Volume 1

Second Edition

equipment design handbook for refineries and chemical plants

Frank L. Evans, Jr.

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Equipment Design Handbook

for Refineries and Chemical Plants

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for Refineries and Chemical Plants
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preface

Mechanical design of refineries and chemical plants involves a combination of user and vendor experiences. Vendors have superior knowledge about the design of their equipment. Users have superior knowledge about how equipment will operate in continuous process plant service. Because refinery and chemical plant units operate on a 24-hour basis—and hopefully 365 days per year—in a rather hostile environment, equipment must be far more reliable than in most industries. Special mechanical design requirements are necessary. Sometimes the designer, whether he is with an operating company or an engineering contractor, cannot reveal sufficient details to the equipment supplier because of the process secrecy agreements. He must do much of the mechanical design himself or check the vendors' design against information he cannot reveal. Most of the time, the designer working in these industries must at least make preliminary equipment estimates, even though he is at liberty to tell the vendor everything necessary to select the equipment.

There is an increasing trend to select and specify equipment by computer programs. Does this mean that engineers are obsolete and computers can take over the mechanical design function? Partly! Engineers will become obsolete unless they understand the basis for the computer programs. A slight error in input data can easily produce a design that is incorrect by an order of magnitude, i.e., ten times or more. Therefore, engineers well grounded in the fundamentals of equipment selection must check the computer's output accuracy. Undoubtedly, the computer will be used more and more as an engineering tool, but it cannot replace engineering judgment any more than the slide rule could replace judgment when its use outmoded hand calculations.

This book provides a practical design guide based on actual user experiences described in over 200 articles published in *Hydrocarbon Processing.* A sentence has been taken here and there—ideas have been rewritten and simplified—equations have been reduced to their most usable form. Teaching by example is the theme of the book. Explanations of how equipment works have been eliminated. An engineer familiar with the refining and chemical industries can use this book to design the major equipment used in those plants. He can put data from Process Engineering into the examples and quickly size equipment for his plant. Engineers who do not deal with mechanical design on a daily basis can use this text easily for preliminary equipment estimates without reading through pages of theory and derivations.

A major criticism of engineering graduates is that, unlike the lawyer or physician, they are unable to solve practical problems immediately after graduation. Unfortunately, the typical engineering college curriculum is so filled with theory that must be absorbed before the basis for practical problem solving can be understood that mechanical engineering students, in particular, are not equipped with the tools to design mechanical equipment. This book provides that tool for the oil refining and chemical industries.

Is this a cookbook approach to engineering? To some extent, yes. A lot of excellent cooks use cookbooks every day! Mechanical design of process equipment demands more than a cookbook approach, however. You will see that in most instances an engineering decision, rather than a simple fill-in-the equation approach, is necessary. This book organizes the engineering equations and decision-making *by example* so that important procedures are not omitted.

My thanks, of course, go to the many authors who have published articles in *Hydrocarbon Processing.* Without such a great wealth of information, this practical book could not have been written.

Without the help and encouragement of my wife, Kay, this book could not have been written. She typed every word including this acknowledgement and my dedication of this book to her.

Frank L. Evans, Jr.

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1. drivers

Motors

Modern technology has reduced the size of motors, increased their expected life and improved their resistance to dirt and corrosion. Other important developments of the last 20 years are brushless excitation for synchronous motors and new two-speed, single-winding, induction motors. The price curves presented (based on 1978 costs) reflect the latest changes in motor sizes, temperature standards and motor design.

This section of the driver chapter describes motors, but does not describe installation or application in hazardous areas. These aspects are well covered by the National Electrical Code and American Petroleum Institute publications, particularly API RP 500A and RP 540.

Cost is the prime factor in the selection of any equipment. Selection should be based on the least expensive motor which will meet the requirements. Improper selection increases operating costs. Oversize motors are commonly purchased either because the actual load requirements are not known or because of anticipated load growth. Motors perform best (maximum power factor and efficiency) at their rating. The best checks against improper size are careful review of drive requirements prior to purchase and periodic checks of the individual motors in operation.

Serious consideration should also be given to enclosure selection. Many improvements have been made in recent years in both enclosures and insulation. Therefore, it is important to review purchasing practices to make sure they are based on today's designs.

Review the motor requirements and specifications to make sure that all the unnecessary, nonstandard, special features have been eliminated. Each special requirement such as nonstandard mounting dimensions and nonstandard bearings should be eliminated unless some useful purpose is served. Many special features are specified because of an isolated case of trouble that occurred years ago. Likewise, some special features may become obsolete by changes in refinery or chemical plant practice or manufacturing techniques.

Price Estimating

Figures 1-1 through 1-6 are approximate curves, useful for preliminary price estimates and comparison purposes only. These curves have been smoothed for readability; the actual curves show discontinuities because of jumps in frame size, etc. The curves are based on published list prices and discounts for large user customers such as typical oil refining and chemical companies. Figures 1-1, 1-2 and 1-3 are based on standard or basic motors, open, or open, drip-proof construction, with voltages reflecting minimum price. Figures 1-4, 1-5 and 1-6 modify these basic prices for different voltages and enclosures.

Synchronous and induction motors cannot always be compared on an equal speed basis. In geared applications such as high-speed (above 3,600 rpm) centrifugal compressor drives, the most economical induction motor speed is usually 1,800 rpm. The most economical synchronous motor speed for the same application might be 900 or 1,200 rpm, depending on the hp required. For compressor drives and other high-speed applications above 3,600 rpm, motor prices must be studied within the *whole job* concept.

For 3,600-rpm pump and compressor drives below 5,000 hp, simplicity of installation almost dictates using the two-pole induction motor. No gear is required and the overall electrical and mechanical installation is the simplest possible.

