Measured Loading of Energy Efficient Motors: The Missing Link in Engineering Estimates of Savings

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In an effort to characterize the loading of motors installed in a wide range of commercial and industrial applications, a representative sample of over 200 motors at 30 sites was monitored. The study sought to measure load factor, defined here as the ratio of actual power during operation to rated full-load input power. Annual average, maximum, and utility peak coincident load factors were determined for three motor size strata. The annual average for the population was estimated to be 0.64—significantly lower than previously used engineering assumptions—resulting in reduced estimates of savings. For most motors, load was relatively steady over the course of a day. The average maximum for the sample—indicative of motor oversizing and useful in the impact analysis of variable speed drives—was 0.74. The addition of data resulting from measurements just completed on 80 more motors decreased the factors slightly to 0.62 (annual average) and 0.73 (average maximum). The long recording interval (one hour) made it difficult to draw conclusions about motor sizing based on this result. Considered along with the observation that average load factors varied widely across the sample (from 0.1 to 1.5), however, previous suspicions that on average motors installed today are likely to be oversized (and some grossly undersized) were confirmed. They are not, on average, so oversized that the benefits of efficiency gains would outweigh operational concerns in decisions to downsize.

Introduction

Impact evaluation of motors replaced by efficient ones through utility conservation programs often relies on engineering analysis rather than measurement because of the relatively low cost and savings per unit and the difficulty of capturing representative performance with spot measurements. Much of the uncertainty in the engineering analysis can be attributed to uncertainty in the actual loading of the motor. In an effort to characterize the loading of motors installed in a wide range of applications through its commercial and industrial DSM programs, New England Power Service Company (NEPSCo), an affiliate of New England Electric System (NEES), commissioned a study to monitor motors a representative sample of over 200 motors at 30 sites. The motors' power consumption and run time was measured for 24 hours and used to calculate loading factors.

The input power of a motor will differ from rated power primarily because of underloading (output shaft power is less than rated), but also because operating efficiency differs from rated efficiency. Because of the difficulty in separating these two effects, the study sought to measure input (rather than output) load factor, defined here as the ratio of actual input power during operation to rated full-load input power:

$$F = \frac{P_{i,run}\eta_{nameplate}}{0.746P_{o,nameplate}} \tag{1}$$

$$P_{i,run} = \frac{P_{i,avg}}{f_{run}} \tag{2}$$

where $P_{i,run}$ = average input power (kW) while running, for measurement interval
f_{run} = fractional run time, for measurement interval
$P_{i,avg}$ = average input power (kW), for measurement interval
$_{nameplate}$ = rated efficiency at full load
$P_{o,nameplate}$ = rated output power at full load (motor HP)
0.746 = kW per HP

In applying load factors so derived to estimates of consumption or savings, it is therefore necessary to use nameplate efficiency. For example, annual energy savings (not accounting for effects such as free riders or persistence) for a motor retrofit might be estimated as follows:

$$E = \left(\frac{1}{\eta_{old}} - \frac{1}{\eta_{new}}\right) \cdot 0.746 P_{o,nameplate} F_{avg} h \qquad (3)$$

where = rated full load efficiencies of old and new motors
F_{avg} = average input load factor
h = annual operating hours

Load factors might also be used to estimate rated motor efficiency as a function of load, using manufacturers' load curves. Since such load curves usually present efficiency as a function of output load (shaft power), it would be imprecise to use them directly with input load factors calculated in the manner discussed here. An output load factor could be calculated, however, from input load factor as follows:

$$F_{output} = F_{input} \frac{\eta(F_{output})}{\eta_{nameplate}} \qquad (4)$$

where (F_{output}) = rated efficiency as a function of load
nameplate = rated full load efficiency

The equation must of course be solved iteratively. In practice, however, Equation 4 may be unnecessary, because using input rather than output load factor will result in an error much smaller than that introduced by the interpolation usually required, given data on efficiency at only a few discrete values of load (e.g. 25%, 50%, 75%).

The objectives of the study were to quantify the following:

- Annual average load factor
- Summer and winter peak coincident load factor
- Average maximum load factor.

The results of this study were used in conjunction with data on hours of use (derived from an independent telephone survey) to estimate energy and demand savings as part of the utility's impact evaluation of motors installed through its programs in 1992. In an extension of the study being performed on motors installed in 1993 (discussed in the Conclusion section below), direct monitoring of operating hours is being done on a subsample of the motors monitored for loading purposes; additional data verifying the operation of all motors installed at a site are also being collected. It should be emphasized that in this discussion, load factors connote loading *while a motor is running,* and that variations in energy consumption or average load due to less than continuous operation are accounted for in estimates of operating hours.

