Evaluation of Markets and Efficiency of Fractional Polyphase Motors

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ABSTRACT

Research has indicated that fractional motors substantially outnumber integral-horsepower motors and account for a significant share of motor electricity consumption. Little information is available on the market for these motors nor is measured efficiency data. This lack of data is in part related to the absence of accepted efficiency test procedures, or the inclusion of efficiency in motor standards. To address the lack of test data, testing was undertaken of a sample of 0.5 and 0.75 polyphase motors using a procedure used for integral motors.

Results indicate that for the most part nameplate efficiencies are reflective of actual efficiency. Additional testing of a larger sample of motors is needed to build confidence in the data. Motor manufacturers are encouraged to begin looking at efficiency, and to encourage the inclusion of efficiency in appropriate standards.

Introduction

In 2000, Southern California Edison (SCE) committed to including fractional polyphase motors in their *Next Step* premium-efficiency motor program. Their contractor, Advanced Proactive Technologies (APT), surveyed available products in the marketplace (APT 2000) and found no test data verifying manufacturer efficiency values. APT contacted ACEEE to oversee an independent testing program evaluating the full-load efficiency of these fractional polyphase motors. Due to the large number of product offerings and limited resources, only a subset consisting of the most efficient products was tested.

The project was conducted in the following five phases:

1. Identify a test facility to undertake this work
2. Work with the facility staff to develop a testing plan
3. Select motor models to be tested
4. Review the test facility's work, and
5. Analyze the test results.

While this data will provide a valuable foundation for the development of future efficiency initiatives for this product class, future testing of a larger sample of products and market research will be needed to better understand this class.

Background

Motors account for more than half of the electricity consumed in the U.S. and almost two-thirds of the electricity used by industry. Over the last decade and a half, energy efficiency advocates have achieved significant success working with regulators and equipment manufacturers to transform the market for integral-horsepower, polyphase motors.

Research has indicated that these motors account for a significant share of motor electricity consumption. Fractional motors substantially outnumber integral-horsepower motors. Fractional-horsepower motors (those with input requirements of less than one horsepower) account for roughly one-third of the drive energy in the residential sector and 2 percent in the commercial sector. In the industrial sector, estimates of the proportion of drive energy represented by fractional-horsepower motors range from 0.5 to 1.5 percent (EPRI 1992; Rosenberg 1996). These motors are produced in both single and polyphase configurations, and are ubiquitous in commercial applications from small pumps and fans to compressors and conveyors.

Knowledge of the efficiency of these motors and their applications are much more limited than for their larger counterparts. Studies have hinted that the energy consumption in this sector is huge, and that opportunities for efficiency improvements are much larger than with large motors. A survey of reported efficiency levels in manufacturers' catalogs indicate that efficiencies can range from less than 50 to over 80% for 0.5 and 0.75 hp polyphase motors.

There has been little focus on efficiency in this class of product from either the efficiency community or from manufacturers. There is no widely accepted test procedure that compares with the IEEE 112 Method B for integral motors. In part this is because of the difficulty in measuring efficiency accurately. Further, the cost of the test is more than the cost of the motor.

Understanding the Market

The major questions that exist in effectively increasing the efficiency in this marketplace are:

- What are the available products in three-phase, 0.5 and 0.75 hp ratings?
- What are the efficiencies of the 0.5 and 0.75 motors in the marketplace?
- In what types of equipment are such motors used?
- What is the distribution channel for such motors?

Preliminary research indicates that one of the most prevalent uses for three-phase fractional motors is in constant torque, right angle, or helical gear drive applications such as conveyor systems (Bonnett 2000). Of this broad group, the predominant subset comprises "case" conveyor systems — i.e., those that move conveyor belts for finished packages and pallets within industry and shipping, as opposed to loose product or components, raw materials, etc. (Pepim 2001).

These are often stock, pre-packaged conveyors offered by the major conveyor system manufacturers. As in most industries, product cost (and hence price competitiveness) is determined in great part by component costs. Lacking any regulatory fractional-horsepower legislation such as EPAct, the least expensive motor (likely the least efficient) will be used in the manufacture of such conveyors.