Two-pole induction motors are available and have been built up to approximately 20,000 horsepower. In considering motors for any of these very large drives (above 5,000 hp), consult the motor manufacturers early. These machines are always custom-designed for the specific application, taking into consideration the driven machine characteristics and the power system parameters and limita-

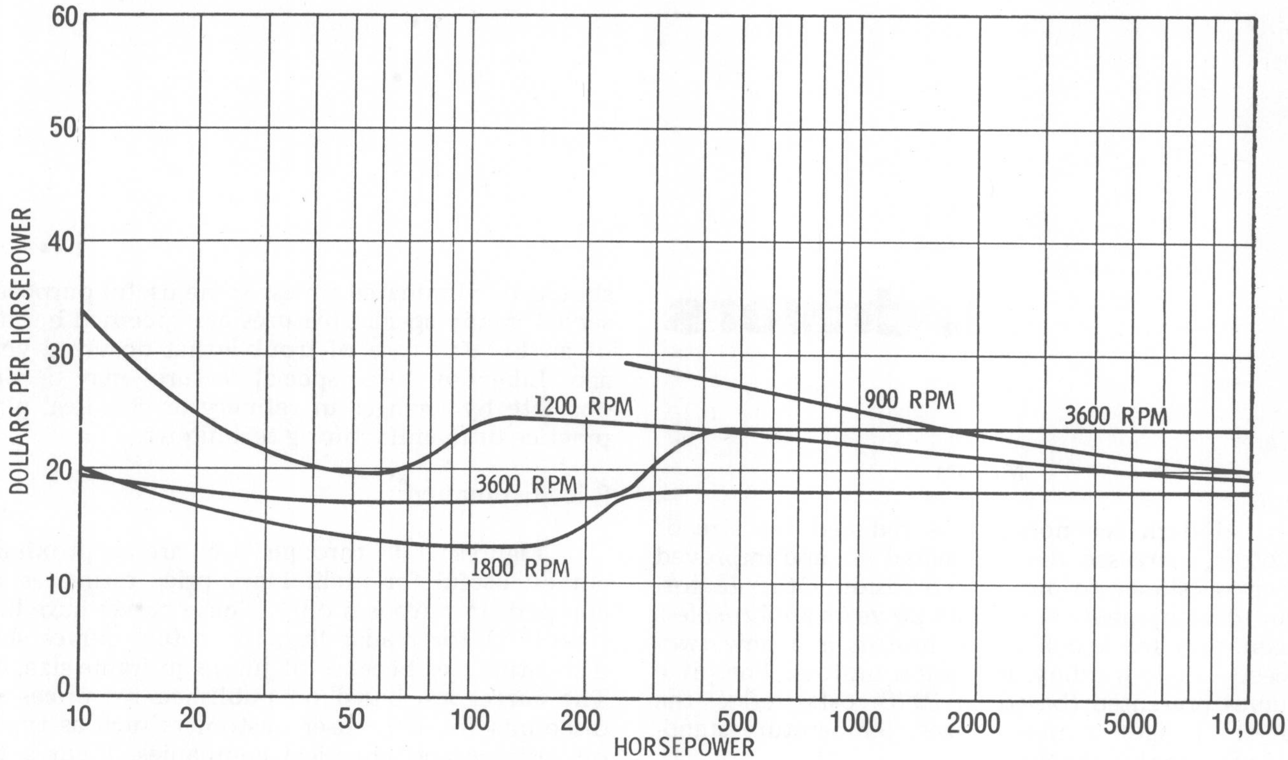

Figure 1-1. Prices for squirrel-cage induction motors, 3-phase, 60 Hz with standard voltages and open, drip-proof enclosures.

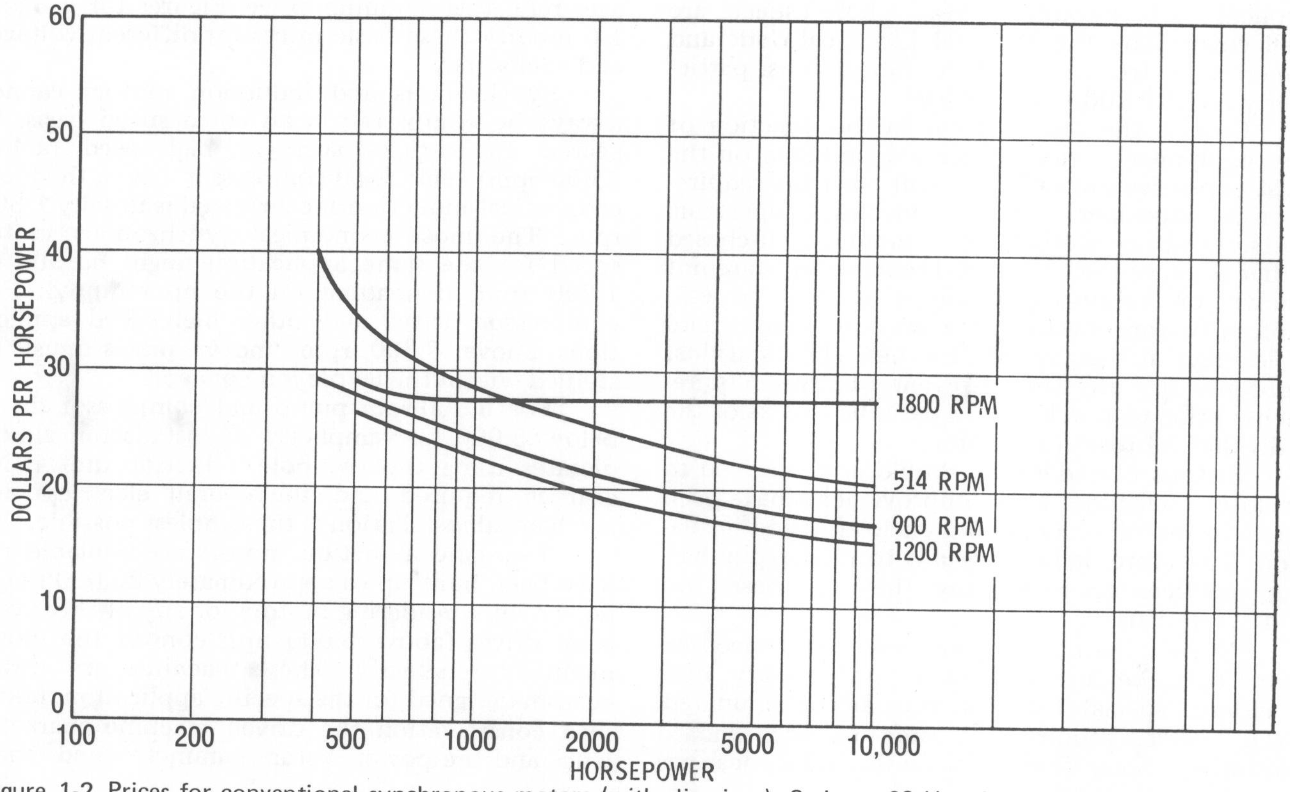

Figure 1-2. Prices for conventional synchronous motors (with slip rings), 3-phase, 60 Hz with standard voltages and open, drip-proof enclosures.

tions. If the motor manufacturer can confer early with the compressor builder and utility system engineers, the optimum drive system solution can be reached.

Voltage

Figures 1-4 and 1-5 show the effect of specified voltage on motor cost. Below 200 hp, the least expensive motors are low voltage (less than 600 volts). Above 500 hp and up to 5,000 hp, the preferred voltage is 4,000 or 4,160 volts. As the motors become larger, more space is available for insulation; thus it becomes economically practical to use higher voltage motors and controls. It is apparent that as the size of a refinery or chemical plant increases, the distribution system increases, and it is desirable or necessary to go to higher system voltages. For distribution system voltages above 5,000 volts, the usual practice is to transform down to 2,400 or 4,160 volts for large motors. Cable and transformer costs now frequently make economical motors with higher voltages such as 13.8 kilovolts. Numerous 11-to-14-kv motors are now in service, even outdoors.

