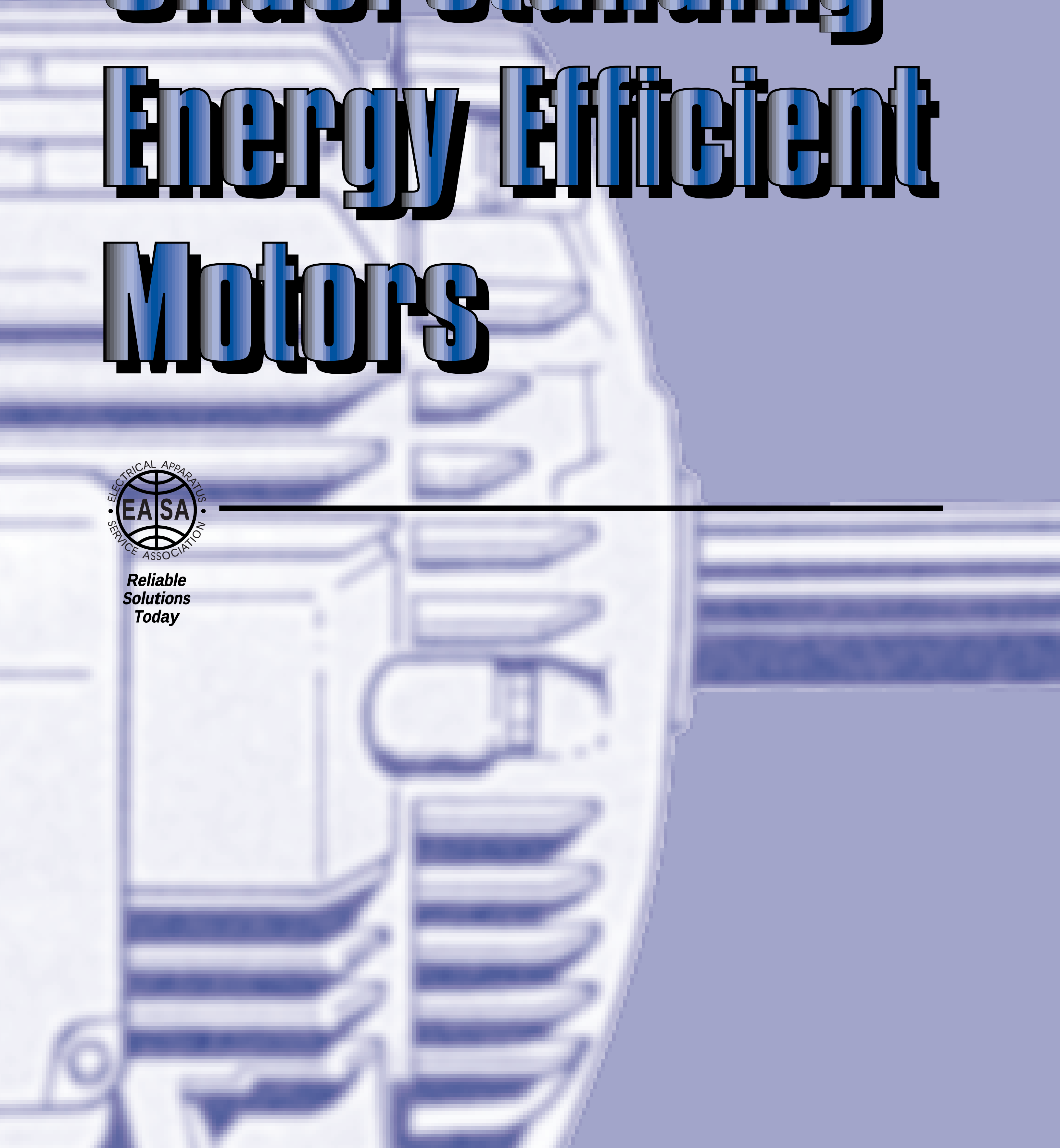
Understanding Energy Efficient Motors



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Introduction

For anyone who specifies, buys, operates, or repairs electric motors today, the issue of motor efficiency is of growing concern—and complexity. An understanding of efficiency and the applicable standards is essential to cost-effective product selection. The information in this publication is intended to enhance that understanding.

Although some general principles apply only to energy efficient motors, most of what we say here is valid for all motors.

What Is Efficiency?

The efficiency of any machine, including an electric motor, is its useful power output divided by the total power input. To be valid, however, input and output must be expressed in the same physical units.

$$\text{efficiency} = \frac{\text{useful power}}{\text{input}}$$

Input to an AC motor is the electrical power in watts (or kilowatts). Motor output is the mechanical power delivered by the shaft—the shaft torque times the speed (rpm). Since motor shaft output is not an electrical quantity, it's normally measured in mechanical units of horsepower. To divide that by electrical input in watts, horsepower must be converted to the electrical equivalent—one horsepower equals 746 watts. (In the metric system, the watt or kilowatt is the measure of both output and input, because different torque units are used.)

Input must always exceed output, the difference being internal power loss in the motor (input = output plus losses; output = input minus losses). Thus, output divided by input can never equal or exceed unity (100%).

Measuring Motor Efficiency

While motor efficiency can be determined by simply dividing the output power by input, in practice this method is inaccurate because the two numbers are so nearly equal. Small errors in measuring either quantity can have a large influence on their ratio.

■ **Direct Input/Output Ratio Method.** For example, suppose we measure both motor output and input with ±3% accuracy. For a true efficiency of 90%, at a rated output of 75 horsepower (electrically equivalent to 56 kilowatts), the apparent motor efficiency derived from the output/input measurements could range from a low of 84.8% to a high of 95.3%. The ±3% uncertainty in the individual measured quantities becomes almost double that in the efficiency itself. The higher the true efficiency, the greater the probable error in the output/input ratio.

Sample Efficiency Calculation—Typical 75 hp motor with "true" full-load efficiency of 90%.

"True" input power = 56 kilowatts divided by 0.9 efficiency, or 62.2 kilowatts. But with a ±3% tolerance the possible range of measured values would be from 60.4 to 64.1. The possible range of measured output, converted to electrical units, would be from 54.3 to 57.6 kilowatts.

The lowest possible calculated efficiency is minimum output divided by maximum input, or 54.3/64.1, which equals 0.848 efficiency. The highest possible efficiency is maximum output divided by minimum input, or 57.6/60.4, which equals 0.953 efficiency. Efficiency as determined by this method therefore ranges from 84.8% to 95.3%.

■ **Measured Input Plus Measured Losses Method.** It's much more accurate to ascertain the total motor loss and then divide that relatively small number by the much larger input value (output plus loss). Subtracting the result from 100 yields the percentage efficiency.

$$\text{efficiency} = 100 - \left(\frac{\text{motor loss}}{\text{total power}}\right)$$

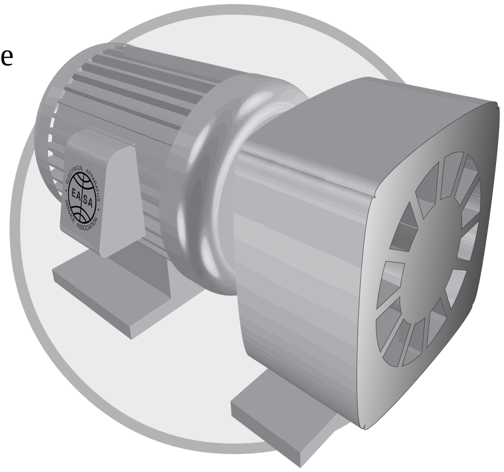
In the present example, assuming the same ±3% tolerance applies to the measured loss also, this method yields an apparent efficiency ranging from 89.4% to 90.6%—a much narrower variation than in the previous calculation. This method is obviously less subject to variation than the simple output/input calculation, especially since most losses can be measured with a tolerance far below 3%.

Sample Efficiency Calculation—Typical 75 hp motor with "true" full-load efficiency of 90%.

"True" value of losses equals 62.2 minus 56, or 6.2 kilowatts. If loss is measured with a ±3% tolerance, the possible range of values is 6.02 to 6.38 kilowatts. The percent of loss could range from 9.96 [100 (6.02/60.4)] up to 10.56 [100 (6.38/60.4)].

Percent efficiency equals 100 minus percent loss, and can therefore range from 89.4 to 90.1. That applies to the lowest value of measured input. For the highest value, 64.1 kilowatts, the similarly-calculated efficiency range is from 90.1% to 90.6%.

