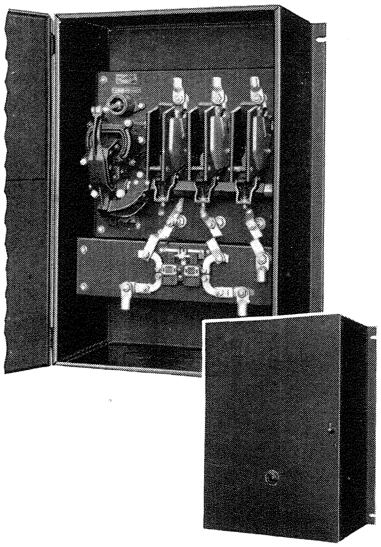
The wound-rotor motor must have both *primary* and *secondary* control.

The primary control is an *across-the-line* starter of the type, and with protective features as discussed previously for squirrel-cage motors.

The secondary control usually have five to seven steps of resistance. On the first step, with all the resistance in, approximately full-load starting torque is developed (see Fig. 38) with slightly more than full-load current inrush. Additional steps of resistance are short circuited as the motor comes up to speed. The normal operating condition is to short circuit all external resistance.

The secondary control may be either manual or magnetic in operation. The manual controller is the familiar drum type control with operating handle, shown in Fig. 49. Moving the handle to the first starting position closes the line contactor through an interlock and places all the secondary resistance across the collector rings. Successive positions short circuit out the resistor sections.

Magnetic controls are pushbutton actuated where secondary control is desired only to obtain low starting current and to control acceleration. The contactors which



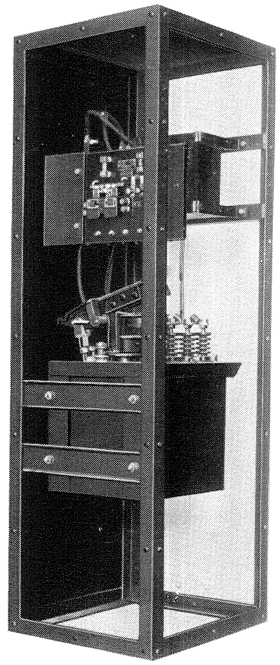


FIG. 44—*Across-the-line, low-voltage magnetic starter for induction motor.*

FIG. 45—*Across-the-line, high-voltage magnetic starter. Enclosing plates removed.*

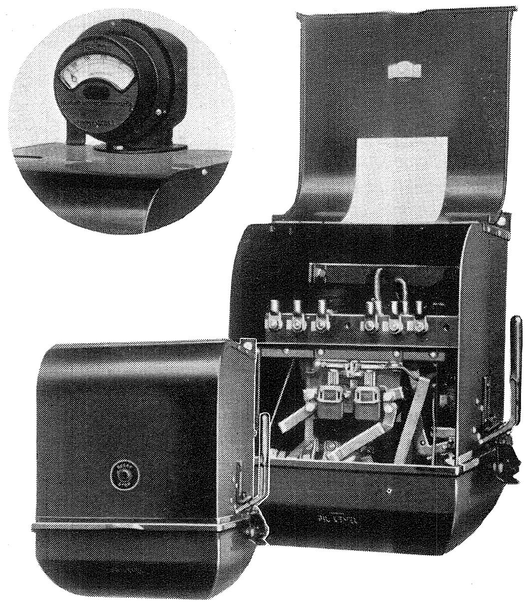
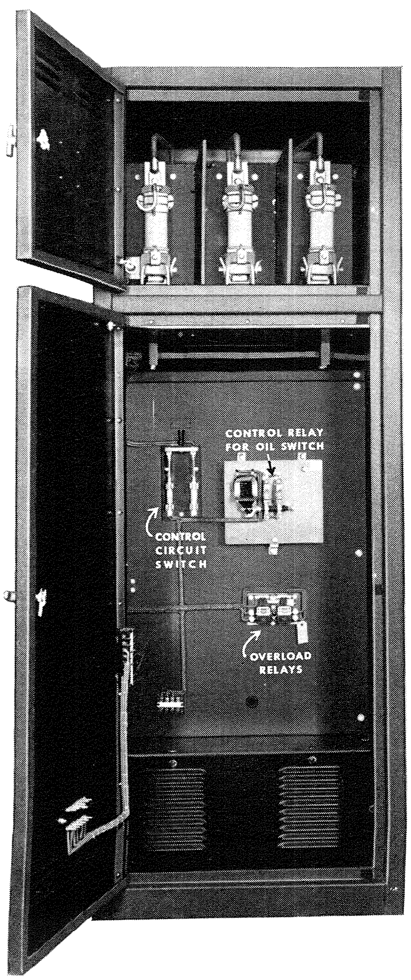