Lightning and switching surges which damage motors are related to high-voltage motors. The insulation level of motors is below that of many other types of apparatus such as transformers, switchgear, cables, etc. Because of the low insulation level, the system lightning arrestors will not protect the motors adequately. Special surge protection equipment is often needed, particularly for large motors with long cores. Surge protection consists of special low spark-over and low-discharge voltage arrestors in parallel with capacitors. The capacitor slopes off the wave front to reduce the motor winding turn-to-turn voltage, and the arrestor limits the voltage rise to a safe value. To give maximum protection, the arrestor should be mounted at the motor terminals as in the surge protection package available as an accessory on large machines.

Most motors below 200 hp are best supplied at the lower standard voltages of 230 or 460 volts. Motor voltage standards have changed recently from 110, 220, 440 or 550 to 115, 230 or 460 or

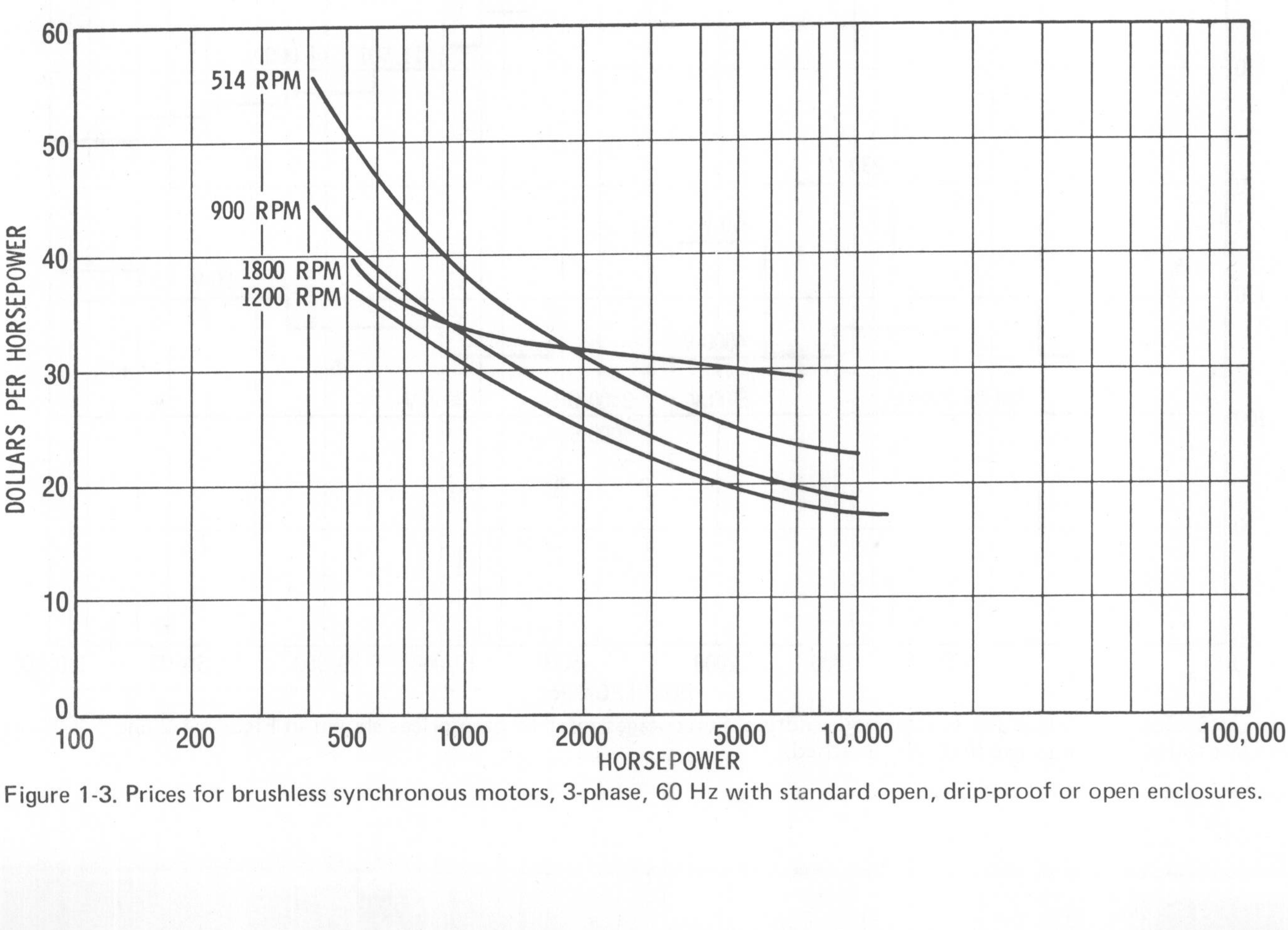

Figure 1-3. Prices for brushless synchronous motors, 3-phase, 60 Hz with standard open, drip-proof or open enclosures.