■ **Effects of Driven Machines on Efficiency.** The examples provided thus far assume that electrical input to the motor supplies only useful output plus internal loss. Some drives include other alternatives. Any belts, gears or clutches between the motor and the driven machine will have their own internal losses that must be supplied from motor input power, yet won't show up in any motor test. Other losses will occur in the power supply conductors, or in external field circuits of DC or synchronous machines. Those losses increase the drive operating cost but are not influenced by motor efficiency.



What Are Motor Losses?

■ **Load-Dependent Losses.** Five internal losses exist in a squirrel cage induction motor. Three of them are "load-dependent," varying quite closely as the square of the load or the load current. These include the I^2R loss in the stator winding ("copper loss"); the I^2R loss in the rotor cage ("slip loss"); and the stray load loss (involving numerous components in various parts of the machine).

■ **Load-Independent Losses.** The two remaining losses are generally considered "load-independent" or "constant" losses—the core or iron loss (which will decrease slightly with increasing load) and the friction and windage loss.

The relative proportions of these individual losses will vary with motor speed and size. Table 1 is typical for industrial motors.

Table 1. Motor Loss Components

Type of Loss	Typical % of Losses 4-Pole Motors	Factors Affecting These Losses
Stator winding losses	35 to 40	Stator conductor size and material
Rotor losses	15 to 20	Rotor conductor size and material
Stator core losses	15 to 20	Type and quantity of magnetic material
Stray load losses	10 to 15	Primarily manufacturing and design methods
Friction and windage	5 to 10	Selection/design of fans and bearings

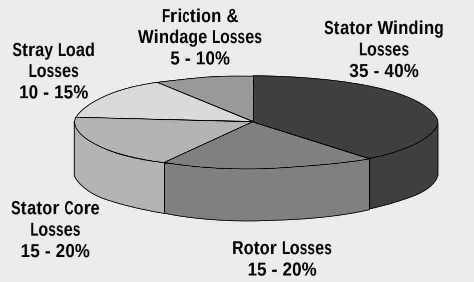
Reference: NEMA Stds. MG 10-1994, Table 2-2.

The above values show the typical loss distribution for medium induction motors. Speed, size, and enclosure type lead to wide variations in some of these proportions, particularly the core and friction and windage losses.

For any machine (including any electric motor), the efficiency will reach its maximum value when the total "load-dependent" loss equals the total "load-independent" loss. At all other load points, efficiency will fall below that maximum value.

The most important thing to remember about the relationship of efficiency and load is that efficiency varies only slightly over a wide range of output. That's because for induction motors of normal design the equality of load-dependent and load-independent

Figure 1. Motor Loss Distribution (100% Full Load) [1]



losses will occur between 60% and 85% load (typically around 75%). Hence, maximum efficiency usually occurs at that point, rather than at rated horsepower. Still, as shown in Figure 2, the curve plotting efficiency vs. load is fairly "flat."

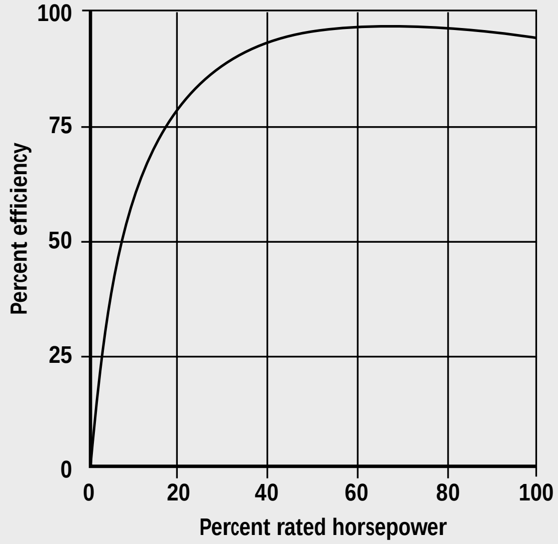


Figure 2. Typical Efficiency vs. Load Curve For Polyphase Induction Motors

Keep in mind, too, that although efficiency drops fairly rapidly as the load decreases below 50%, the actual energy wasted—the losses themselves—is much lower than at full load. Those losses represent energy cost without benefit. If they are small, their cost is small, despite the poor efficiency percentage. In other words, a large percentage of a small amount of power is still a small amount. In the extreme, the lowest possible efficiency for any motor is zero—at no load. But the total power used at that point is usually negligibly small.

Equipment operating cost analysis concerns itself more with actual power usage than with efficiency values, so relating actual watts loss (W) to efficiency (E) is often useful. Here's the formula:

$$W = \text{output power} \times \left(\frac{100 - E}{E}\right)$$

Where: W = loss, output power is in equivalent watts, and E = efficiency in percent.

For an output of one horsepower or 746 watts:

$$W = 746 \times \left(\frac{100 - E}{E}\right)$$

At any value of efficiency, it's easy to calculate the corresponding loss in watts per horsepower. For a 5 hp motor, multiply W in the formula by 5 to get total watts loss; for 100 hp, multiply W by 100;

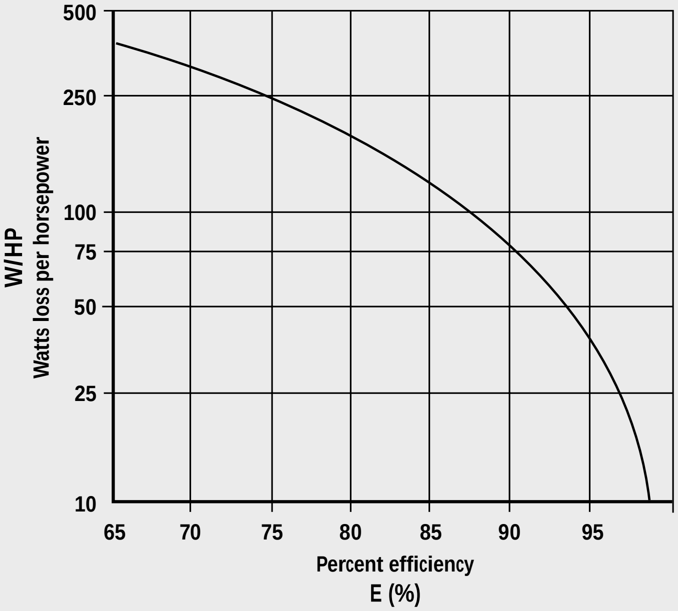


Figure 3. Efficiency Vs. Watts Loss

For any motor, at any horsepower output, watts loss per horsepower at that load is related to efficiency at that load by this curve.

and so on. Such calculations produce the curve of Figure 3. For a motor, at any actual load, multiply the watts from this curve by the actual horsepower to get total motor loss.

This curve also shows that the higher the motor efficiency may be, the less benefit is gained by making it still higher. For simplicity, consider a 1 hp motor that undergoes two different efficiency changes. First, an efficiency change at high levels, from 91% to 93%.

$$W = 746 \times \frac{(100 - 91)}{91} = 74 \text{ watts}$$

$$W = 746 \times \frac{(100 - 93)}{93} = 56 \text{ watts}$$

The change in watts loss per horsepower is: 74 - 56 = 18 watts.

Now consider an efficiency change at lower levels, from 66% to 68%.

$$W = 746 \times \frac{(100 - 66)}{66} = 384 \text{ watts}$$

$$W = 746 \times \frac{(100 - 68)}{68} = 351 \text{ watts}$$

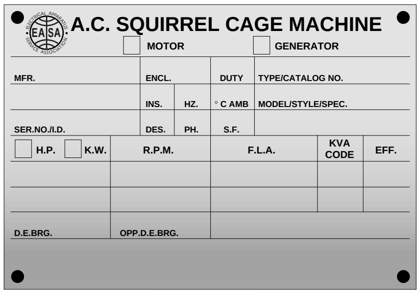
The change in watts loss per horsepower is: 384 - 351 = 33 watts.

Thus, raising a low efficiency is much more beneficial than raising a high efficiency by the same amount. (That's just as well, because the higher the efficiency level is to start with, the greater the difficulty of pushing it still higher.)

Interpreting Quoted Efficiency

The foregoing discussion defines efficiency in general and motor efficiency in particular. The next step is to learn how to interpret motor efficiency values that may appear in catalogs or on nameplates.

Nameplate Efficiency Values



The practice of marking on motor nameplates an efficiency derived from a specific test was originated by the National Electrical Manufacturers Association (NEMA) in 1980. Even today nameplate efficiency values are often misunderstood. They apply to standard AC polyphase machines, whether the motors are energy efficient designs or not.