Conversely, conveyor system integrators, who design and build custom systems, are often designing larger, more complicated systems for a special purpose. Such integrators have noted that clients often ask that a 1 hp motor be substituted where a fractional is specified simply to avoid stocking yet another motor when they already inventory 1 hp motors (Rock 2001). Given the generally higher efficiency of EPAct 1 hp motors, any under-loading penalty is probably mitigated, in spite of the increased current demand.

As 90% of conveyor motors are sold via the original equipment manufacturers (OEMs) channel (Drucker 2000), it would seem that the most effective intervention point would be the OEM repair/end-user interface.

Two strategies to influence the use of higher efficiency fractional motors emerge:

1. Promote the use of the highest energy-efficient motors to conveyor manufacturers through incremental costs rebates direct to OEM's; and
2. Offer an incremental cost rebate to the end-user to upgrade to high-efficiency motors during the failed motor replacement situation. The OEM would be encouraged to offer a choice of high-efficiency replacement motors when called for servicing. Likewise, motor dealers would be encouraged to stock high-efficiency motors for this market. The latter scenario is the current model employed by SCE's *Next Step* motor program.

Both these require the active participation of the OEM market players and their willingness to advance more energy-efficient products. But while motor dealers in SCE territory are active in promoting premium-efficiency motors through the *Next Step* program, the dealers' sales of fractional motors are dwarfed by the direct OEM replacement sector.

Fractional motors are an important sector of the motor market that has received limited attention. This work only represents a first step into this area and needs to be followed up with further testing, complimented by market research to understand how these motors reach the end-user and how they are used in the field.

Motor manufacturers mirror the lack of attention to this sector by the energy efficiency community. They have not expended much effort on improving efficiency of this class of product until now because there has been no market demand for energy-efficient products. If the energy efficiency community focuses attention on this area, manufacturer response is likely to be similar to the response to the integral motor efficiency programs.

Research Objectives

The goal of this research was to determine how efficient fractional, polyphase motors are, and how reliable manufacturers' reported efficiency data are. The project team decided upon two sets of tests:

1. Testing of motors with relatively high nameplate efficiency from a wide range of manufacturers to determine how close the reported efficiencies were to measured values.
2. Since there is natural variation in the efficiency of motors (as discussed in the next section), test multiple samples of the same motor model from the leading manufacturers to quantify the degree of product variation.

Measuring Efficiency

It is important to understand motor efficiency and how it is determined in order to interpret the results of the testing in this report. Initially, efficiency in these motors will be defined, and then variation inherent in motors, labeling of efficiency, and effective and objective measurement of efficiency will be discussed.

Definition of Efficiency

Motor efficiency has a slightly different definition than most other efficiency measurements because motor ratings are based on power output rather than fuel input. Efficiency, η, is expressed as:

$$\eta = \frac{dW}{dW + l}$$

where dW is the energy output of the motor, and l is the sum of the losses. This variation on the normal efficiency calculation is often not recognized and has led to confusion and calculation errors. The focus on motor losses stems from the approach used to design efficiency in a motor.

Variation

The efficiency of different units of the same motor model will vary. These variations can be attributed to differences in raw materials and random factors in the manufacturing processes, as well as variations in the results of efficiency testing (see NEMA MG 1-1998, 12.58.2). A 10% difference in the iron core losses, which is within the tolerance of magnetic steel manufacture, can by itself produce a 0.3% change in the efficiency of a 10 hp motor. Mechanical variations can also affect efficiency by altering the size of the air gap (a 10% difference in air gap size is not uncommon) and consequently in the stray losses. As noted above, precision machining of motor parts is costly and motor manufacturers settle for a tradeoff between precision and cost when purchasing the equipment used in the production line.

The determination of efficiency is further complicated by variations due to uncertainty in test results. Efficiency determination is a complex and demanding exercise, and a significant difference can be introduced by variations in technicians' practices as well as measurement errors. In a study of different motors of the same model, losses varied often by 10% and sometimes by as much as 19%, corresponding to efficiency reductions of one to two percentage points (NEMA 1999).