FIG. 47—*Typical "Compensator" for reduced-voltage, auto-transformer starting. Compensator above is low-voltage type.*

Typical Controls for Large Squirrel-Cage Induction Motors



"HI-FUSE" CONTROL

FIG. 46—*Front and back views of full-voltage, high-interrupting capacity, current-limiting fuse type, high-voltage, magnetic control for induction motor. Fuses provide high-speed interruption of current in the event of short-circuit. Fuses are coordinated with the oil switch and overload relays for normal starting and protection. Total enclosure and compartmenting for safety of operating personnel.*

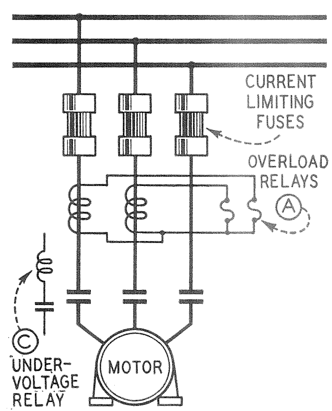
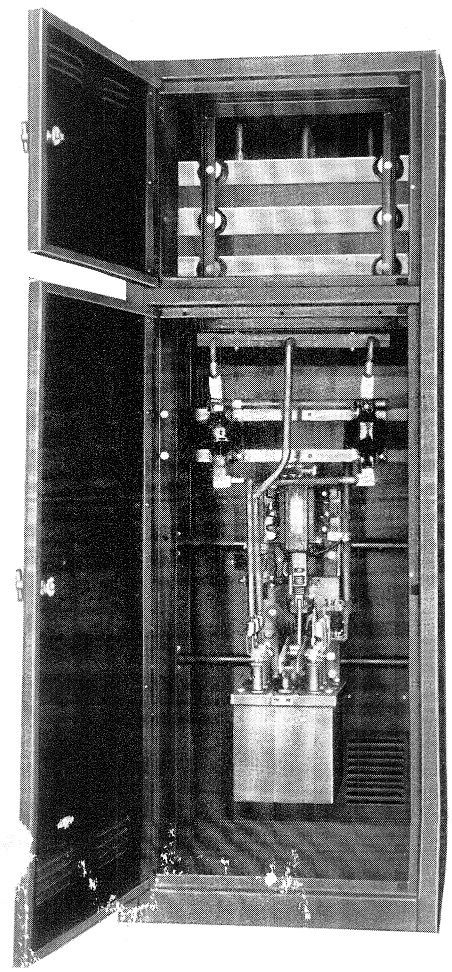


Diagram shows elements of short-circuit protection (fuses) and normal operating protection (overload and undervoltage relays) provided in Hi-Fuse Control.



successively short circuit resistor sections may be controlled by timing, current, or frequency relays.

On cranes, hoists, etc., reversing is accomplished by the use of two primary contactors, properly interlocked, one for forward and one for reverse rotation.

On centrifugal refrigerating compressors and centrifugal pump installations, the unit is frequently called upon to operate continuously at reduced speed to control output. Magnetic contactors in a special secondary control are actuated by a load control device, and short circuit the proper amount of secondary resistance to secure the desired speed and output.

The number of reduced speed steps available is equal to the number of resistor steps, usually five, six or seven, although any number from one to eleven are used. However, *for boiler draft fan duty* and some centrifugal pump applications even a large number of steps does not give the required precision of speed control without introducing other refinements such as dampering the fan outlet or throttling the pump discharge between speed steps. Similar results could be obtained by using a secondary resistor having essentially an infinite number of steps. So-called "liquid slip-regulators" are sometimes used for this purpose. They consist of a tank containing an electrolyte in which three electrodes, one connected to each secondary lead, can be immersed. Resistance is controlled by varying the depth of immersion of the electrodes. Some heat-exchange arrangement is necessary for cooling the electrolyte.

Adjustable-Speed Magnetic Drive

Wide-range, precision control of speed, using a *single-speed squirrel-cage motor* rather than a wound-rotor motor can be accomplished with the *Magnetic Drive*. This form of precise, adjustable speed is increasing in popularity for fans and centrifugal pumps.

The Magnetic Drive consists of two elements, the "Ring" driven by a constant speed motor, and a "Magnet" connected to the load.

The ring of the Magnetic Drive revolves at the same speed as the driving motor. The Magnet, separated by an air-gap from the Ring, is free to revolve within the Ring. Poles of the Magnet are excited by direct current through collector rings on the Magnet shaft.

Difference in speed between the Ring and the Magnet results in a cutting, by the Ring, of the magnetic flux produced by the Magnet. This induces currents in the Ring, forming magnetic poles which pull on the poles of the Magnet, thus causing the Magnet to revolve.