Two terms that must be understood are "nominal" and "minimum" full-load efficiency. NEMA first adopted the wording in the 1970s. Here are the latest definitions, from MG 1-1993, Part 12.58.2:

- **Nominal full-load efficiency:** " . . . shall be not greater than the average efficiency of a large population of motors of the same design."
- **Minimum full-load efficiency:** Losses are no more than 20% greater than for the nominal efficiency (from Table 12-8 of NEMA MG 1).

Obviously, the terms "average" and "large population" lead to an unavoidable tolerance on the nominal efficiency value for any motor. Manufacturing and test variations can be minimized—never eliminated.

■ **Nominal Efficiency.** The nominal efficiency average is not derived from whichever method of testing the manufacturer may choose. Only one procedure is allowed by NEMA and the Energy Policy Act of 1992 (EPACT): IEEE Standard 112, Method B (dynamometer), 1991 version, as outlined in detail in MG 1, Part 12.58.1. (Canadian Standards Association Standard C390 is considered equivalent.)

No standard ever attempted to prescribe a nominal efficiency value that had to be met for a motor to be sold as a NEMA standard machine. That was left strictly between buyer and seller.

The "energy crisis" of the early 1970s, however, brought a new emphasis on motor efficiency into the marketplace. NEMA responded first by requiring nominal efficiency values to be stamped on the nameplates of the following standard machines: polyphase, single-speed, 900 - 3600 rpm, low-voltage, 1 - 125 horsepower, NEMA Designs A or B (or the "equivalent Design C," although the meaning of "equivalent" here was not made clear). Multispeed, NEMA Design D, medium-voltage, synchronous, and single-phase machines were (and are) not included.

Table 2. Sample Nameplate Nominal and Minimum Full-Load Efficiencies

Nominal Efficiency, %	Minimum Efficiency, %
94.1	93.0
93.6	92.4
93.0	91.7
92.4	91.0

This excerpt from NEMA MG 1, Table 12-8, shows standard values allowed for nameplate marking of nominal full-load efficiency, and the corresponding "minimum" values. Each "minimum" represents 20% higher motor loss than the associated nominal figure.

The nameplate efficiency was (and is) required to be a value chosen from Table 12-8 in the NEMA standard, part of which is reproduced here in Table 2. In this table, which includes nominal efficiencies ranging from 50.5% to 99%, the separation between any two adjacent values is based on the manufacturing/test variations mentioned earlier. The numbers were so chosen that the likely variation (established in an extensive series of round robin tests on the same set of motors by a number of manufacturers) from any one number would not be great enough to throw it into the range of the next number. In other words, no overlap was to be expected. A loss difference of 10% between adjacent numbers in the table was considered adequate for that purpose.

NEMA's nameplate marking standard also requires that the nameplate identify the marked efficiency as "NEMA Nominal" or the abbreviation "NEMA Nom." It cannot be called simply "efficiency."

Despite the 125 hp limit in the standard, manufacturers began marking nominal efficiencies on nameplates for motors up through 200 hp, and often well beyond that (see Figure 4, Page 8). Since then, NEMA has revised its tables to set limits for "energy efficient" motors up through 500 hp, depending upon speed. However, motor users may not be able to rely as much on the integrity of those numbers when the motor horsepower falls beyond the governing range of the NEMA standard.

■ **Minimum Efficiency.** Although NEMA does not use the word "guaranteed," the accepted interpretation of the "minimum efficiency" definition has always been that any individual motor of that particular design must meet that efficiency level. The "nominal" value is recognized as an average. Some motors meet it; some exceed it; others may fall short. But the "minimum" has to be met by each unit.

At present, after development of as many as three successive generations of more efficient motors by some manufacturers, many products on the market exceed even the Table 12-10 efficiencies by a considerable amount. Nevertheless, that table provides a good benchmark against which to compare designs. It is particularly convenient to public utilities.

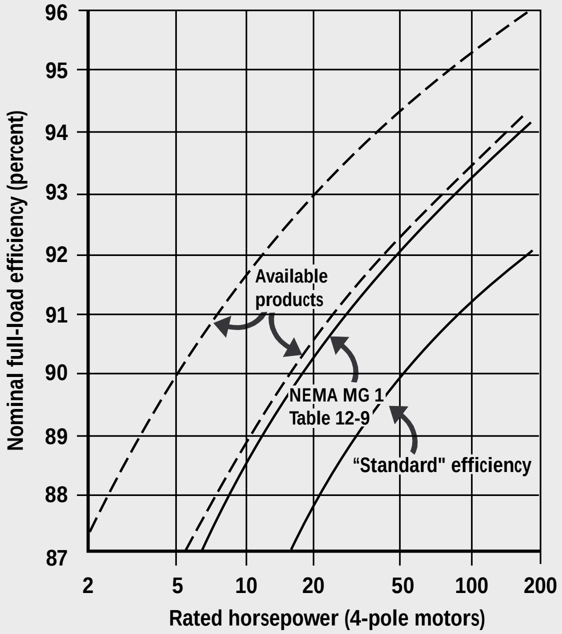


Figure 4. Range of Efficiencies in Market About 1990

Combined data from several manufacturers shows the range of efficiencies in the market about 1990. Note that many motors were available with efficiencies well above the NEMA Table 12-9 standard for "energy efficient" products. The same is true for NEMA Table 12-10 values.

■ **Nominal Efficiencies & Conservation Programs.** Throughout the United States and Canada, at least 150 rebate programs once existed in which utilities offered customers cash incentives to purchase more efficient motors. The resulting energy conservation helped utilities postpone or eliminate the need to add new generating capacity.

Utilities quickly realized that "qualifying" motor efficiencies that didn't match nameplate numbers from some NEMA table would be open to question. If they were lower than might be achieved with "standard" motors, the rebate would be hard to justify. Why pay a user to buy a product carrying no price premium? If the qualifying efficiency were just above what Brand X could provide, then that manufacturer might cry "foul." When, however, a utility chooses NEMA Table 12-10 as the qualifying level, the numbers became those chosen by the motor industry itself to represent energy efficient machines. They need not be defended by the utility as either arbitrary or subjective.

With the advent of utility deregulation and competition, most utilities have scaled back or eliminated incentive programs, though many still promote higher motor efficiency in other ways. But even if rebates are not involved, the standardized values in NEMA Table 12-10 have become logical benchmarks for any evaluation of motor economics. For that reason, too, NEMA Table 12-10 was

Table 3. NEMA's Latest Energy Efficiency Goals

	NEMA Table 12-9		NEMA Table 12-10*	
HP	Nominal	Minimum	Nominal	Minimum
7.5	87.5	85.5	89.5	87.5
20	90.2	88.5	91.0	89.5
75	93.0	91.7	94.1	93.0

These figures show how the latest NEMA "energy efficient" goals have been raised for three representative 1800 rpm TEFC ratings.

*Note: NEMA defines an "energy efficient" motor as one that meets the nominal full-load efficiencies in NEMA Table 12-10. Products described in sales literature and catalogs as "premium efficient" or "high efficiency" may or may not meet NEMA's definition. Always check the nominal full-load efficiency on the nameplate.

chosen as the required performance level in the Energy Policy Act of 1992 (EPACT), although 250-500 hp, and all 900 rpm, ratings were excluded.

■ **Design E Motors.** Since 1993, NEMA has added a new Table 12-11 giving efficiencies for a "Design E" line of "energy efficient" motors, with performance going beyond the legislated values. As yet, few Design E motors are on the market, largely because of their higher locked-rotor currents.

■ **Questionable Practices.** With all that as background, it's clear that the efficiency stated by the motor manufacturer has assumed great importance. It is needed for the financial calculations justifying the purchase of more efficient motors. For a time, it also was important for obtaining a rebate on that purchase. In North America today the stated efficiency is required for EPACT in the United States and the Energy Efficiency Act of 1992 in Canada.

At the same time, it remains to the manufacturer's advantage to push the quoted figure as high as possible in comparison with competitive products. The user should therefore be extremely careful in obtaining and interpreting efficiency figures when considering a motor purchase. Several questionable practices have brought uncertainty into that process.

One such practice is the widespread publication of catalog figures not matching any NEMA table, including 12-8. For example, two adjacent values in that table are 91.7% and 92.4%. Suppose a manufacturer properly tests a 20 hp design and concludes that the "correct" nominal full-load efficiency is 92.3%. In accordance with the NEMA standard, the nameplate marking must be the next tabulated value below that test figure—which would be 91.7%.