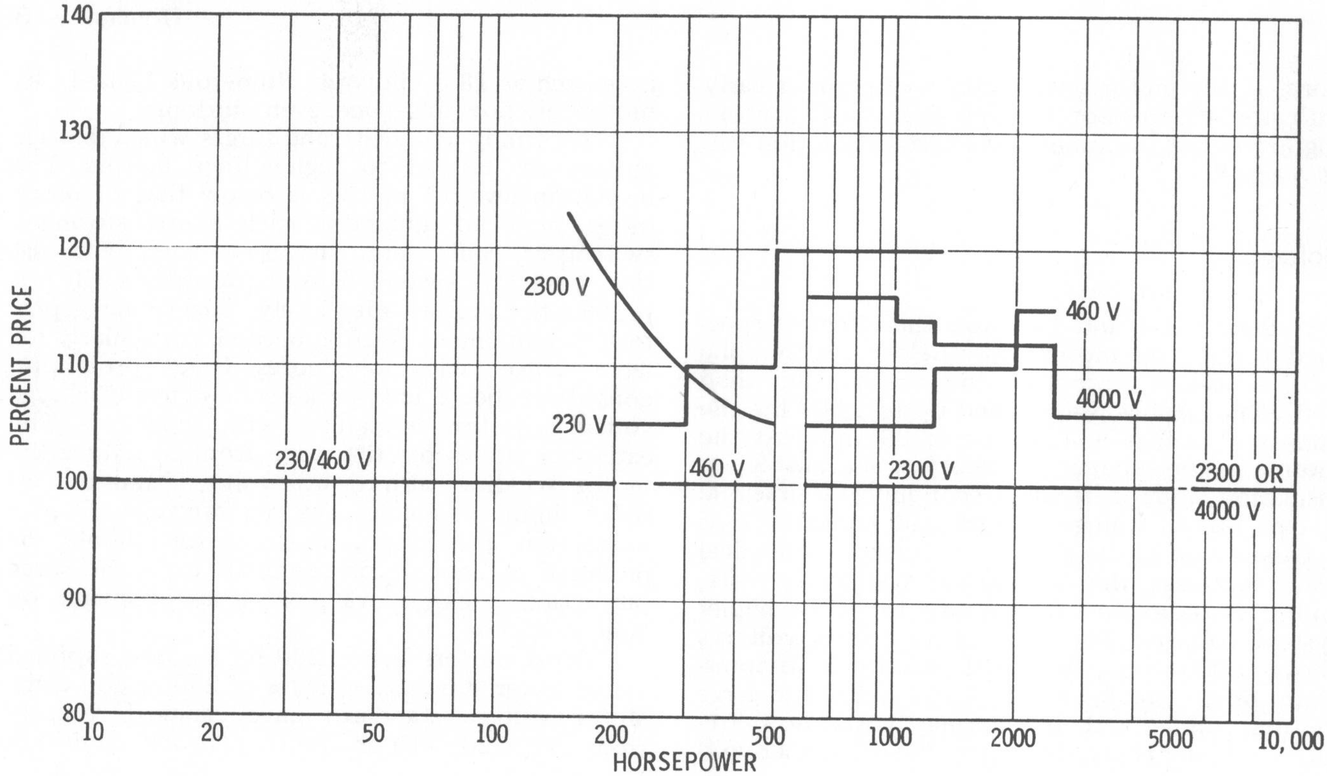

Figure 1-4. Cost vs. voltage for squirrel-cage induction motors. Percentages refer to base prices shown in Figure 1-1. Curves read from left to right; at steps use first value reached.

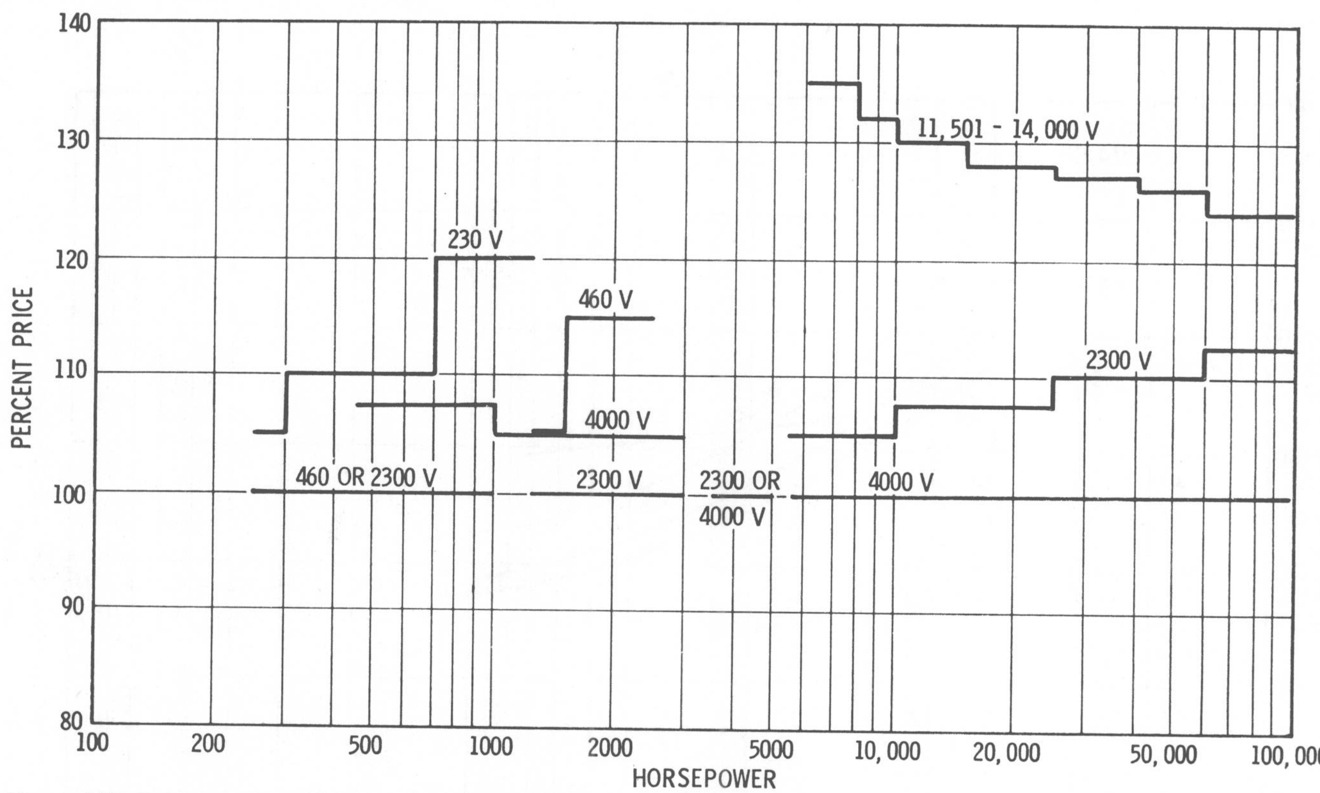

Figure 1-5. Cost vs. voltage for synchronous motors. Percentages refer to base prices shown in Figures 1-2 and 1-3. Read from left to right; at steps use first value reached.

575 volts. Motor voltages will be closer to those existing in modern stiff distribution systems nominally at 120, 240, 480 or 600 volts. In the past, 220-volt motors could be operated at their rated hp on 120/208-volt systems; the new 230-volt motors are not designed to operate properly without overheating at 208 volts. However, this is not serious in refineries or chemical plants where few motors are operated on 120/208-volt lighting systems.

Enclosures

The enclosure selected affects cost substantially. Corrosive and hazardous atmospheres encountered dictate the protection needed. Figure 1-6 illustrates the relative cost of different motor enclosures common to petroleum refineries and chemical plants.

Today's standard motor enclosure is the *open, drip-proof* for induction and high-speed synchronous motors. For large motors, open, drip-proof construction is available up to about 20,000 hp and is used for squirrel-cage, synchronous and wound-rotor motors.