Labeling of Motor Efficiency

In the late 1970s and early 1980s, NEMA established a labeling program for the most common types and sizes of motors ranging from 1 to 125 hp. Under this program, the nominal and minimum efficiency ratings for a motor are listed on its nameplate (where nominal efficiency is analogous to the average efficiency of a sample of motors of the same design and minimum efficiency roughly represents the fifth percentile of the sample). Since variations in materials, manufacturing processes, and testing result in motor-to-motor efficiency variations, NEMA specified a standard procedure for labeling efficiencies. The standard assumes that the distribution of efficiencies for a population of a given motor is normal. The motor should be labeled with a value from a table of allowable values that is less than or equal to the nominal value of the sample population (NEMA 1999).

The strength of the labeling program is that it embodies the natural variation in individual motors and provides a standard measure of motor performance that makes comparison between different manufacturers' products easy.

Figure 1 graphically presents motor population efficiency distributions for three adjacent nameplate efficiencies presented in NEMA MG 1, Table 12-9. As can be seen in Figure 1, there is significant overlap in the distribution between adjacent values, so two nameplate steps are required for a statistically significant difference in efficiency. The average is considered the nominal efficiency of the motor and is used to predict the power requirements for a given installation. The minimum efficiency represents a near-worst-case combination of raw materials and manufacturing tolerances. However, 5% of the motors in a population may, depending on the manufacturer, have efficiencies lower than the minimum (NEMA 1999).

The NEMA labeling method currently defines the minimum full-load efficiency of a motor as that level corresponding to 20% higher losses than the listed nominal value.

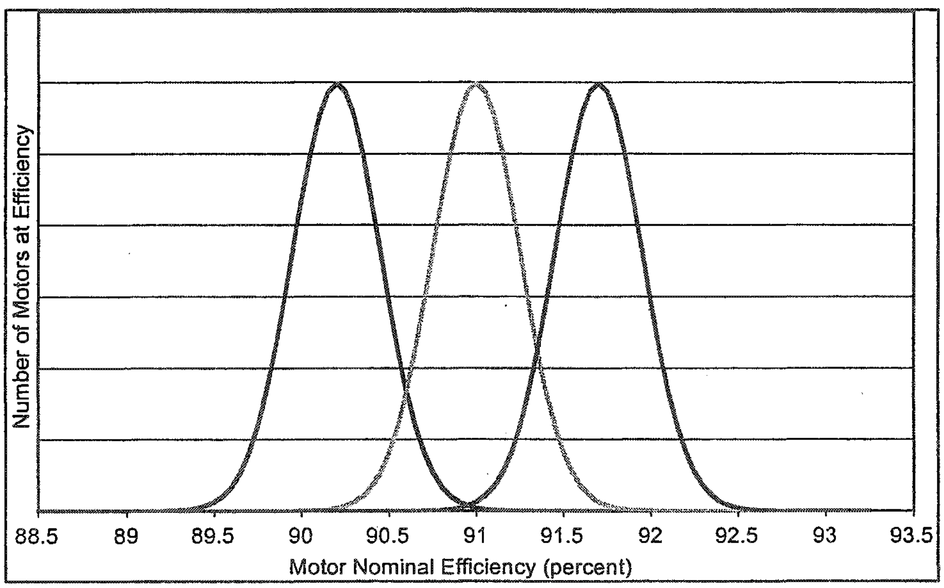

Figure 1. Variation in Motor Efficiency between Adjacent Nameplate Efficiencies

Test Procedures

The Institute of Electrical and Electronics Engineers (IEEE) Standard 112 Method B (IEEE 1996) and Canadian Standards Association (CSA) Standard 390 (CSA 1993) are accepted test procedures for the efficiency determination of integral-horsepower polyphase motors. However, a similarly accepted test procedure does not exist for fractional and single-phase motors. In the early 1990s, the Canadian Electrical Association (CEA) undertook an effort to develop such a test procedure (CSA 1993). This work was based on IEEE 114-1982 and British Standard 4999, Part 102, and resulted in the drafting of CSA 747-1994. This procedure has not been accepted because of problems with reproducibility, and cost and difficulty in conducting the test. Many of the problems stem from needing to very accurately measure small differences in electricity consumption and power output. This situation is more difficult for part-load efficiency determinations.