But the manufacturer argues—and so has the NEMA Technical Committee—that the 92.3 figure is "more nearly correct." That may be true, but the NEMA standard does not allow its use.

That standard, however, says nothing about what's stated in catalogs. It regulates only nameplate markings. So the manufacturer is perfectly free to use "92.3" in sales literature, while using "91.7" on the nameplate.

Comparative studies have shown that, depending upon the motor rating, up to one-fifth of the catalog efficiencies for U.S.-built motors do not match NEMA tables. Sometimes these values aren't even called "NEMA Nominal," which is legitimate; the terminology, as well as the number, is required only on motor nameplates.

For motors built overseas, by manufacturers not members of NEMA, a wider variation exists, which is also legitimate. In 1992 catalogs for imported products, nearly half the published efficiencies for a typical rating did not match NEMA tables.

For example, catalog efficiency may be (in percent) 81.0, 82.9, 83.0, or 95.1—values not countenanced by NEMA. Since they don't appear in NEMA Table 12-8, they fall outside the requirement that they be determined by any particular test. More important, they fall outside the requirement that a particular "minimum" efficiency exists for the design. The user cannot be sure, therefore, of the accuracy of a payback cost analysis for that design.

Motor Efficiency Legislation

■ **United States.** In the United States, motor efficiency is only one of many topics dealt with in the 1992 Comprehensive Energy Policy Act (Public Law 102-486), referred to here as "EPACT." The legislation also covers appliance standards, usage of natural gas, clean coal technology, electric vehicles, even global climate change, plus many other matters.

Broadly speaking, however, EPACT requires that as of October 24, 1997, all nonexempt, general purpose motors manufactured for use in the United States must meet the nominal efficiencies in NEMA Table 12-10 (see Table 4). These are T-frame, horizontal foot-mounted, single speed, 230/460 volt NEMA Design A or B, dripproof and totally-enclosed, 1200 - 3600 rpm, 1 - 200 hp only. (See the Appendix for more information about EPACT.)

■ **Canada.** Canada has similar legislation called the Energy Efficiency Act (1992). The associated Energy Efficiency Regulations were last published in December 1997. In general, this legislation applies to motors imported into Canada and sold from one province to another. Motors manufactured and sold within a province are subject to provincial energy efficiency legislation.

The Canadian law covers single-speed, polyphase squirrel cage induction motors rated for continuous duty, open or enclosed, NEMA Design A or B. The minimum efficiencies are the same as those in the EPACT legislation except that no distinction is made between open and enclosed frames.

Other features of motors covered by Canada's Energy Efficiency Act are: 2, 4 or 6 poles; ratings of 600 volts or less; 50/60 Hz and not more than 200 hp; T-frame with standard, R or S (tapered or short) shafts; foot, C-face or D-flange mounting; and IP code 00 to 66 (degree of enclosure protection).

Also included are IEC design N, S1 duty motors with the following features: 2, 4 or 6 poles; ratings of 600 volts or less; 50/60 Hz between .746 kW and 150 kW; frame numbers 90 or above; and IP code 00 to 66.

For more information, contact: Residential, Regulatory, and Information Programs, Natural Resources Canada, 580 Booth St., 18th Floor, Ottawa, ON, Canada K1A 0E4; Fax: 613-943-1590.

What Are The Operating Conditions?

As mentioned earlier, nameplate nominal efficiency, as standardized by NEMA, applies only at "full load." That means at the motor's nameplate horsepower.

Knowing the actual load is important, even though efficiency itself is fairly constant over a wide range of load, from nameplate horsepower down to about half that (see Figure 2, Page 4). That's because an efficiency of, say, 90% at half rated load means a much smaller energy loss in the motor (and therefore much less saving in operating cost through efficiency improvement) than the same 90% at full load. Thus, if the existing motor runs mostly at the lighter load (and a more efficient replacement does also), the economic justification for the replacement may be marginal.

■ **Motor Output.** Determining actual motor output can be difficult. Current, voltage, slip, and input power measurements can be used in various combinations, but all such tests contain unavoidable inaccuracies—sometimes quite large (more about that later).

The most troublesome applications are those in which load continually varies (see Figure 5). Obviously some compromise is needed to arrive at a usable horsepower/time relationship.

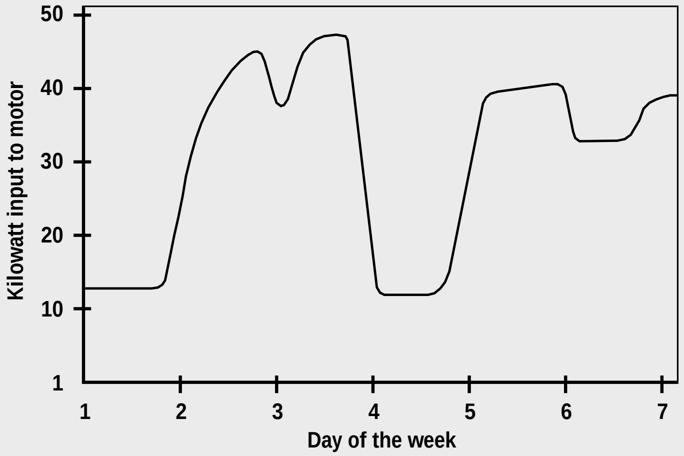


Figure 5. Load Variations

When load varies like this, determining motor efficiency is particularly difficult. The 75 hp motor was driving a tannery mixer.

- **Running Time.** Running time is at least as important as load. Given a known, constant motor output, any investment payback analysis for a higher efficiency replacement motor must involve the number of hours of operation at that load. Motor sales literature or handbooks typically assume in economic analysis that a motor runs at full load 8,760 hours a year, around the clock. This is almost never true. Most motors run only 2,000 to 4,000 hours a year. The fewer the hours, the smaller the savings available from higher efficiency. Both actual load and actual operating hours at that load must be determined with as much accuracy as is expected from the cost analysis. Remember, too, to base payback calculations on the time the motor actually runs—not process time.

- **Terminal Voltage.** Nameplate efficiency is also valid only when motor terminal voltage is perfectly sinusoidal, balanced, and at the nameplate value. Although other NEMA standards still require a motor to operate "successfully" at voltages ±10% of rated, the stated efficiency will not necessarily apply.

If, therefore, motor circuit voltage is known to vary widely—perhaps with significant phase unbalance, meaning over 1% in NEMA terms—don't expect a new "energy efficient" motor on that circuit to deliver the performance expected from either catalog or nameplate efficiency.

- **Effect of Harmonics.** If variable frequency drives or other harmonic-producing devices are on the same circuit, harmonic voltages are likely at the motor terminals. The greater the waveform distortion, the lower will be the motor's efficiency; and the decrease will not be predictable.

All that is equally true for "standard" motors having lower efficiencies. However, the reaction of individual motor losses, such as core loss, to applied voltage variations isn't likely to be the same for such a motor as it will be for a new, energy efficient replacement. So don't look for observed performance changes for the original motor to be matched by its replacement under the same operating conditions.

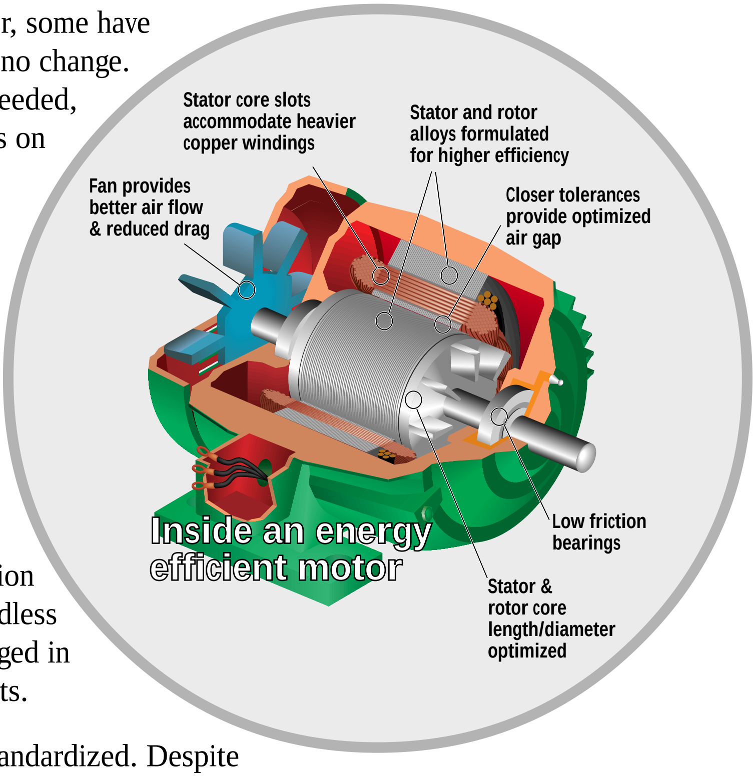
Common Misconceptions About Energy Efficient Motors

Many misunderstandings have arisen concerning the characteristics of today's more efficient motors. Some of them lead to unfair criticism of such motors. Other equally inaccurate notions lead users to expect more than these motors will deliver. One thing is sure—with the growing importance of high efficiency, proper selection, application, and operation of motors has also become more important. EASA sales and service centers can assist users with these tasks. In addition, realistic expectations must precede the correct choices. Here are just a few of the unrealistic ones.