For larger motors, the next degree of protection above open, drip-proof is *Weather protected, Type I*, which is an open machine with ventilating passages constructed to minimize the entrance of rain, snow and airborne particles to the electric parts. All openings are screened. A few years ago, this type of motor could not have been used outdoors because the insulation available could not withstand the moisture and other deteriorating effects. With today's vacuum-pressure, epoxy-impregnated insulation it is possible to use these motors outdoors.

Where a higher degree of protection and longer life is desired, *Weather protected, Type II* motors are recommended for large motors. They are equipped with extensive baffling of the ventilating system so that the air must turn at least three 90° corners before entering the active motor parts. In this way, rain, snow and dirt carried by driving winds will be blown through the motor without entering the active parts.

Totally Enclosed Fan-Cooled (TEFC) motors. The obvious choice for severe applications below 250 hp is the TEFC motor. TEFC motors separate the internal and external ventilating air; breathing is the only way external air ever gets inside.

Above 500 hp, enclosed motors with water-to-air coolers cost much less than TEFC motors and in large ratings of synchronous motors cost even less than WP II. Large synchronous machines are frequently supplied enclosed with coolers for mounting in the motor foundation at lower cost than integral mounted coolers used as the reference in Figure 1-6.

Totally enclosed motors offer the highest degree of protection against moisture, corrosive vapors, dust and dirt; they also offer the advantage of reduced noise level.

Division 1 Enclosures. Explosion-proof motors can withstand an internal explosion without igniting an inflammable mixture outside the motor. These motors are totally enclosed fan-cooled except that they are specially machined to meet Underwriter's Laboratory Standards. Explosion-proof squirrel-cage motors are available up to 3,000 hp at 3,600 rpm, but the larger sizes are usually not practical or economical.

Force-ventilated motors are suitable for hazardous locations. Safe air is brought in through a duct system, passed through the motor, and then discharged preferably through another duct system to the limits of the hazardous location. The ventilating ducts should be pressurized to prevent entrance of contaminated air. This indoor construction has been largely replaced by outdoor motors such as weather-protected or totally enclosed types.

Inert gas-filled motors can also be used in refineries and chemical plants, but their applications are limited. They have tightly fitted covers and oil seals around the shaft to minimize gas leakage, are continually pressurized with an inert gas or instrument air, and are equipped with an internal air-to-water heat exchanger. Inert gas-filled motors are suitable for any hazardous location but require auxiliaries such as cooling water, gas pressurizing system and control accessories.

Insulation

Electrical insulation is being improved every year. The motor manufacturers make use of this and other technological developments to put more power into smaller, lighter, more efficient packages. Modern insulating materials can withstand heat, moisture and corrosive atmospheres and new metals can take mechanical punishment longer. Computer design techniques are also helpful. The truly dramatic effect of these and previous developments and rerates is evident in comparisons of old and new designs as reflected in the 1967 NEMA T-frame size assignments. In 1956 a 10-hp, 1,800-rpm motor was built on a 256 frame; today's standards call for 20 hp on this frame at the same speed.

Insulation systems were first classified according to the material used and permissible temperatures were established based on the thermal aging characteristics of these materials. For example, Class B insulation was defined as inorganic materials such as mica and glass with organic binders; 130°C was the allowable maximum operating temperature. The present definition of insulation system Class B stipulates that the system be proven". . .by experience or accepted tests. . .to have adequate life expectancy at its rated temperature, such life expectancy to equal or exceed that of a previously proven and accepted system." The definition is now functional rather than descriptive.

The newest catalogs show standard induction motors designed with Class B insulation for operation in a 40°C ambient with 80°C rise by resistance at 100% load for motors with 100% service factor. Previously, induction motor ratings were based on temperature rise by thermometer. Large synchronous motor catalogs still refer to temperature rise by thermometer.

These changes require an explanation. NEMA standards show three methods of temperature determination: (1) thermometer, (2) resistance and (3) embedded detector. Motor engineers have long recognized that measuring temperature rises by placing a thermometer against the end windings does not give the best indication of insulation temperatures near the conductors in the slot. Temperature rise of any motor can be measured by resistance; this will give a better indication of the temperature in the hottest part of the winding than will thermometer measurement. On machines equipped with temperature detectors there will usually be a difference in the readings taken by embedded detector and by winding resistance, with the detector reading usually slightly higher. This is not recognized at present in the NEMA standards. For example, the standards allow 80°C rise by either method for Class B insulated stator windings.

The resistance method gives an average temperature of the whole winding. Some parts will be hotter than others; usually the end turns will be somewhat cooler than parts of the winding in the middle of the iron core. NEMA committee members have been collecting test data on many machines to determine the correlation between