Testing Plan

Introduction

The reported nameplate efficiencies of fractional polyphase motors varies significantly, so the goal of the testing was to compare several brands and models of fractional-horsepower, three-phase motors to determine if measured efficiency differences between models correlates to differences in manufacturers' stated efficiencies. ACEEE selected Advanced Energy's Industrial Energy Laboratory's motor testing laboratory to conduct the testing. This facility, located in Raleigh, North Carolina, is the only independent laboratory in the United States accepted under Underwriters Laboratory's *Energy Verification Services Program*, and is the first lab to be accredited by the National Institute for Standards and Technology's (NIST) *National Voluntary Laboratory Accreditation Program* (NVLAP) for motor efficiency testing.

Motor Selection

The motors tested were 0.5 and 0.75 hp, foot mounted, four-pole, three-phase, 230 or 460 volt, 60 Hz ratings. Only 1,800 rpm product was tested as it represents the largest market share, with weighting toward enclosed (i.e., totally enclosed fan cooled or TEFC) product. The highest available efficiency products from all the major manufacturers in the southern California area were selected. Motor models were selected from a list compiled by APT (APT 2000), which was augmented to include two additional manufacturers. For the variability runs, one 0.75 hp TEFC motor from five different major manufacturers was tested. Subsequent to the testing, we discovered that the 0.75 hp Marathon motor (model 56T17T5328) is a wash-down duty motor with contact bearing seals. These bearings have a higher friction than conventional bearings, which would reduce the efficiency relative to a motor with standard bearings (Schibline 2001).

Test Procedure

Because of the large variation in efficiency among the available fractional three-phase motor, a high level of precision was not required. ACEEE and Advanced Energy decided to use a modification of the IEEE 112 Method B (IEEE 1996) to estimate full load. Reducing the amount of data collected allowed Advanced Energy to test more motors. Data collected included voltage, current, electrical power input, mechanical power output, and motor temperature (from skin-mounted thermocouple and motor winding temperature rise determined by resistance).

The basic testing involved:

1. Running each motor at no load with fan inlet blocked a minimum of 8 hours to purge excess grease from ball path in new bearings to stabilize friction losses.
2. Installing one direct contact thermocouple per motor in the following prioritized preference location: motor winding end turn (out of airflow); stator core iron (also out of

airflow); or motor frame surface at a location where the frame is in direct thermal contact with core iron.

3. Measure cold winding resistance on each motor to be tested.

To test variability, five identical motors were tested at the end of a 10-minute run as defined in Step 4a. The efficiency of each motor model was determined in Step 4b.

4a. Complete full load (cold) tests on each designated group of five identical motors. Set up motor on the dynamometer. Start motor, load to full load rated conditions, and record full-load data point within 10 minutes or less of motor start. Shut down motor and remove from stand.

4b. Complete full load heat run tests per IEEE 112 Method B on each motor *model* provided, including *one* motor from each designated group of five identical motors. Conclude test with a full-load-rated condition data point and hot resistance measurement.

Steps 3, 4a, and 4b could be completed in any sequence but tests in Steps 3 and 4a had to be started only with motors thermally saturated at *room temperature.*

Test Results

Test proceeded with a good level of reproducibility. In general, the test numbers appear lower than the nameplate efficiency numbers, though for several motors they are very close to the reported values. This trend, though not significant, might suggest a slight test bias toward lower values. The presence of bias cannot be assessed without independent testing at another test facility, which the project resources did not allow.

Variation in Efficiency

The results from the five sets of variation runs on 0.75 hp TEFC motors, as described in Step 4a, are presented in Figure 2. The "nameplate efficiency" is the level reported on the motor, except for the Marathon motors and the 0.5 hp Reliance motor, which had no nameplate efficiency, so the efficiency level reported in the manufacturer's catalog was used. The guaranteed minimum efficiency was calculated based on 20% of full-load losses (FLL) as discussed in a previous section.

The motors tested had a very tight distribution. All were above the guaranteed minimum levels as defined in the previous section. Since under MG 1 (NEMA 1999) motors are allowed 10% variation due to materials, we chose as an arbitrary reference 2.5% of FLL. Relative to the average efficiency of the sample, only the Marathon motor showed a variation in efficiency of just slightly more than 2.5% of FLL.