- **Misconception 1: "An oversized motor is less efficient."** Many authorities continue to stress the need to match motor rating more closely to actual load horsepower, contending that "oversized" motors are inherently inefficient. Many surveys have indeed shown most motors to be at least 30% underloaded. But as Figure 2 (Page 4) shows, motor efficiency typically peaks at such a load rather than at full rated horsepower. A 3 hp load, for example, is more efficiently carried by an underloaded 5 hp motor than by a fully loaded 3 hp machine. The larger motor will likely have a lower power factor and higher starting current. Those may or may not be problems, but have nothing to do with efficiency.

■ **Misconception 2: “A more efficient motor also has higher power factor.”** Many motor design modifications may be made to increase efficiency. Some of them will also increase the power factor, whereas others (such as a larger air gap) will decrease it. Comparing “energy efficient” machines with their less efficient predecessors shows that some do have higher power factor, some have lower power factor, and some exhibit no change. If power factor improvement is ever needed, an easy way to get it is with capacitors on the motor circuit—an economical corrective measure that isn’t available to improve efficiency.

■ **Misconception 3: “More efficient motors run cooler.”** That’s a fallacy. So is the reverse proposition, “cooler motors must be more efficient.” Temperature and heat are not the same thing, so they should not be confused with each other. Temperature ratings for insulation systems or motors are the same regardless of motor efficiency; they haven’t changed in 30 years. They are internal rating limits.



External surface temperature is not standardized. Despite the ease of measurement, it is notoriously unreliable as an indicator of what’s going on in the winding, and is never a proper basis for comparing one motor with another.

If two motors are otherwise identical, the one with the lower internal heat also will exhibit a lower temperature inside and out. If one of them has been converted to a higher efficiency design, however, by reducing its internal loss, it will have a different loss distribution and need less cooling air flow. Such a motor is likely to have a smaller cooling fan. That also raises efficiency by lowering windage loss. But when less cooling is combined with lower loss, the net result is likely to be little or no change in operating temperature.

Furthermore, the two motors are likely to have different heat transfer characteristics between interior and exterior. The relationship between internal winding temperature and external surface temperature may therefore be quite different for each unit.

■ **Misconception 4: "An energy efficient motor develops less torque, and may not accelerate the load."** Lower rotor resistance, often used to achieve higher efficiency, does tend to reduce motor accelerating torque. But it is not the only influence. And the expected amount of torque reduction is seldom harmful except for loads such as full conveyors that shouldn't be using a NEMA Design B motor anyway.

Figure 6 compares a typical pump load accelerating torque requirement with the capability of a range of both standard and "energy efficient" motors, and with NEMA standard locked-rotor and breakdown torques. (NEMA MG 1 does not provide typical speed-torque curves or curve shapes for any motors.) The more efficient motor clearly has ample torque (well above published standards) to accelerate such a load. Furthermore, an energy efficient unit usually contains more copper and steel than a standard motor, giving it greater thermal capacity to handle severe starts or periodic overload.

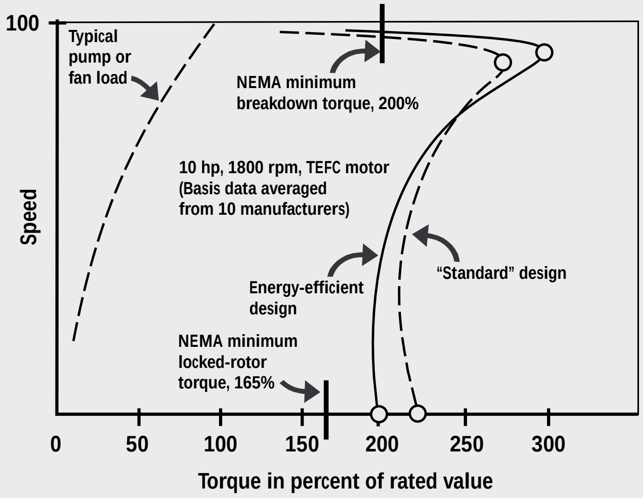


Figure 6. Typical Speed-Torque Curves for Standard and Energy Efficient Medium Motors.

Whether "standard" or "energy efficient," medium motors should have no trouble accelerating loads in accordance with NEMA standards, as shown by this typical relationship.

While many other popular misconceptions could be discussed, those mentioned clearly show why any motor user needs to understand just what an "energy efficient" motor does and does not offer. Operating cost savings are potentially great—for those who buy the right motor, for the right system, and operate and maintain it in the right way.

Determining Efficiency On The Jobsite

The NEMA/IEEE tests for determining nameplate (and EPACT) efficiencies are complex and precise. They involve dynamometer loading, balanced and closely-held voltages, and temperature corrections. They also employ mathematical data analysis to eliminate obviously erroneous readings, arrive at stray load loss, and produce highly accurate results.

Neither the test conditions nor the equipment is available at the jobsite, or in all but a handful of service centers. Motor efficiency determined in the field must therefore be considered an estimate only. How useful that estimate may be is a subjective judgment. Even an "exact" answer would apply only at the motor's actual load during the test, which seldom equals the nameplate horsepower for which factory efficiency is determined.

Possible Reasons for Estimating Efficiency at the Jobsite

- To find out how efficient an existing motor is, as part of a cost study to evaluate its possible repair or replacement.
- To see if an "energy efficiency" motor lives up to expectations once it's in service.

Because it's impossible to approach factory test accuracy in the field, no one should attempt the second of these tasks. To accomplish the first, recognizing that an exact answer can't be expected, requires measuring any *two* of the following three items:

- **Electrical power input.**
- **Losses within the motor.**
- **Mechanical power output.**

■ **Electrical Power Input.** It usually is easy to measure electrical power input quite accurately, given the proper instruments. If the motor is 2300 volts or above, however, the test becomes more difficult, because current and voltage transformers are needed for metering. (Clamp-on equipment, if suited to the voltage level, isn't nearly as accurate as directly-connected switchboard-type instrumentation.)

■ **Losses Within the Motor.** Measuring the five internal motor losses is not feasible. If the motor can be uncoupled for idle running, and if the voltage can be varied over a suitable range of 3 or 4 to 1, the "no-load" losses (core plus friction & windage) can be determined. Measurement of stator winding resistance, with the motor disconnected from its feeder circuit, can be coupled with measured line current to give the stator I^2R loss. A slip (rpm) reading leads to rotor I^2R loss.

The remaining component, stray load loss, has a strong influence on efficiency but cannot be determined from any field test (see Table 1, Page 3). Most advocates of field efficiency testing propose using an arbitrary percentage of motor output as the stray loss. European (IEC) standards, for example, stipulate a value of 0.5%; an American National standard (ANSI C50.41, written only for form-wound power plant motors above about 200 hp) uses 1.2% up to 2500 hp.

Recognizing that such values are unreasonably low for medium horsepower motors, the 1991 revision of IEEE 112 assigns the arbitrary stray loss allowances in Table 4 for test methods E and F (no dynamometer).

Table 4. Stray Load Loss Allowances for IEEE 112 Test Methods E and F (no Dynamometer)

Motor Hp Rating	Stray Loss, % of Rated Output
1 - 125	1.8%
150 - 500	1.5%

Using any such percentage, however, cannot be construed as a “test.” It’s an estimate—a value one is forced to use because no test is possible. Such fixed percentages aren’t allowed in the NEMA/ IEEE 112 Method B procedure on which all nameplate efficiencies are based.

■ **Mechanical Power Output.** Measuring mechanical power output is deceptively simple; all that’s needed is a reading of actual speed (rpm) and actual shaft torque. In most situations, the speed is measurable within one revolution.