Torque is thus transmitted *magnetically* through the air-gap between Ring and Magnet. The amount of torque is varied precisely and over a wide range by varying the excitation of the Magnet, to control the speed of rotation of the Magnet.

Control of excitation to the Magnet of the Magnetic Drive, and thus control of the speed, is accomplished positively and precisely with an electronic controller. A three-phase 220- or 440-volt supply is rectified and controlled in the "Regutron" controller to maintain, with stability and accuracy, the adjustable speed requirements.

Output of a small tachometer generator driven from the Magnet shaft actuates the "Regutron" control to hold operating speed accurately at selected speed. Speed of the load is selected by positioning the arm of a small potentiometer which is actuated by some type of automatic control such as an automatic combustion control for boiler draft fans, or liquid level pilot actuator for pumps. The potentiometer is balanced electrically against the speed-control tachometer, and operates through an amplifier circuit to regulate the output of power rectifier tubes to supply excitation for the required speed of the Magnetic Drive.

The "Regutron" holds the speed at the desired point under all conditions.

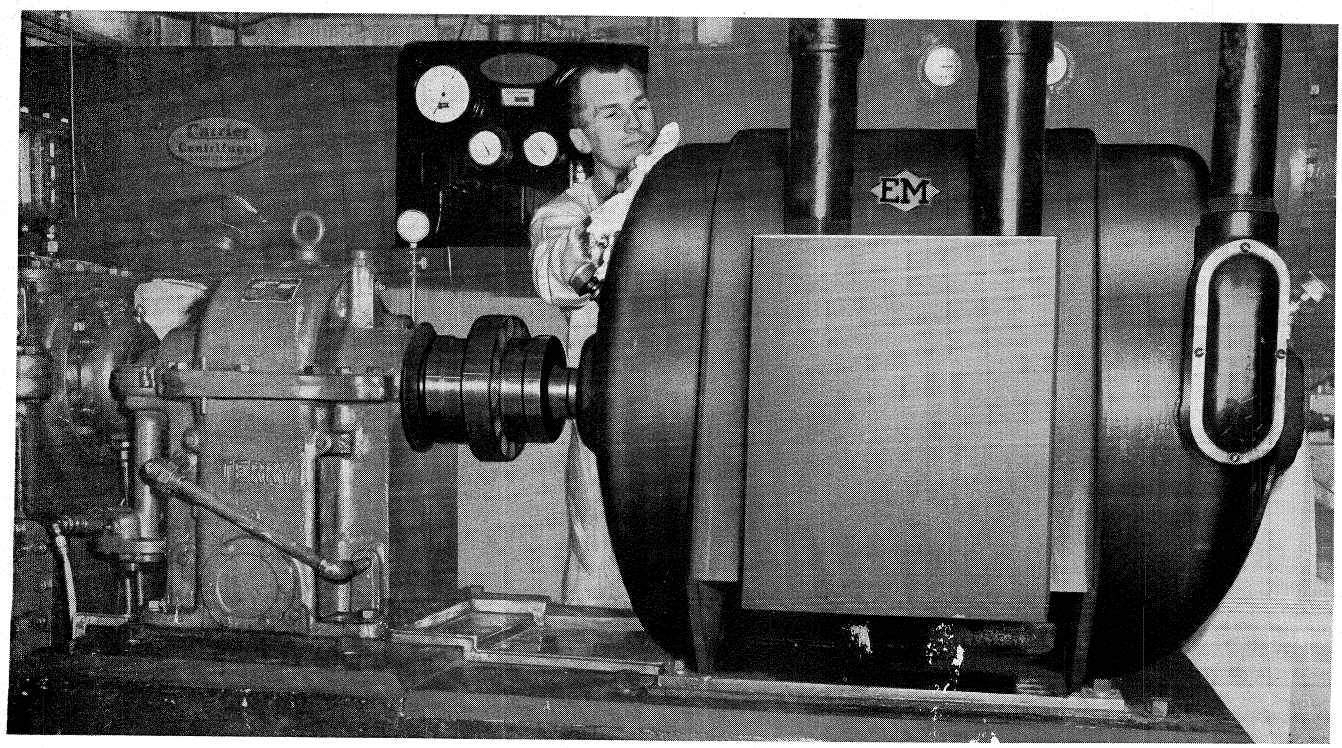


FIG. 48—*Wound-rotor induction motor, with automatic secondary resistance control provides adjustable speed for centrifugal refrigeration compressor for air conditioning in a hotel. Motor is 300 hp, 1800 rpm.*