Motor Efficiency

Table 1 and Figures 3a and 3b present the results from the full-load efficiency determinations (as described in Step 4b) for eleven 0.75 hp motors and eight 0.5 hp motors. The two Marathon motors and one of the 0.5 hp Reliance motors did not have an efficiency on the nameplate, so the efficiency levels reported are those in the manufacturers' catalog. These values may be less accurate than nameplate data since some manufacturers may report typical data in their catalogs (Schibline 2001).

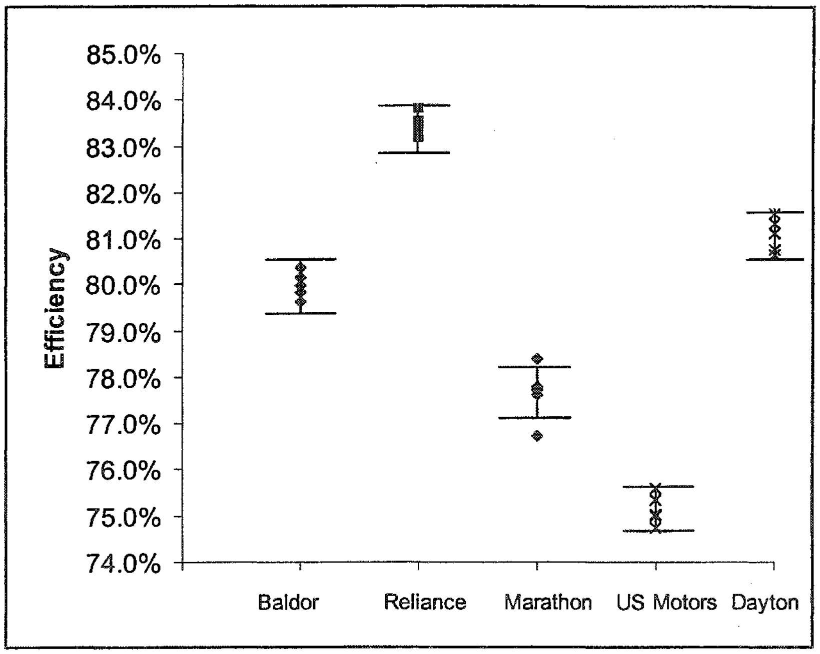

Figure 2. Variation in Efficiency among Five Samples of ¾ hp TEFC Motors from Five Manufacturers

All but five motors exceed the guaranteed minimum efficiency level corresponding to the nameplate efficiency. Both the 0.5 and 0.75 hp Leeson motors fell slightly below the minimum level, as did two of the 0.75 hp Reliance motors. The highest-efficiency 0.75 hp Baldor, all the Dayton, the 0.75 hp Marathon, the 0.75 hp Tatung, one 0.5 hp Reliance, and both of the Toshiba motors came very close to meeting their nameplate efficiencies as can be seen in Figures 3a and 3b.