To read shaft torque requires some kind of strain-measuring equipment on the shaft. (Although newer technology needs no direct contact between the shaft and stationary instrumentation, something on the shaft surface must directly respond to the twist in the shaft caused by the transmitted torque.) Such equipment is expensive. Neither the average motor service center nor the average industrial motor user has it. And, in many drives, the shafting isn’t accessible enough to use the test devices.

Other Field Efficiency Test Methods

Several other “test” methods support judgment of probable efficiency of a motor in the field. None of them is accurate. The best that can be hoped for is that at least two methods will agree with one another well enough to justify some single efficiency value. That remains a subjective decision. No one should ever consider such an efficiency as a “tested” value—only as a likely estimate, certainly not as accurate as a factory test or a nameplate value. Here’s how they work.

■ **Current Ratio Method.** In this procedure, motor current is measured, adjusted for actual motor voltage, and then compared with nameplate amperes to arrive at the relative horsepower load. If that is at or above 50% of the nameplate rating, efficiency can either be taken as equal to the nameplate figure or (for an older motor having no nameplate efficiency) used to pick the appropriate efficiency value from an efficiency vs. load curve obtained from the manufacturer or plotted from catalog data.

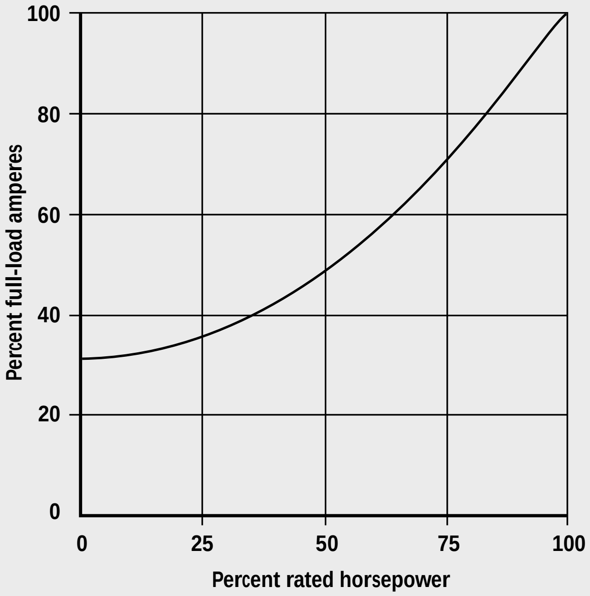


Figure 7. Typical Curve Of Motor Current vs. Load.

Shape of the curve and the value at no load will vary with motor speed and size.

The problem is that amperes is not a linear function of load (see Figure 7). But if the current is at least half the nameplate value, except for motors less than 5 hp or below 900 rpm, linear approximation is probably good enough. Some engineers use a mathematical “straight line function” formula to approximate the shape of the lower part of the curve, but this does a poor job at higher loads (Figure 8, Page 18).

■ **Input Current and Power Method.** Here, the same current measurement is taken to arrive at the probable output power. The input electrical power is then measured, and the efficiency is calculated as a simple output/input ratio. This is highly inaccurate for two reasons. One is the uncertainty of the amperes vs. horsepower relationship, as already described. The other is that output and input are two relatively large numbers (compared to losses) that are close to each other numerically. As explained earlier, measurement errors of equal magnitude in those two items typically will lead to double that error in their ratio (the efficiency). In the NEMA/IEEE test method, the process is greatly modified to eliminate such gross errors.

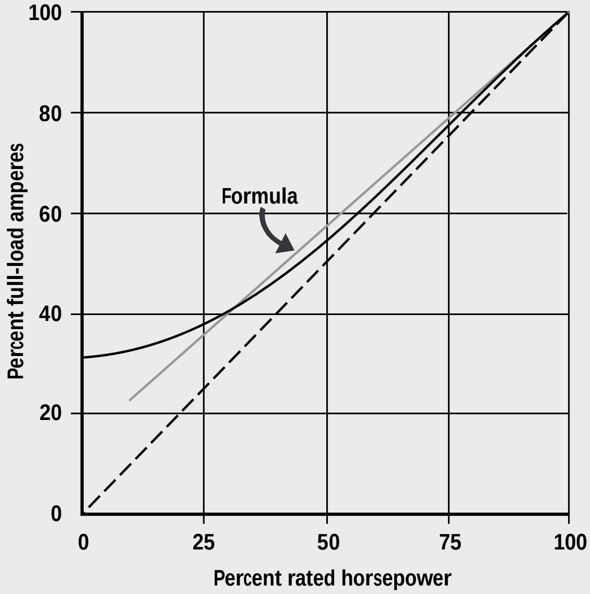


Figure 8. Current Variation With Load

Because the actual current vs. load curve is seldom available, some field engineers use a formula that follows a straight line such as that plotted here (for an assumed no-load current). For loads below 50%, it's a somewhat better "fit" than assuming current directly proportional to load (the dashed line). But above 50% load, it's a worse fit.

■ **Slip Method.** Here, the input power is measured along with actual speed (rpm). The slip (synchronous rpm minus actual rpm) is then simply compared with the slip corresponding to nameplate speed (which supposedly represents full load). Half the nameplate slip would represent half rated load, for example, because slip varies linearly with load. A voltage correction may be needed, because at any given horsepower output, slip varies with the square of the applied voltage—the higher the voltage, the lower the slip (see Figure 9).

As an example, suppose a 460 volt motor's "true" full-load rpm is 1760. The slip is then 1800 minus 1760 or 40 rpm. NEMA allows ±20% difference between actual slip and nameplate slip when the ambient temperature is 25° C (MG 1-12.46). Thus, depending upon manufacturing and test variations, the nameplate could properly be stamped 1760 ±20% of 40 rpm, or:

Maximum slip = 48; rpm = 1752

(1750 would probably be used; almost all nameplate—and catalog—speeds are rounded to some multiple of 5 rpm.)

Minimum slip = 32; rpm = 1768
(1765 would probably be used.)

Suppose ambient temperature varies by 10° C from season to season, so that in winter the ambient is only 15° C. A rise of 80° C over ambient for a rotor (where the temperature effect on slip takes place) would change that true slip of 34 rpm to 33 rpm. Now suppose the terminal voltage is 500 (within the 10% NEMA voltage tolerance). A "true" slip of 40 rpm becomes $(460/500)^2$ times 40, or 34 rpm.

What if the motor nameplate had been marked "1750"? Full load then implies a slip of 50 rpm. Because the actual slip at full load, for the conditions just stated, would be only 33 rpm, the measured speed would be 1767. From that value alone, we would conclude that the motor load is 33/50 or only 66% of its rated horsepower—when in actuality the load is 100%.

What if the actual measured speed (rpm) had been 1750? Since that's the value on the nameplate, we would assume the motor is supplying rated output. In actuality, the load would be 50/33 or 152% of rating.

Many other examples could be given. A user aware of the dependence of slip upon both voltage and temperature could estimate corrections to allow for those effects. But rotor temperature can't be measured, and the user can't be sure if the nameplate rpm is correct.

Most motors probably won't be subject to such large errors. But how do you know? Again, this procedure leads only to an estimated, not tested, efficiency—i.e., it is not comparable to NEMA nameplate efficiency.

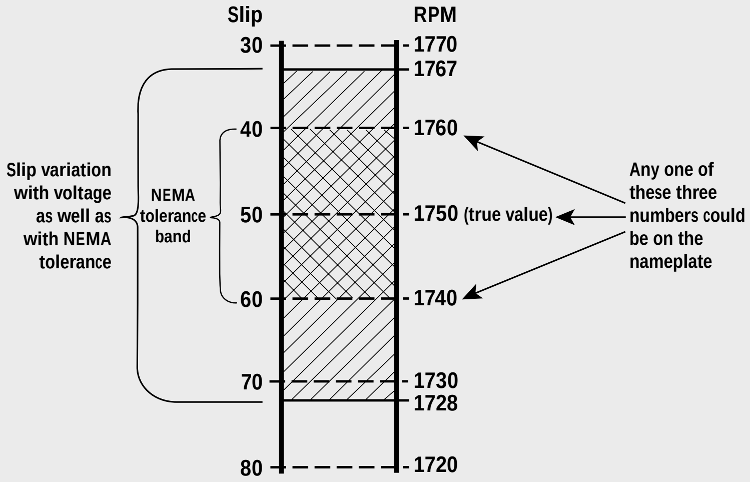


Figure 9. Slip Variation With Voltage

Although actual slip can be measured accurately under load, it is quite sensitive to terminal voltage. Also, the slip corresponding to motor nameplate speed (rpm) is subject to a broad tolerance. A "correct" or true rpm of 1750, for example, could actually be anything from 1728 through 1767, even without considering the effect of rotor temperature on slip.