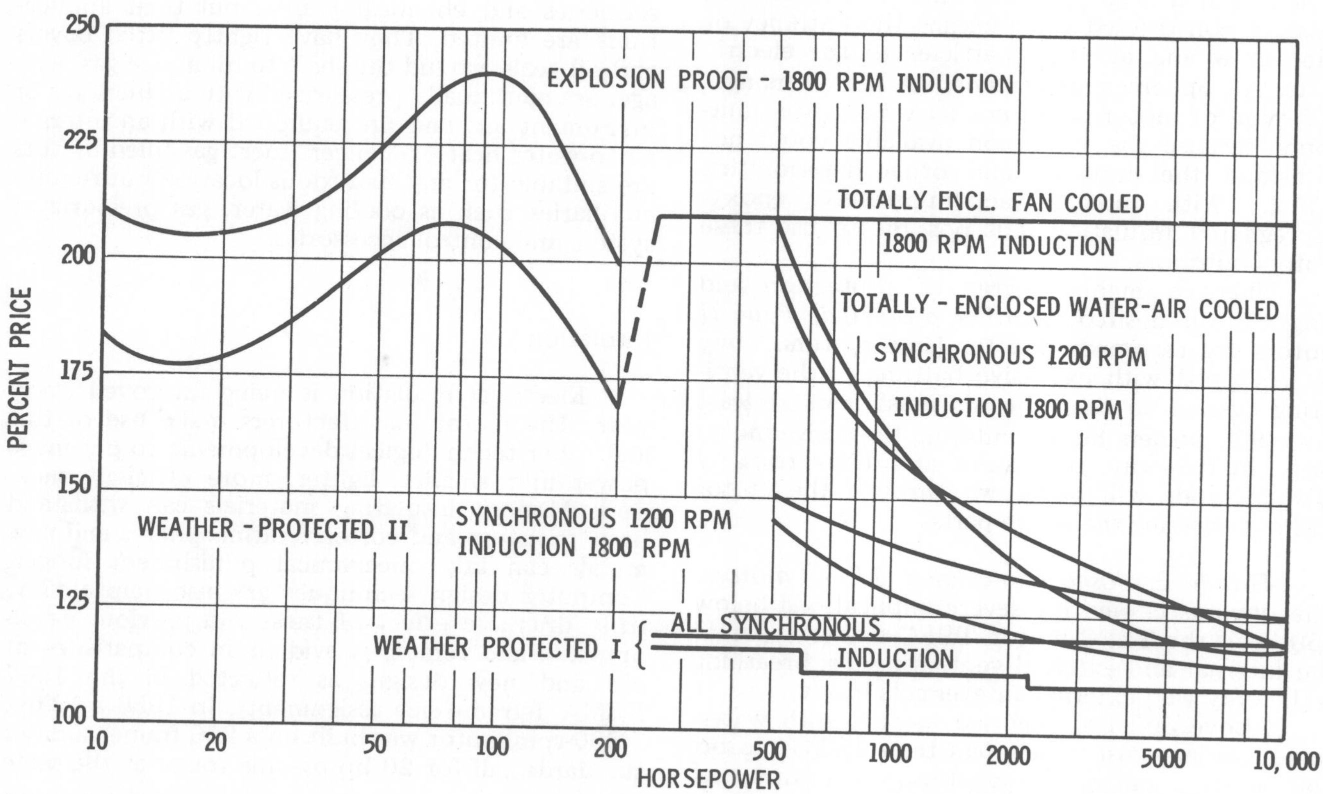

Figure 1-6. Approximate percentage price vs. various enclosures for induction and synchronous motors. Curve applies to Figures 1-1, 1-2 and 1-3 after application of Figures 1-4 and 1-5.

temperature measurements by detector and by resistance. It is hoped that future standards will recognize the difference.

NEMA standards do not give any limiting maximum total operating temperature for any class of insulation. Briefly, NEMA states that insulation of a given class is a system which can be shown to have suitable thermal endurance when operated at the temperature rise shown in the standards for that type of machine. Standards for synchronous motors and induction motors with a 100% service factor specify 80°C rise by resistance for Class B insulation. Also, the total temperature for any insulation system is dependent upon the equipment to which it is applied. For example, railway motors with Class B insulation have rated *standard* rises by resistance of 120°C on the armature; induction motors with service factor have 90°C rise at the service factor load.

Service Factor

For many years it was common practice to give standard open motors a 115% service factor rating; that is, the motor would operate at a safe temperature at 15% overload. This has changed for large motors, which are closely tailored to specific applications. Large motors, as used here, include synchronous motors and all induction motors with 16 poles or more (450 rpm at 60 Hz).

New catalogs for large induction motors are based on standard motors with Class B insulation of 80°C rise by resistance, 1.0 service factor. Previously, they were 60°C rise by thermometer, 1.15 service factor.

Service factor is mentioned nowhere in the NEMA standards for large machines; there is no definition of it. There is no standard for temperature rise or other characteristics at the service factor overload. In fact, the standards are being changed to state that the temperature rise tables are for motors with 1.0 service factors. Neither standard synchronous nor enclosed induction motors have included service factor for several years.

Today, almost all large motors are designed specifically for a particular application and for a specific driven machine. In sizing the motor for the load, the hp is usually selected so that additional overload capacity is not required. Therefore, customers should not be required to pay for capability they do not require. With the elimination of service factor, standard motor base prices have been reduced 4-5% to reflect the savings.

Users should specify standard hp ratings, without service factor for these reasons:

1. All of the larger standard hp are within or close to 15% steps.
2. As stated in NEMA, using the next larger hp avoids exceeding standard temperature rise.
3. The larger hp ratings provide increased pull-out torque, starting torque and pull-up torque.
4. The practice of using 1.0 service factor induction motors would be consistent with that generally followed in selecting hp requirements of synchronous motors.
5. For loads requiring an occasional overload, such as start-up of pumps with cold water followed by continuous operation with hot water at lower hp loads, using a motor with a short time overload rating will probably be appropriate.

Induction motors with a 15% service factor are still available. Large open motors (except splash-proof) are available for an addition of 5% to the base price, with a specified temperature rise of 90°C for Class B insulation by resistance at the overload horsepower. This means the net price will be approximately the same. At nameplate hp the service factor rated motor will usually have less than 80°C rise by resistance.

Motors with a higher service factor rating such as 125% are also still available, but not normally justifiable. Most smaller open induction motors (i.e., 200 hp and below, 514 rpm and above) still have the 115% service factor rating. Motors in this size range with 115% service factor are standard, general purpose, continuous-rated, 60 Hz, design A or B, drip-proof machines. Motors in this size range which normally have a 100% service factor are totally enclosed motors, intermittent rated motors, high slip design D motors, most multi-speed motors, encapsulated motors and motors other than 60 Hz.

Synchronous Motors

Synchronous motors have definite advantages in some applications. They are the obvious choice to drive large, low-speed, reciprocating compressors and similar equipment requiring motor speeds below 600 rpm. They are also useful and desirable on many large, high-speed drives. Typical applications of this type are geared, high-speed (above 3,600 rpm), centrifugal compressor drives of several thousand horsepower.

One interesting characteristic of synchronous motors is their ability to provide power factor correction for the electrical system. Standard synchronous motors are available rated either 100 or 80% leading power factor. At 80% power factor, 60% of the motor-rated kva is delivered to the system as reactive kva for improving the system power factor. This leading reactive kva increases as load decreases; at zero load with rated field current the leading reactive kva is approximately 80% of the motor-rated kva. The unity power factor machine does not provide any leading current at rated load. However, at reduced loads, with constant field current, the motor will operate at leading power factor; at zero load, the leading kva will be about 30% of the motor-rated kva.

Because of their larger size, 80% power factor motors cost 15-20% more than unity power factor motors, but they may be less expensive than an equivalent bank of capacitors. An advantage of using synchronous motors for power factor correction is that the reactive kva can be varied at will by field current adjustment. Synchronous motors, furthermore, generate more reactive kva as voltage decreases (for moderate dips), and therefore tend to stabilize system voltage better than capacitors, since they supply maximum leading kva when the voltage is at a minimum.

When higher than standard pull-out torques are required, leading power factor motors (80%) should be considered. The easiest way to design for high pull-out is to provide additional flux, which causes leading power factor. The leading power factor motor may therefore be less expensive.

In addition to power factor considerations, synchronous motor efficiency is higher than similar induction motors. Efficiencies are shown on Table 1-1 for typical induction and unity power factor synchronous motors. Leading power factor synchronous motors have efficiencies approximately 0.5-1.0% lower.

Direct-connected exciters are common for general purpose and large, high-speed synchronous motors. At low speeds (514 rpm and below), the direct-connected exciter is large and expensive. Motor generator sets and static (rectifier) exciters are widely used for low-speed synchronous motors and when a number of motors are supplied from a single excitation bus.