The average maximum load factor, an indication of motor oversizing, was used in the utility's evaluation of savings for variable speed drives (VSDs). In this analysis, the maximum load factor was used to adjust raw engineering estimates of savings, which had been computed assuming the maximum output of the motor was equal to rated horsepower.

Sampling and Enlistment

Considerable effort was put into selecting which sites and motors would be monitored, so as to better ensure statistical significance of the results.

Site Selection

Savings for each motor installed through the utility's programs in 1992 were estimated and aggregated to the program level. On the basis of the aggregate savings, the motor population was stratified into three size groupings ("S_i", 0-10 HP, "M_i", 15-30 HP, and "L_i" over 30 HP), such that the sum of the estimated savings in each of the three ranges, or strata, were approximately equal. Stratification is a sampling technique frequently used to ensure that a satisfactory precision is attained at reasonable total cost. Because the project budget constrained the number of motors that could be monitored to about 200, preliminary analysis was performed to estimate whether adequate precision in the results could be obtained given this " constraint, and if not, how much larger a sample would be required to achieve adequate precision. The analysis, based on motor part-load estimates from another study, indicated that a relative precision of 5% (at 95% confidence) could be attained, and that precision did not vary greatly for the range of sample sizes being considered. [1] That level of precision was thought to be sufficient for the utility's purposes.

The population from which the sample was drawn consisted of 3,776 motors installed through the utility's programs in 1992. To achieve adequate representation with a minimum number of sites (as part of additional efforts to meet budget constraints), priority was given to sites with motors in all three size strata. To do this, sites were ranked by how many size strata were covered. Approximately 80 customers who installed motors in all three size strata were targeted as the group from which the sample would be drawn ("List A"). Because many customers with large motors had *only* large motors, however, Stratum L was therefore under-represented. Additional sites with Stratum L savings over 5 kW were therefore added to List A, so that savings for Stratum L would equal that of the other strata. To overcome any potential bias due to exclusion of sites with motors in only one or two of the smaller strata, up to 16 motors per stratum were to be sampled from sites on List B, a list of sites with motors only in the smaller motor size strata. The resulting sample targeted 73 motors in each of the two smaller strata and 76 motors in the largest stratum (i.e., roughly proportional to the total estimated savings), as summarized in Table 1.

Sites were to be enlisted and surveyed sequentially, and motors were to be selected so that the distribution of motor functions in the sample matched that of the population. The protocol specified that if the monitoring technicians were not able to monitor the quota of motors at a given site, the shortfall was to be made up at subsequent sites. To ensure that the results were statistically significant, the maximum allowable shortfall was 10 motors per stratum.

Motor Selection

Several objectives influenced the protocol used to select motors at a site, once the sites were chosen:

- The sample should be random, and therefore be representative of the motors at a site and in the population.
- The sample should represent the diversity of the population.
- The sample should represent the distribution of motor functions in the population.

To meet the first two objectives, all motors at a selected site were randomized within each stratum, and selected in proportion to the estimate of total savings for each stratum. This resulted in targets of 2, 2, and 3 motors for measurement in Strata S, M, and L. The same number of motors would be measured at each site, therefore—regardless of how many were installed there—thereby ensuring that one or two large sites didn't drive the results. Field staff were instructed to maintain these average targets for each stratum as the solicitation and monitoring proceeded.[2] Meeting the third objective was difficult, because we lacked information on motor function of the motors in the study population. In lieu of this, a distribution of seven motor functions resulting from the previous year's telephone survey was used to devise a motor function check-off list, in which the frequency that a given function appeared was proportional to its share of the distribution in the previous year's data. At each site, if a choice of motors of the same size was available, the motors were to be chosen in the order that the functions appeared on the list, beginning after the last function checked for the previous site.

Forty-one of the 61 potential participants targeted were called and agreed to go ahead with the engineering site survey. The reasons for failure to enlist some customers were:

- Unable to reach customer contact (13)
- Not operating (seasonal business) (3)
- Participating in another NEPSCo study (2)
- Customer contact left; no one familiar with project (1)
- Too busy (1).

A listing of the sites not enlisted and associated site functionality and motors per stratum is presented complete study report (Savage 1993). Generally, the customers who we called were cooperative and willing to participate in an engineering site assessment.