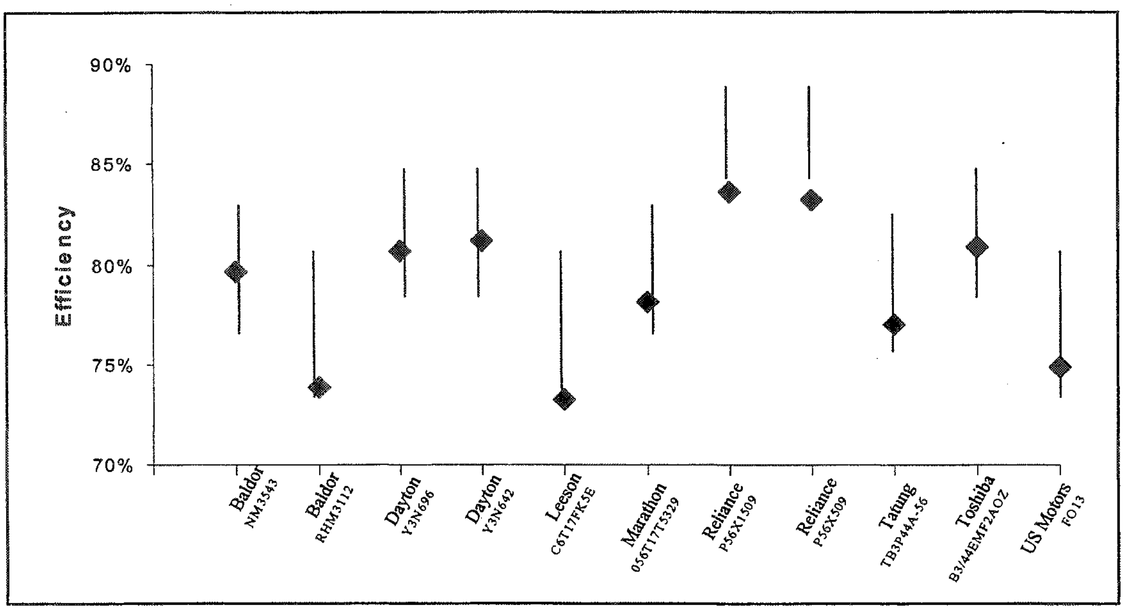

Figure 3a. Full-Load Efficiencies for 0.75 hp Motors

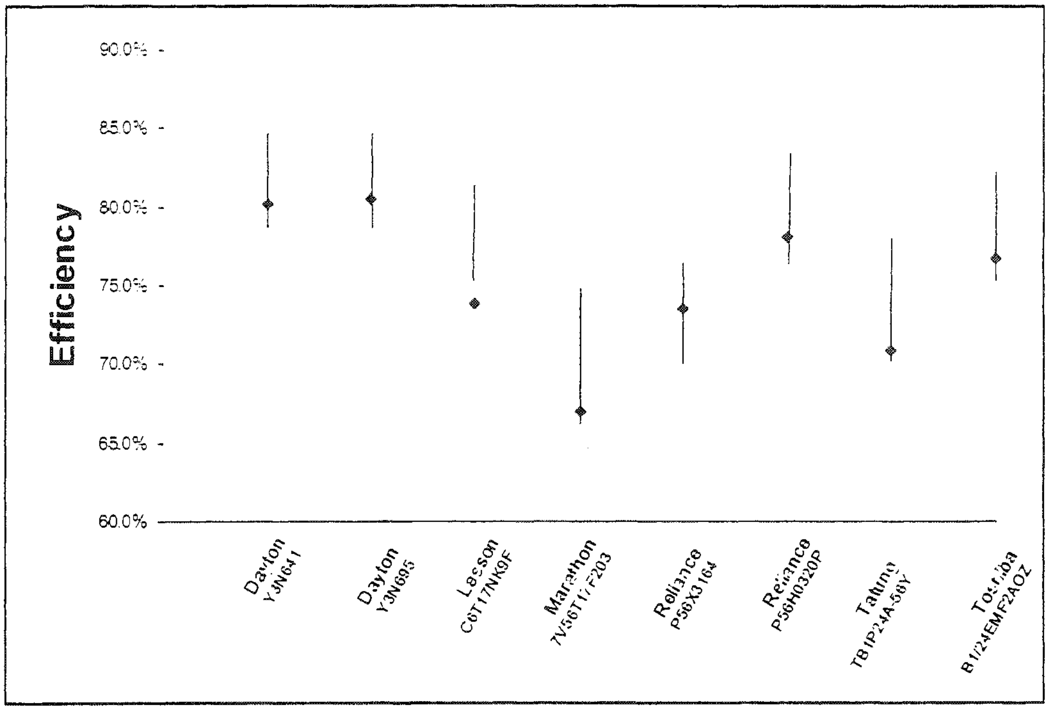

Figure 3b. Full-Load Efficiencies for 0.5 hp Motors

Discussion and Recommendations

This testing and the Southern California Edison efficiency program that it supports represent the first venture into fractional motors by the energy community since the Canadian work in the early 1990s. Results indicate that efficiency opportunities in the program are actually being realized in the field. The manufacturing processes for these motors appear to be sufficiently uniform to result in limited variation in efficiency between samples. The test could not assure that these motors represented a variation over time, which could produce additional variation due to variation in materials. However, because the samples were so tightly grouped, it appears unlikely that any of the manufacturers would experience unacceptable variability.

The reliability of the nameplate information does appear to vary by manufacturer. However, all the measured efficiency values fall below the nominal values. If this trend extends to all of this class of product, as would be anticipated, then the difference in efficiency will be similar to that projected from the nameplate values.