Table 1-1
Full Load Efficiencies

hp	3,600 rpm	1,200 rpm	600 rpm	300 rpm
5	80.0	82.5	—	—
	—	—	—	—
20	86.0	86.5	—	—
	—			82.7*
100	91.0	91.0	93.0	—
	—		91.4*	90.3*
250	91.5	92.0	91.0	—
	—	93.9*	93.4*	92.8*
1,000	94.2	93.7	93.5	92.3
	—	95.5*	95.5*	95.5*
5,000	96.0	95.2	—	—
	—	—	97.2*	97.3*

*Synchronous motors, 1.0 PF

Brushless Excitation

One of the most significant developments in recent years is brushless excitation for synchronous machines. This development became possible with the availability of reliable, long-life, solid-state control and power devices (diodes, transistors, SCR's, etc.). As the name indicates, there are no brushes, collector rings, or commutators on the motor or exciter. This eliminates brush, collector ring and commutator maintenance and permits the use of synchronous motors in many hazardous (Class I, Group D, Division 2) and corrosive areas where conventional motors could not be used without extensive additional protection. All the advantages of conventional synchronous motors are retained—constant speed, high efficiency, power factor correction and varied performance capability. High precision, fast-acting, solid-state field application control is rotor-mounted and provides the same full complement of functions as a conventional synchronizing panel.

The exciter is an AC generator with a stator-mounted field. Direct current for the exciter field is provided from an external source. Exciter output is converted to DC through a three-phrase, full-wave, silicon-diode bridge rectifier. Thyristors (silicon controlled rectifiers) switch the current to the motor field and the motor-starting, field-discharge resistors. These semiconductor elements are mounted on heat sinks and assembled on a drum bolted to the rotor or shaft.

Semiconductor control modules gate the thyristors, which switch current to the motor field at the optimum motor speed and precise phase angle. This assures synchronizing and minimum system disturbance. On pull-out, the discharge resistor is reapplied and excitation is removed to provide protection. The control resynchronizes the motor after the cause of pull-out is removed if sufficient torque is available. The field is automatically applied if the motor synchronizes on reluctance torque. The control is calibrated at the factory and no field adjustment is required. The optimum slip frequency at pull-in is based on total motor and load inertia. All control parts are interchangeable and can be replaced without affecting starting or running operation.

Multi-Speed Motors

Since about the turn of the century, it has been possible to provide two-speed motors with a 2:1 speed ratio with a single stator winding. Other speed ratios, however, required two separate stator windings until the principle of pole amplitude modulation (PAM) was formulated. This new induction motor design has been a commercial success in England, with over 350 units built. Ratings as large as 3,200 hp are in service.

Many drives are ideally suited for the two-speed PAM motor, such as forced or induced draft fans for boilers. Used with fans having vane control, this motor offers definite advantages over a hydraulic coupling/motor/fan combination. Other typical refinery and chemical plant applications are ventilating fans, centrifugal pumps, compressors and cooling tower fans.

This multi-speed motor has numerous advantages. Two speeds can be obtained with any combination of pole pairs (as 8/10 poles-900/720 rpm, or as wide as 4/20 poles-1,800/360 rpm) and only one winding. PAM motors are smaller than equivalent two-winding machines and approximately 10% lighter. The entire winding works for both high and low speed, resulting in greater thermal capacity and higher efficiency. All coils have identical size and pitch, permitting efficient manufacturing. These single-winding motors require less active material and winding labor and therefore cost less than two-winding machines. Torque, noise and loss characteristics compare favorably to those of two-winding motors.

Table 1-2 shows the results of comparing a two-winding 1,200/600-hp, 900/720-rpm motor with a single-winding motor operating at the same speeds.

The PAM principle is to modulate the stator flux field of an AC machine. Both electrical and mechanical engineering recognize that if a signal of one frequency is acted on (or modulated) by another frequency, the result is two other frequencies equal to the signal frequency plus and minus the modulating frequency. Thus, 60 Hz modulated by 2 Hz gives resultant frequencies of 58 and 62 Hz. Likewise, if a six-pole field is modulated by a two-pole field the result is a four-pole field and an eight-pole field. Modulation is accomplished by reversing all the coils in half the periphery of the machine. If only a remaining eight-pole field is desired, the four-pole field can be eliminated by proper spacing of the starting point of each phase winding. Such a motor will then run at six-pole speed when connected normally and at eight-pole speed when half the coils are reversed.

Table 1-2
Two-Winding vs. Single-Winding
1,200/600-hp, 900/720-rpm Motors

	2-Winding Motor	PAM Motor
Total motor weight	13,000 lb.	11,000 lb.
Weight of largest part	4,900 lb.	4,300 lb.
Dimensions of largest part	71 in.	63 in.
Motor losses—maximum		
High speed	65.4 kw	60.1 kw
Low speed	36.3 kw	31.6 kw

Useful Motor Equations

The following equations are useful in determining the current, voltage, horsepower, torque and power factor for AC motors:

Full Load I = [hp(0.746)]/[1.73 E (*eff.*) PF (three phase)
= [hp(0.746)]/[E (*eff.*) PF] (single phase)

kVA input = IE (1.73)/1,000 (three phase)
= IE/1,000 (single phase)

kW input = kVA input (PF)

hp output = kW input (eff.)/0.746
= Torque (rpm)/5,250

Full Load Torque = hp(5,250 lb.-ft.)/rpm

Power Factor = kW input/kVA input

where:

E = Volts (line-to-line)
I = Current (amps)
PF = Power factor (per unit = percent PF/100)
eff = Efficiency (Per unit = percent eff./100)
hp = Horsepower
kW = Kilowatts
kVA = Kilovoltamperes

A typical medium-size, squirrel-cage motor is designed to operate at 2-3% slip (97-98% of synchronous speed). Synchronous speed is determined by the power system frequency and the stator winding configuration. If the stator is wound to produce one north and one south magnetic pole it is a two-pole motor; there are always an even number of poles (two, four, six, eight, etc.) The synchronous speed is

$$n = 60f/\ (P/2)$$

where:

n = revolutions per minute (rpm), f = frequency in Hertz (cycles per second) and P = number of poles.

The actual operating speed will be slightly less by the amount of slip. Slip varies with motor size and application. Typically, the larger the motor the less slip; a standard 10-hp motor may have 2½% slip, whereas motors over 1,000 hp may have less than ½% slip.

Selecting Compressor Motors

The first step in selecting motors for large compressors (1,500 hp and over) is to determine the motor voltage, speed and enclosure type.

Voltage. Motor voltage selection requires a determination of the most economical voltage level at which adequate system capacity is available to permit motor starting without excessive voltage drop. Restrictions by the utility or by size of the plant's generating capacity may limit the maximum drop to less than 20%. However, in the usual refinery or chemical plant process unit, large blowers and compressors are started very seldom once the plant has been on stream for some time. The undesirable effects normally associated with drops as high as 20% have been tolerable when occurring infrequently.