Using such approximations to decide where the motor is operating on a curve of efficiency vs. load, or to decide how much oversize a motor might be compared to a smaller replacement, is often good enough. But to use such methods to arrive at an actual load, then divide that by measured electrical input to directly determine motor efficiency, can give wildly inaccurate results.

The point is that field measurements can neither "prove" nor "verify" any motor's efficiency. Recognizing this difficulty, the U.S. Department of Energy (DOE) has begun extensive research into better methods of determining motor efficiency in the field. Other agencies are also involved. Whether or not these methods will deserve to be called "tests" rather than "good estimates" remains to be seen. Meantime, a user must make the best measurements possible and try to cross-check one method against another, recognizing that the result will be far less reliable than any factory test or laboratory test. More importantly, the measurements must allow for overvoltage or undervoltage. Either condition can seriously skew the results of most tests.

In that regard, realizing that voltage magnitude and phase balance are often "out of spec" (e.g., deviating from nameplate rating) and not controllable, a user may conclude that "it makes no difference" because such deviations will influence a new, more efficient motor to the same degree as the existing lower efficiency machine. That, too, is a judgment call, based on no hard data. It can't be verified—and is not justified, because the distribution of the five losses within the motor will surely be different for the two machines.

Repair Concerns

From the beginnings of the modern trend towards more efficient motors, the fear was that normal repairs to such machines would inevitably reduce their initially high efficiency to unacceptably low levels. Some facility operators, and some service centers, still believe this to be true. But ample evidence shows that efficiency is not necessarily degraded by the repair process.

Typical stator with new windings installed

■ **Core Loss.** The most serious risk was assumed to be breakdown of interlaminar insulation in the stator core, caused by high burnoff oven temperature, which would greatly increase the core loss.

Attempting to measure that effect, EASA undertook its well-known "core loss study" in the early 1980s [2]. The initial EASA tests didn't involve complete wound stators, and the conclusions were limited, but from them as well as other studies, including recent research by the British Association of Electrical and Mechanical Trades (AEMT) [3], a "safe temperature limit" for parts was established for shop guidance. Ovens designed to maintain such limits are widely available, as are core loss test instruments for direct comparison of core condition "before and after stripping." Stripping methods not involving oven heating are also available.

Through properly controlled procedures, then, service centers can rewind energy efficient motors without reducing their efficiencies. The motor user needs to make sure the repair firm doing the work is familiar with this background, and capable of doing a proper job.

■ **Winding Configuration.** More recently, other research has shown that core loss is not the only concern when a motor is rewound. Many standard motors today are wound at the factory by machine. That process requires a particular winding configuration. Some service centers have the capability to replicate the original winding configuration or convert to an equivalent lap winding. Depending upon the particular conversion, the motor efficiency may be affected due to a change in the winding resistance, reactance or harmonics.

■ **Bearings And Seals.** Still another efficiency concern arises even if no rewind is needed. As part of any routine overhaul, most service centers replace ball bearings. When that was done to one group of motors as part of a test program involving several repair facilities, each unit exhibited a lower post-repair efficiency. Investigation showed that in those units the original bearings had contained non-contact, frictionless seals. The replacement bearings most readily available to the service centers were identical except that they included grease seals that added some friction loss. That lowered the motor efficiency.

In summary, repair methods and materials can adversely influence motor efficiency. But they need not do so. Motor users should make sure the repair service they purchase is based on understanding of the possible loss changes, and on service center procedures that will avoid those changes.

Glossary

Ambient temperature—The temperature of the surrounding cooling medium. Commonly known as room temperature when the air is the cooling medium in contact with the equipment.

Efficiency—The ratio between useful work performed and the energy expended in producing it. It is the ratio of output power divided by the input power.

Friction and windage—The power loss within any rotating electrical machine caused by bearing friction, air friction against rotating surfaces, and the movement of air circulating fans.

Full-load speed—The speed at which any rotating machine produces its rated output.

Full-load torque—The torque required to produce rated power at full-load speed.

General purpose motor—Per North American legislation, an AC induction motor of 200 horsepower or less, open or enclosed construction, continuous duty, designed in standard ratings with standard characteristics for use under service conditions without restriction to a particular application (see also NEMA MG 1-1.06.1).

Harmonic—A multiple of the fundamental electrical frequency. Harmonics are present whenever the electrical power waveforms (voltage and current) are not pure sine waves.

IEEE—Institute of Electrical and Electronics Engineers.

Interlaminar insulation—The insulating coating or “coreplate” on the surfaces of stator laminations, to block the flow of loss-producing “eddy currents” between laminations in AC machines.

Linear function—The relationship between two variable quantities in which a change in one is always directly proportional to the change in the other.

NEMA—National Electrical Manufacturers Association.

Payback—The time period at which the added cost of a more efficient piece of equipment is equaled by the operating cost savings achieved through its use.

Phase unbalance—In a polyphase circuit, the measure of difference between the magnitudes of voltage in each of the individual phases.

Poles—The magnetic poles set up inside an electric machine by the placement and connection of the windings.

Power factor—The ratio of watts to volt-amperes of an AC electric circuit.

Rated temperature rise—The permissible rise in temperature above ambient for an electric machine operating under load.

Rotor—The rotating element of any motor or generator.

Slip—The difference between synchronous and operating speeds, compared to synchronous speed, expressed as a percentage. Also the difference between synchronous and operating speeds, expressed in rpm.

Small and medium motors—Machines generally in the range of 1 through 500 horsepower, including those ratings subject to NEMA “energy efficient” standards.

Stator—The stationary part of a rotating electric machine. Commonly used to describe the stationary part of an AC machine that contains the power windings.

Stray load loss—The power loss within a rotating electric machine caused by magnetic field “leakage” or straying outside the intended, useful paths through the core.

Synchronous speed—The speed of the rotating magnetic field created by the stator winding.

$$\text{synchronous speed} = \frac{(\text{frequency} \times 120)}{(\text{number of Poles})}$$

Torque—The rotating force produced by a motor. The units of torque may be expressed as pound-foot, pound-inch (English system), or newton-meter (metric system).

Appendix

The Energy Policy Act of 1992 (EPACT)

As of October 1997, the Energy Policy Act of 1992 (EPACT) requires most general-purpose, 1 - 200 horsepower polyphase induction motors manufactured for use in the United States rated to meet minimum efficiency standards (see Table 4). These motors include T-frame, single-speed, foot-mounted, continuous-rated, polyphase induction motors of NEMA Designs A and B, both open and enclosed, that are designed to operate at 1200 - 3600 rpm [synchronous speeds] on 230/460 volts and 60 hertz.

The law is hard to follow, because much of the material about motors doesn't stand on its own. Rather, it's written as amendments to earlier legislation—the 1975 Energy Policy and Conservation Act (Public Law 94-163), supplemented by the 1978 Public Law 95-619. That earlier material, printed in Title 42 of the United States Code (42 USC), is referred to here simply as "CONACT." Table 5 cross references major portions of CONACT with the corresponding EPACT sections.

Table 5. EPACT &Legislative Provisions

EPACT Section	Corresponding CONACT Section	42 US Code Section
122	340 342 343 344 345	6311 6313 6314 6315 6316
124	346	6317

How EPACT (1992 Energy Policy Act) provisions most important for motors relate to other legislative provisions.

EPACT's basic provisions concerning small and medium AC motors appear in Title I, subtitles B, C, and D. They apply to individual motors and to motors built into other apparatus.

■ **Motors Covered by EPACT.** EPACT Section 122 (amending CONACT Sections as noted in the table) provides that 60 months following passage of the law—meaning by October, 1997—most polyphase AC motors manufactured in the United States must have nominal full-load efficiencies at least as high as those published in NEMA MG 1 Table 12-10 (a portion of which is reproduced in the EPACT text). The 60 months becomes 84 for UL-labeled explosion-proof machines.

Motors regulated by EPACT Section 122 are defined in the law as “general purpose.” As noted above, these motors are T-frame, horizontal foot-mounted, single speed, 230/460 volt NEMA Design A or B, dripproof and totally-enclosed, 1200 - 3600 rpm, 1 - 200 horsepower only.

■ **Exempt Motors.** The law doesn’t apply to speeds of 900 rpm or below, to horsepowers 250 and above, NEMA high-slip designs, or multispeeds. Those motors may remain available in whatever their efficiencies may be. That is also true for motors of any design rated 200, 208, or 575 volts, and for U-frame machines.