CONTROL FOR WOUND-ROTOR INDUCTION MOTOR

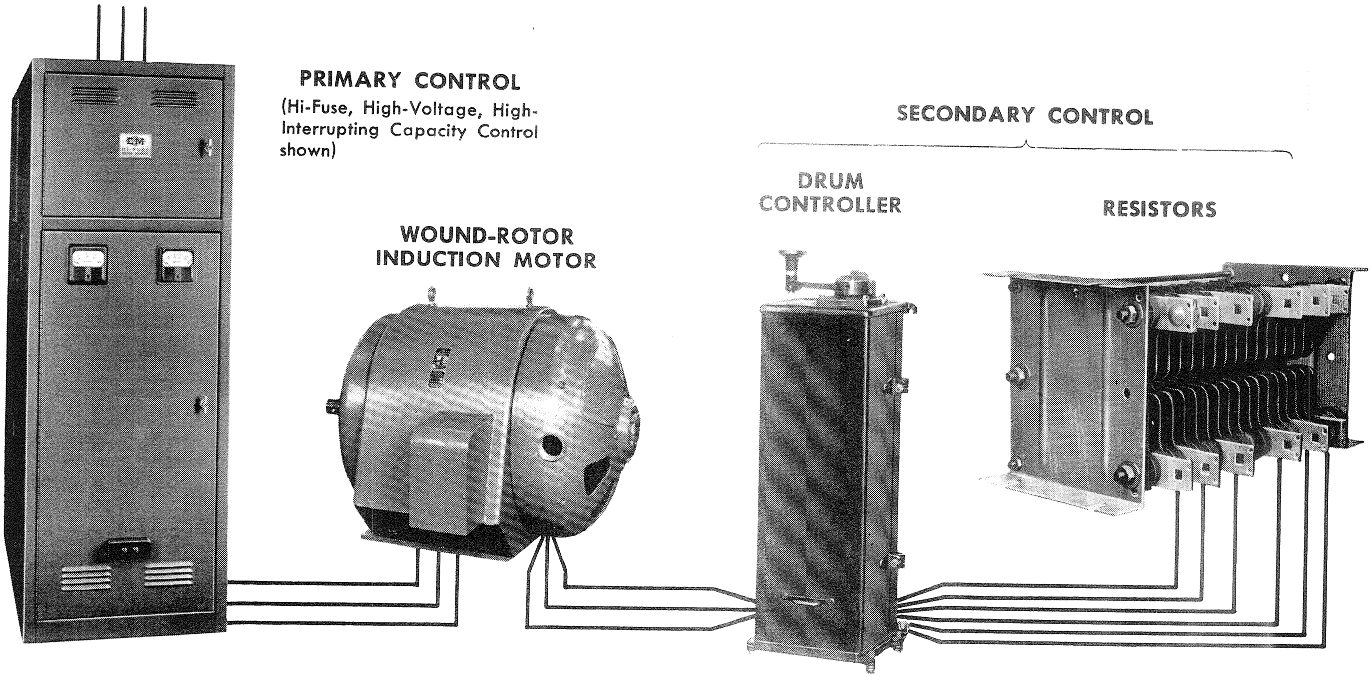


FIG. 49—*Elements of control for high-voltage wound-rotor motor. Primary control is magnetic, Hi-Fuse, full-voltage starter. Secondary control is manual, drum-controller type with cast resistors. Operation of the drum controller inserts successive steps of resistance in the rotor of the motor.*