Table 1-3 indicates the relative cost of drip-proof 1,200-rpm motors at three voltage levels. The motor cost is but one facet of any cost study for selecting voltage level. The study must compare installed cost of motor, starting equipment, transformers and power and control cables at the various levels under consideration.

Higher voltage levels such as 13,200 volts are sometimes more economical overall, although the cost of the motor itself is higher than at 2,300 or 4,160 volts. For example, if the plant has a 13.8-kv distribution system, it can be more economical to install a 13,200-volt motor than to provide the primary switchgear, transformer and secondary motor control switchgear required for lower voltage motors. Operating experience at levels as high as 13,200 volts has been good, but it is not extensive compared to lower voltages. The number of manufacturers with experience at these levels is limited. Further, there are motor design considerations which limit the minimum size at which these high voltage levels can be applied. The motor manufacturer probably would not recommend a 3,000-hp, 13,200-volt motor as a first choice.

Table 1-3
Relative Cost at Three Voltage Levels of Drip-Proof 1,200-rpm Motors

	2,300-Volts	4,160-Volts	13,200-Volts
1,500-hp	100%	114%	174%
3,000-hp	100	108	155
5,000-hp	100	104	145
7,000-hp	100	100	133
9,000-hp	100	100	129
10,000-hp	100	100	129

When the plant distribution voltage is above utilization levels, for instance 23 kv or higher, economics will usually favor the 2,300-volt motor. However, each application has its own peculiarities. An examination of the relative cost of alternate schemes sometimes favors 4,160 volts. This is true particularly with motors in the 4,000 hp and larger sizes, and short circuit levels are above 150 mva.

Speed. Table 1-4 indicates the relative cost of 1,200-1,800-and 3,600-rpm, 2,300-volt, drip-proof motors. Where speed-increasing gears are used, the

Table 1-4
Relative Cost at Three Speeds of Drip-Proof 2,300-Volt Motors

	3,600-Rpm	1,800-Rpm	1,200-Rpm
1,500-hp	124%	94%	100%
3,000-hp	132	100	100
5,000-hp	134	107	100
7,000-hp	136	113	100
9,000-hp	136	117	100
10,000-hp	136	120	100

higher cost and less favorable torque characteristics of the 3,600-rpm motor eliminate its use for all practical purposes.

The motor and gear combination must provide the proper input speed to the compressor. Therefore, speed selection should consider whether the 1,800-rpm, or the 1,200-rpm motor and the corresponding gear provides the more economical combination. Before selecting motor speed, motor characteristics should be obtained for both speeds. The speed-torque and speed-current curves, power factor and efficiency values should be compared and evaluated.

The most important considerations in matching the motor to a pump or compressor are:

1. Motor speed-torque characteristics
2. Load accelerating torque requirements
3. Motor supply voltage during acceleration

Speed-torque characteristics. The closer motor and pump or compressor speed-load curves are to each other, the longer the drive will take to reach full speed, and the hotter the motor will get (see Figure 1-7).

A motor speed-torque curve for a large pump or compressor (250 to 1,000 hp or more) does not look the same as a smaller machine (10 or 20 hp). See Figure 1-8. National Electrical Manufacturers Association (NEMA) Standard MG-1 gives minimum locked rotor torque values as a function of motor size at 1,800 rpm. See Table 1-6.

Before a pump can deliver the desired flow, efficiency, and pressure, the motor must accelerate it to operating speed. Ask for a pump or compressor speed-torque curve and compare it with the proposed motor curve.

Load acceleration torque. High speed centrifugal pumps generally follow the square law curve of Figures 1-7 or 1-8 (i.e. torque varies as the square of the speed). However, a quite different characteristic can be found in other types of pumps. For example, the screw-type pump may be used with a torque characteristic as shown in Figure 1-9.

Even centrifugal pumps have different starting conditions. If the pump discharge can be closed during starting, torque requirements are less (see Figure 1-10).

Some engineers specify that the motor driver can be selected by assuming a typical centrifugal compressor curve. What is typical? Avoid impossible conclusions by matching motors to specific pump or compressor curves. (See Figure 1-11.)

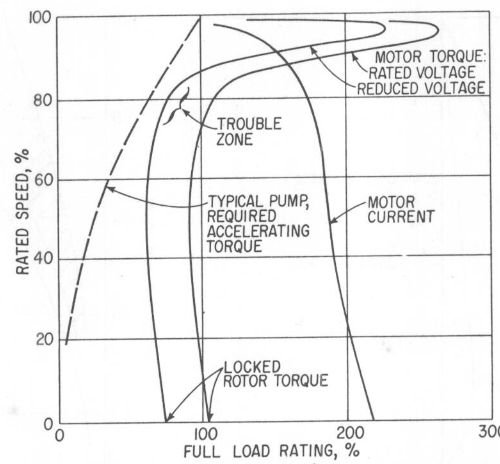

Figure 1-7. Startup difficulty probably occurs at the "trouble zone" in a typical, large 3,600-rpm motor accelerating a centrifugal pump.

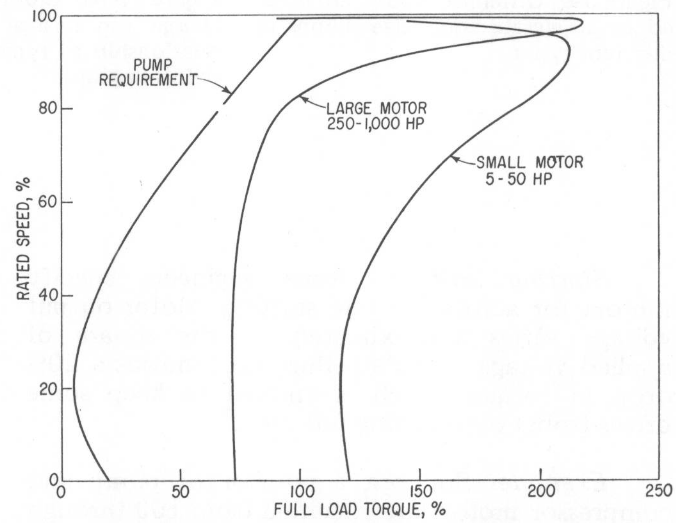

Figure 1-8. Typically large motors have relatively smaller capacities for accelerating their loads than small motors. Special designs can lessen the difference, but seldom eliminate it.

Table 1-5
Locked Rotor Torque
vs. Motor Size

Rated hp	Minimum locked rotor torque, percent of full load torque
5	185
10	165
100	125
250	80
2000	60