As noted earlier, it is difficult to accurately measure the efficiency of small motors, and the procedure used by Advanced Energy extended the IEEE 112 Method B beyond its proven range, so the efficiency levels should be taken with some degree on uncertainty. The efficiency values of all motors fell at or below the mean for the nameplates, which might indicate that the test procedure produces values with a slight negative bias. However, consistent patterns did emerge from the testing.

Table 1. Full Load Efficiency Determinations for 0.5 and 0.75 Horsepower Motors

Manufacturer	Model	Nameplate Efficiency (%)	Guaran. Min. Efficiency	Measured Efficiency	Margin above Minimum
0.75 horsepower motors					
Baldor	NM3543	80.0	76.9%	79.6%	2.71%
Baldor	RHM3112	77.0	73.6%	73.8%	0.21%
Dayton	Y3N696	81.5	78.6%	80.7%	2.10%
Dayton	Y3N642	81.5	78.6%	81.2%	2.56%
Leeson	C6T17FK5E	77.0	73.6%	73.3%	-0.35%
Marathon[1, 2]	056T17T5329	80.0	76.9%	78.1%	1.19%
Reliance	P56X1509	86.5	84.2%	83.6%	-0.60%
Reliance	P56X509	86.5	84.2%	83.2%	-1.02%
Tatung	TB3P44A-56	78.9	75.7%	77.0%	1.30%
Toshiba	B3/44EMF2AOZ	81.5	78.6%	80.9%	2.29%
US Motors	F013	77.0	73.6%	74.9%	1.26%
0.5 horsepower motors					
Dayton	Y3N641	81.5	78.6%	80.1%	1.53%
Dayton	Y3N695	81.5	78.6%	80.5%	1.94%
Leeson	C6T17NK9F	78.5	75.3%	73.9%	-1.40%
Marathon[1]	7V56T17F203	70.0	66.0%	67.0%	0.94%
Reliance[1]	P56H0320P	74.0	70.0%	73.5%	3.50%
Reliance	P56X3164	80.0	76.9%	78.0%	1.10%
Tatung	TB1P24A-56Y	74.0	70.3%	70.9%	0.51%
Toshiba	B1/24EMF2AOZ	78.5	75.3%	76.7%	1.45%

[1] Nameplate efficiency values are from manufacturers' catalogs. May be less accurate.
[2] Wash-down duty motor with contact seals.

While 0.5 and 0.75 hp three-phase motors are not covered under Section 12 of NEMA MG 1 (NEMA 1999), the test results for most manufacturers indicate that the measured efficiency falls within allowable variation. Several manufacturers, particularly Dayton, Marathon, and Toshiba, appear to be notably "conservative" in labeling their motors, with test values falling close to the nameplate mean. However, both Leeson and Reliance show a pattern of test efficiency values substantially below their nameplate.

The Reliance results send a mixed message for the SCE program. Reliance's 0.75 hp motors have by far the highest nameplate efficiencies. While the nameplate efficiency levels appear optimistic, they were the most efficient motors tested during this analysis by one to two NEMA bands.[1]

From this analysis we can conclude that significant differences exists in the efficiency level for fractional polyphase motors, and that the savings from the more efficient products

[1] A NEMA efficiency band is the allowable range of efficiencies that are characterized by a given nominal value as defined in MG 1, Table 12-9 (NEMA 1999), which represents a variation from nominal of approximately 20% of full-load losses.

would result in significant energy savings in applications with high operating hours. For most motors tested, the nameplate or catalog efficiency represents a good indicator for the actual motor efficiency. However, it does appear that these numbers may be optimistic. To confirm this, additional testing is required. An opportunity also exists to use this testing to open a dialog with manufacturers, who have as yet seen limited market demand for efficient product.

While this work and the previous work by APT to catalog product begin to address the first two of the four questions defined earlier in this paper:

- What are the available products in three-phase, 0.5 and 0.75 hp ratings?
- What are the efficiencies of the 0.5 and 0.75 motors in the marketplace?
- In what types of equipment are such motors used?
- What is the distribution channel for such motors?

To achieve the energy savings that are the goal of the SCE program, we must also have a better understanding of market channels. As noted, we are beginning to understand where these motors are being used, but additional market research is needed to understand how they reach the consumer, and what options are available to influence motor decisions in these applications.

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