THE ADJUSTABLE-SPEED MAGNETIC DRIVE

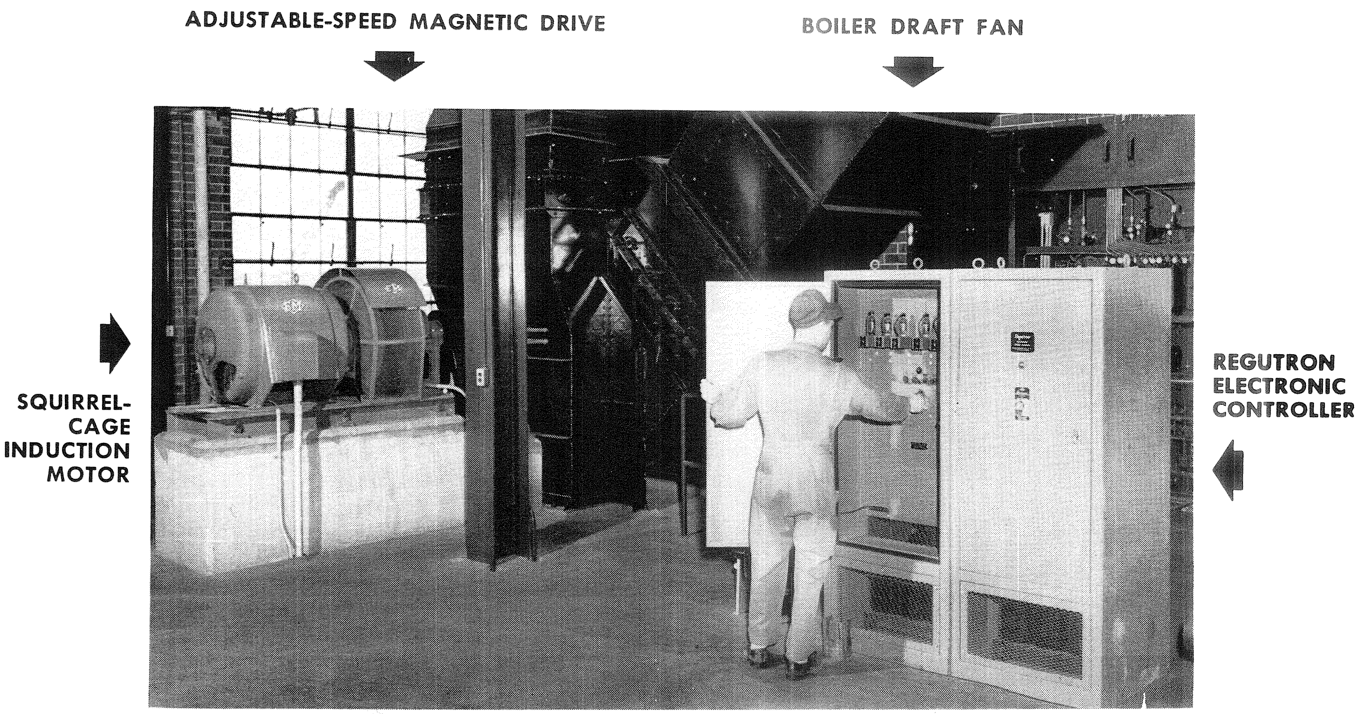
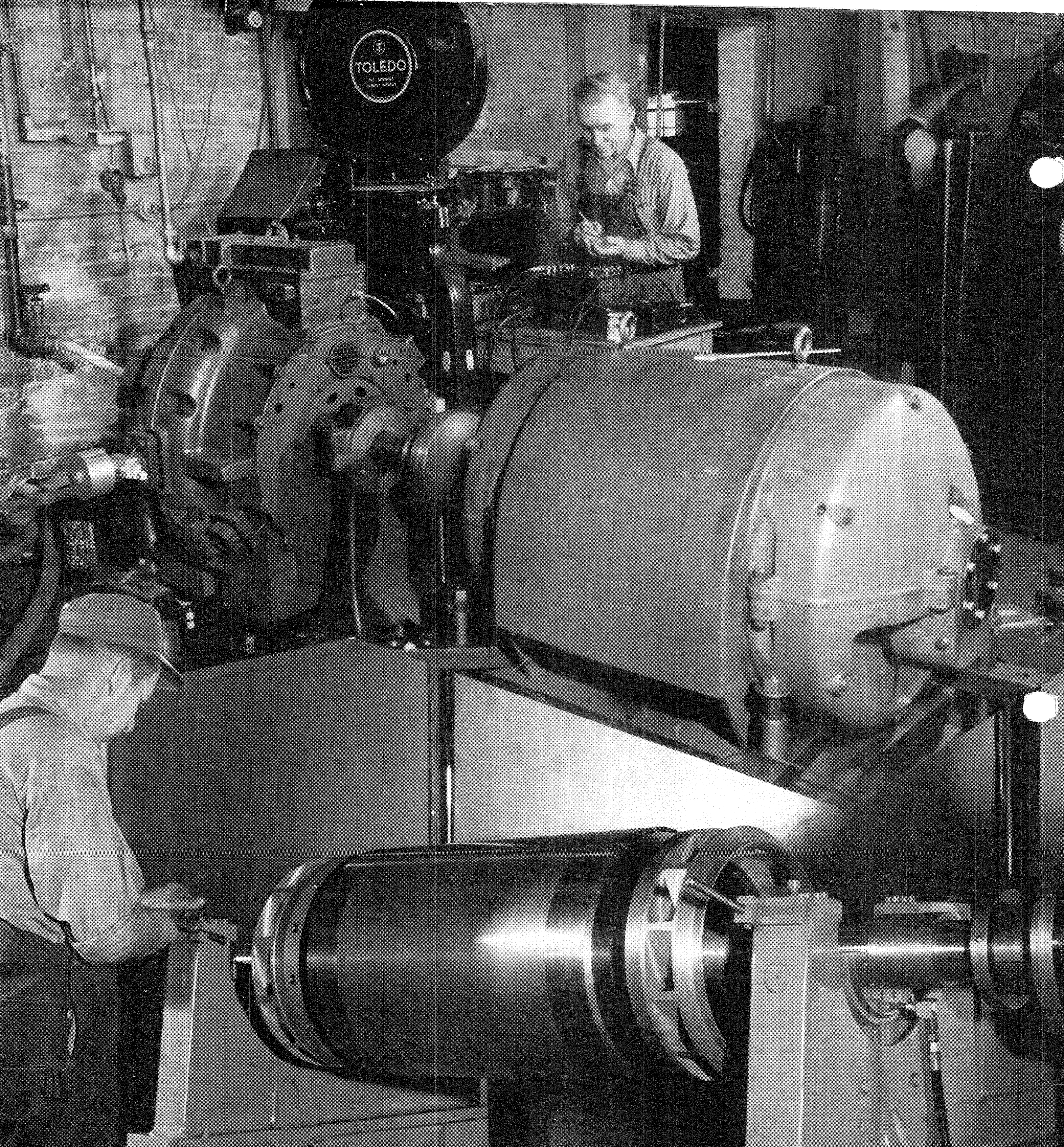
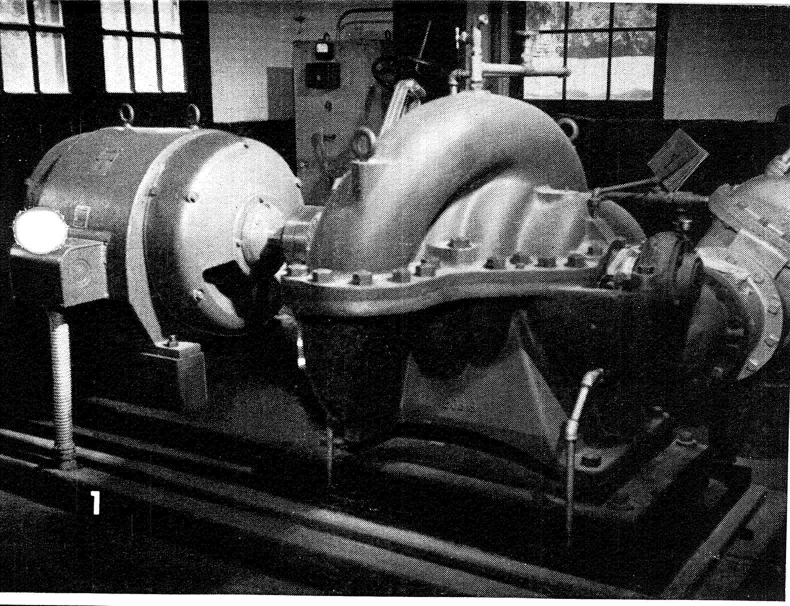