Other motors exempt from EPACT are all “definite purpose” and “special purpose” types, for which both EPACT and NEMA definitions are:

> A definite-purpose motor is any motor designed in standard ratings with standard operating characteristics or mechanical construction for use under service conditions other than usual or for use on a particular type of application.
> (NEMA MG 1-1.10)

A definite-purpose motor is typically a standard unit applied in some nonstandard way. The special-purpose motor is of nonstandard design intended for a specific application. The distinction is often blurred. Vertical high-thrust motors, close-coupled pump motors, crane drives, hermetics, submersibles—all these are specifically identified by NEMA as “definite-purpose.”

A special-purpose motor is a motor with special operating characteristics or special mechanical construction, or both, designed for particular application and not falling within the definition of a general-purpose or definite-purpose motor (NEMA MG 1-1.14).

The DOE has not been entirely satisfied with some of these definitions in NEMA MG 1 or in the law itself, and its rulemaking procedure for interpreting the legislation has included somewhat different wording.

Whatever the interpretations, a large number of motors are clearly exempt from EPACT’s provisions. Moreover, EPACT gives the Secretary of the Department of Energy the option of exempting from the law any other motors for which:

> (i) compliance with . . . standards would not result in significant energy savings because such motors cannot be used in most general purpose applications or are very unlikely to be used . . .
>
> (ii)standards . . . would not be technologically feasible or economically justified.

Motor manufacturers may petition the Secretary for product exemptions. With due allowance for public comment, the Secretary is directed to “rule” on such petitions within a year. To date, no petitions have been filed, because the motor industry has recognized that motors subject to exemption are in general already of the excluded definite-purpose or special-purpose categories.

Another provision of EPACT Section 122 requires each covered motor to carry an appropriate efficiency label.

■ **Small Motors.** EPACT sets no efficiency standards for "small motors"—below 1 hp, mostly single-phase—defined as having two-digit frame numbers, such as the 56 frame. Section 124, however, does require the Secretary to eventually ". . . prescribe testing requirements for those small electric motors for which the Secretary makes a determination that energy conservation standards would be technologically feasible and economically justified, and would result in significant energy savings."

Following issuance of such test requirements, says the law, the Secretary shall "prescribe, by rule, energy conservation standards for those small electric motors . . ." and "labeling requirements . . ."

Leaving aside the obvious vagueness of such terms as "significant" and "feasible," we still find in the law that between 1997 and 2001 the performance and labeling of many small motors should become legally standardized.

Unfortunately, the only IEEE single-phase motor test standard, No. 114, was allowed to lapse and was withdrawn several years ago. Furthermore, it offered nowhere near the demonstrated accuracy of the polyphase motor test standard upon which NEMA and EPACT performance is based. A Canadian test standard has been written for single-phase motors, but it is a much simpler procedure than IEEE 112 and has not been recognized by the U.S. Department of Energy, NEMA, or the IEEE.

■ **Efficiency Testing and Certification.** Concerning polyphase tests: EPACT Section 122 allows the Secretary to "prescribe test procedures." However, the text adds this requirement:

> . . . the test procedures shall be . . . [those] . . . specified in NEMA Standards Publication MG 1-1987 and IEEE Standard 112 Test Method B for motor efficiency, as in effect on the date of enactment of . . . [EPACT] . . . If the . . . requirements . . . of NEMA MG 1/IEEE 112 are amended, the Secretary shall amend . . . [the EPACT-based rules] . . . to conform to such amended test procedure requirements unless the Secretary determines, by rule, published in the Federal Register and supported by clear and convincing evidence, that to do so would not . . . produce test results which reflect energy efficiency . . .

Thus, existing NEMA/IEEE testing, already in use by all U.S. manufacturers, will apply unless proven unreliable.

But are the manufacturers getting the right answers? Section 122 of EPACT also says:

> . . . the Secretary shall require manufacturers to certify through an independent testing or certification program nationally recognized in the United States, that such motor meets the applicable [standards] . . .

Such "third-party certification" today is typified by the way Underwriters Laboratories has established design/test requirements for explosion-proof equipment. But evaluating efficiency of an entire spectrum of standard general-purpose motor manufacturing will be impossible for any single agency or laboratory. In originally proposing the EPACT wording just quoted, NEMA's expectation was that each motor manufacturer would continue to use its own in-house test facility, but that those facilities would have to be certified in some way by a national overseer such as the National

Institute of Standards and Technology. That would meet the law's terminology of "or certification program . . ." Such a program has begun, but details are still being worked out.

Regardless of who is involved, many questions remain to be settled by DOE rulemaking, such as how many motors or motor tests, on which ratings, must be made how often, and with what results to allow a motor manufacturer to claim EPACT compliance. That rulemaking process has commenced, with drafting of a new addition to the Code of Federal Regulations, titled 10 CFR Part 431. It will prescribe the certification, sampling, and other procedures to be used under EPACT authority to support motor efficiency testing and labeling.

Such questions become more difficult when imported motors are considered. EPACT provisions don't specifically mention that issue. For example, motors entering this country could be diverted on some sampling basis to a U.S. lab for efficiency verification. Or some means might be found to "certify" the manufacturer's overseas test facility.

■ **Motors Manufactured Outside of the U.S.** A more important question is: will EPACT allow sale in this country of imported motors, built by nonmembers of NEMA, that do not meet EPACT's efficiency standards written for domestic products? The DOE view is that such motors cannot legally be imported after 1997. At one time, an earlier draft of what has become EPACT used these words: " . . . any general-purpose electric motor manufactured or imported . . . . after the 60-month period beginning on the date of enactment . . . shall have a nominal full-load efficiency of not less than . . ." the tabulated values. The words "or imported" were deleted from the law's final text. The DOE will probably rely on wording within CONACT Section 6302, which prohibits "distribution in commerce" of any "new covered product" that is standardized by the CONACT rules now amended by parts of EPACT. CONACT Section 6301 says products violating that prohibition "shall be refused admission into . . . the United States . . ."

■ **Motors Manufactured Before EPACT Took Effect.** According to a DOE bulletin (DOE/GO-1096-312), EPACT applies only to motors manufactured or imported after October 24, 1997. Existing motors and those manufactured or imported before the "implementation date are not governed by EPACT. Motors installed or in stock at industrial motor end-user facilities are unaffected."

■ **Repaired, Redesigned and Rebuilt Motors.** Regardless of the status of new motors, EPACT is definitely silent concerning repair, redesign, or rebuilding of any motors already in a user's hands when the law becomes effective. The DOE bulletin mentioned above does, however, include "rebuilt, repaired, or rewound motors" among examples of motors that are not covered by EPACT. Technically, they are not newly manufactured machines, so they are exempt from any EPACT requirements. No mention is made of service center methods or "certification."

Many uncertainties obviously remain about the Department of Energy's EPACT enforcement procedure; about how each motor manufacturer's products will meet the legislation; about possible amendments to EPACT; and about utility conservation incentives. Like many sweeping laws, EPACT has seemed to raise more questions than answers.

■ **What About Larger Motors?** Users of “large” motors (1000 to 5000 hp, for example) have been efficiency-conscious for many years. Detailed payback analysis, tight performance guarantees, witnessing of tests and certification—all these have been routine for utilities, refineries, and other major electrical equipment purchasers. Supplier bids have commonly been evaluated on efficiency (each kilowatt of loss may be worth $3,000 to $10,000 in price).

That is one reason why EPACT included no “energy efficient” criteria for motors 250 hp and larger. A second reason is the small size of the market for the larger machines, or for any ratings at 2300 volts or above. Relatively few units are sold, built by relatively few manufacturers.

A third reason is that the larger machines are less subject to detailed construction/operating standards than are the smaller units. A 600 hp motor, for example, will almost certainly be “custom designed” for application characteristics peculiar to the order. Imposing standard efficiency requirements on motors possessing few standard attributes is neither practical nor necessary.

References

[1] *NEMA Standards MG 10-1994*, Table 2-2 (National Electrical Manufacturers Association, Rosslyn, VA, 1994).

[2] *Core Iron Study* (Electrical Apparatus Service Association, Inc., St. Louis, MO, 1984).

[3] *The Repair of Induction Motors: Best Practices to Maintain Energy Efficiency* (Association of Electrical and Mechanical Trades in cooperation with the Department of Environment, Transport and the Regions, Nottingham, England, 1998).

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Notes