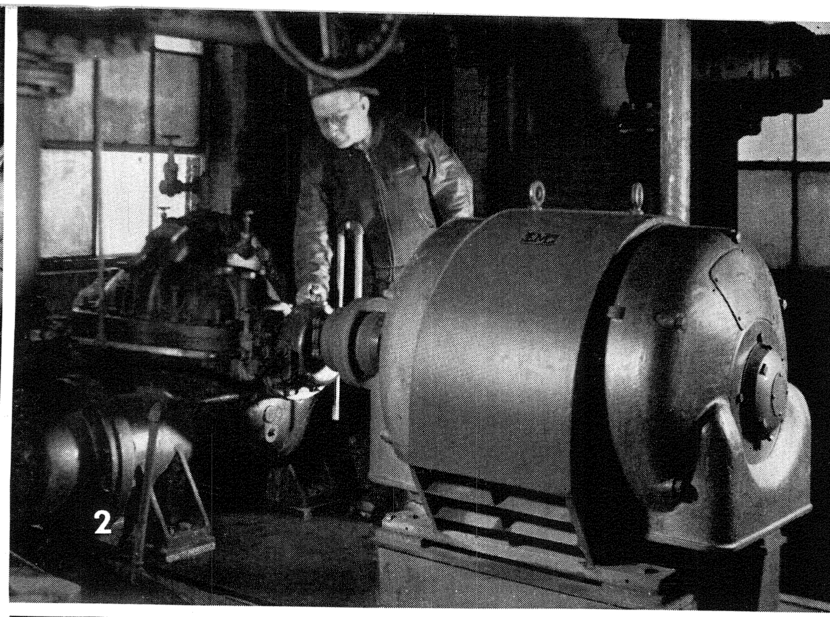
FIG. 50—*Elements of Magnetic Drive applied to forced draft fan on boiler in central-station generating plant. Magnetic Drive, with electronic controller converts constant speed of squirrel-cage motor to precisely-held adjustable speed to provide required draft for varying loads on boiler.*

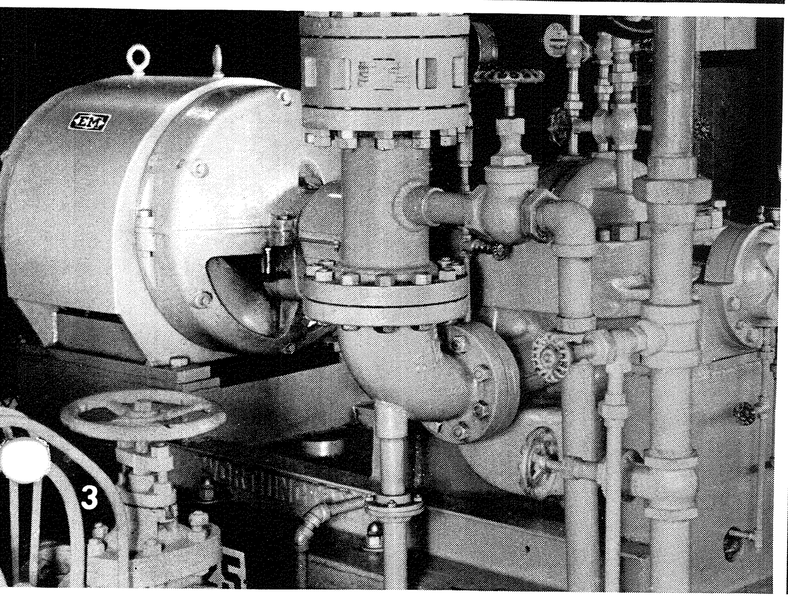


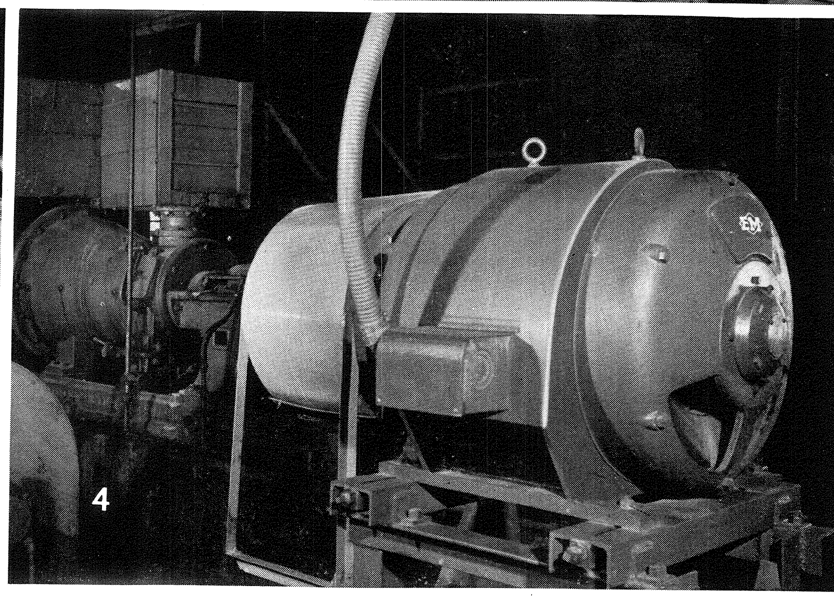
Insuring Performance

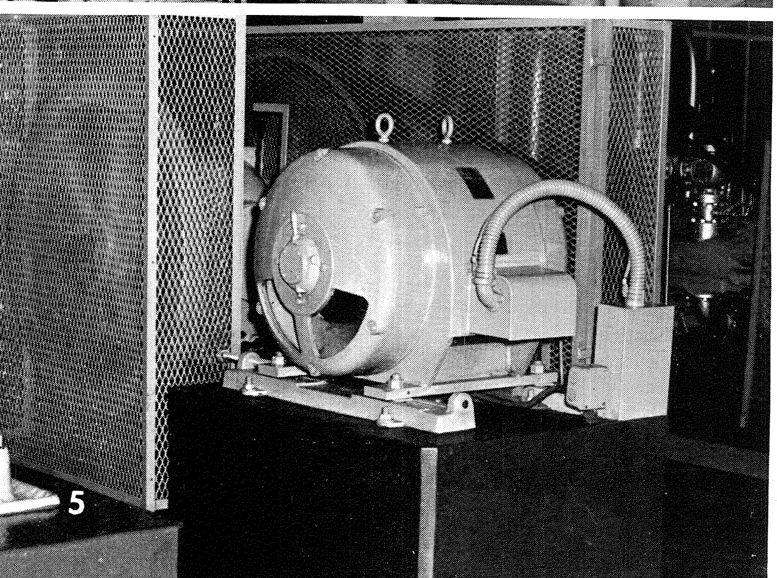
Typical of the precision in manufacture to insure that induction motors will perform as guaranteed are the testing machines above. *Dynamic balancer* is Dynetric electronic type capable of measuring unbalances which cause vibrations as little as .000025 inch. *Dynamometer* provides accurately controllable load and indicating instruments for measuring motor torques.

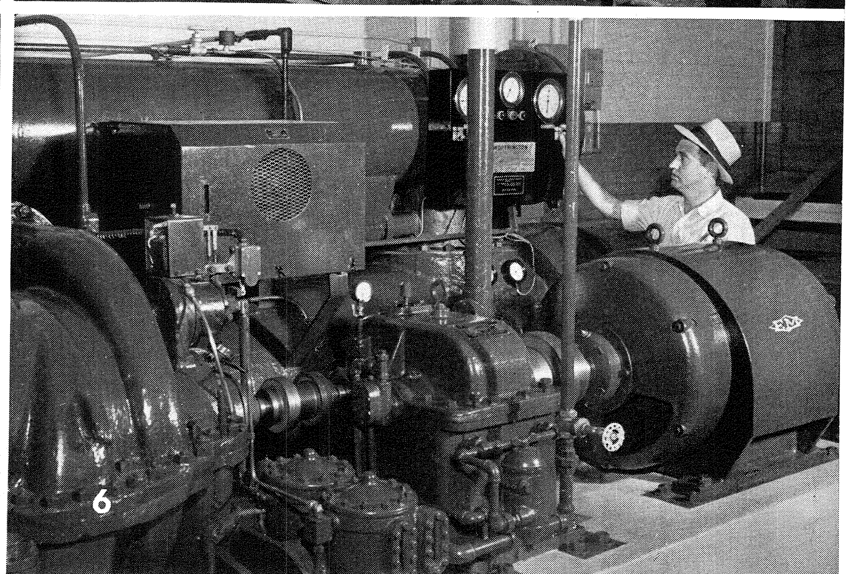












On the Job

1 — 250 HP Motor Drives Pump, Albuquerque, N. Mex. Waterworks.
2 — 150 HP Splash-Proof Motor, on Centrifugal Pump in Steel Mill.
3 — High-Pressure Pump in Rubber Mill Has 250 HP, 3550 RPM Motor.
4 — Jordan in Paper Mill Is Belt Driven By 150 HP, 700 RPM Motor.
5 — High-Torque Motor on Air Compressor in Western Rubber Mill.
6 — Refrigeration Unit in Textile Mill Powered By 250 HP Motor.

THE ABC OF THE ORGANIZATION BACK OF E-M *HEAVY-DUTY* INDUCTION MOTORS

Extensive Background—E-M has been building rotating electric equipment since 1897. Thus, E-M is a pioneer manufacturer of electrical equipment, with over a half century background of design, manufacturing and installation experience. E-M engineers have taken a major part in developing and applying large motors to industrial drives.

Half Century of Specialization—The major part of E-M manufacture is rotating electrical machinery, including synchronous motors, synchronous generators and induction motors. E-M specialized "know-how", both in the factory and in the field offices, is one of your best assurances that you can place full confidence in E-M Motors, and in E-M engineering recommendations.

Skilled Personnel—E-M has a large staff of highly trained electrical and mechanical engineers, with many years of experience in the development, design and manufacture of large motors. The key personnel of the Factory organization average over a quarter century of experience in manufacture of rotating machinery.

Unexcelled Performance—E-M Heavy-Duty Induction Motors have balanced electrical and mechanical design to provide efficient operation, and to amply meet the rated requirements. The mechanical design is based on an extensive field knowledge of motor requirements to provide a trouble-free, easily maintained unit. The motors comform to the ASA, AIEE and NEMA standards where applicable.

Careful Testing—Each motor is critically tested before leaving the Factory, to check its performance from the standpoint of the insulation, electrical operation and the running characteristics.

Experience Engineering Service—The success of a motor drive depends on the right kind of preliminary engineering. E-M field engineers are concerned not only with the sale of motor equipment, but also with providing an adequate, effective, dependable, and correctly engineered installation. This engineering often involves coordination with the machine manufacturer to match the motor characteristics with those of the drive.

Quick Field Service—E-M has engineering offices and available service facilities in over 50 principal cities. The engineers in these offices are specialists with a long background of experience in electrical power apparatus and with a genuine interest in its continuous, successful performance. They, together with the factory organization geared to quick attention to repair and replacement parts, are your assurance of speedy servicing.

S. P. BORDEAU,
Editor

THE E-M SYNCHRONIZER

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Minneapolis 13, Minnesota

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