Engineering Site Assessments

A project monitoring and analysis plan, outlining the procedures used to conduct site surveys, perform monitoring, and analyze the data was developed, and is documented in the complete report. A site survey, or engineering site assessment (ESA) identified the motors available for monitoring, recorded nameplate data, motor function, operating

Table 1. Summary of Sample Selection

		Stratum S 0-10 HP		Stratum M 15-30 HP		Stratum L > 30 HP	
List	**No. of Sites**	**Motors Per Site**	**Total**	**Motors Per Site**	**Total**	**Motors Per Site**	**Total**
A	19	3	57	3	57	4	76
B	4	4	up to 16	4	up to 16	0	0
Total	23		up to 73		up to 73		76

hours and seasonal operating data, verified the feasibility of monitoring, identified sensor and meter locations, and identified hardware requirements. The result of the ESA was a site monitoring and analysis plan specifying the motors to be monitored, and the equipment required, to be used by the technicians performing the installation. In some cases, not all of the motors at a site were surveyed.

In practice, many sites either had fewer motors than the sampling protocol called for, or motors were not available for monitoring. As monitoring progressed, the total number of motors surveyed and available for monitoring was tabulated. When it became apparent that there could be a shortfall in a given stratum, the ESA's at subsequent sites targeted those strata. The shortfalls increased the proportion of motors monitored at later sites, and increased the overall number of sites required.

There were several reasons why motors might not have been available for monitoring:

- The motor could not be located during the site assessment.
- There was restricted access to the motor (e.g., on top of equipment, in hazardous areas).
- The motor had failed and had not been replaced yet or had been replaced by a standard efficiency motor.
- Equipment had been removed, and the motor was no longer in service.
- The motor was on-site, but installation was not complete.
- The motor operated only seasonally.
- The motor was part of a system where two or more pumps/compressors/etc. were used, with one serving as a backup.

In the last two cases, motors were surveyed but not monitored.

The motor function portion of the motor selection protocol proved difficult to implement. Due to time constraints, sites were surveyed in parallel by two separate teams, and many sites did not have more than two or three motor functions. When a site had a limited number of motor functions, following the strata sampling protocol usually meant covering all of the functions available at that site. This was especially true at later sites, when most or all of the motors at a site in a stratum were being monitored because of previous shortfalls. Several of the enlisted sites were not monitored, for the following reasons:

- Concerns regarding safety and/or liability issues (5 sites)
- No additional sites required from the given list (2 sites)
- The plant was not operating during the window for monitoring (1 site)
- All motors were inaccessible for monitoring (2 sites)
- Could not schedule ESA (1 site).

Monitoring and Analysis Methodology

A data recording interval of one hour was thought to be sufficient for determining annual average load factor and peak coincident load factor, defined as the average load factor coincident with the utility's peak demand. Determining maximum load factor (corresponding to maximum load on a motor) was not part of the original scope of the study; had it been, a shorter recording interval would have been used, so as to pick up short duration peak motor loads. Although monitoring for longer than 24 hours would have reduced uncertainty, time and budget constraints precluded this.

In cases where loads were expected to be seasonal, such as motors on variable volume HVAC fans, measured hourly load factors were multiplied by adjustment factors to account for predictable changes in motor loading throughout the year.[3] As discussed below, this was required for only a small portion of the sample. The average load factor for an individual motor was calculated simply as the average of the 24 hourly average load factors. The utility required load factors specific to the its peak periods for its evaluation of coincident demand impact. Analysis of the historical demand data indicated that the majority of system peak demands occurred between the weekday hours of 10 a.m. to 3 p.m. during the summer, and 5 p.m. to 7 p.m. during the winter. Coincident load factor for a given motor, therefore, was estimated by averaging the hourly load factors during those periods. Maximum load factor for a given motor was determined as simply the maximum of the 24 hourly measurements.

Averages for each stratum where then calculated, and weighted up to the population to yield overall averages (annual, coincident, or maximum), taken as the means of the stratified sample:

$$\bar{P}_{st} = \frac{\sum P_i N_i}{N} \tag{5}$$

where P_i = Average load factor for Stratum i
N_i = Population of installed motors in Stratum i
N = Total population of installed motors

If a motor was not running during the summer or winter coincident peak hours, then it was excluded from the average for that parameter.

Monitoring

Multi-channel portable power monitors and dataloggers were used to measure true power and runtime. For motors controlled by VSDs, dataloggers tolerant of distorted wave forms were used. Monitoring equipment was installed, and the installation verified by technicians in conjunction with a licensed electrician. Each motor was monitored for 24 hours during a weekday, during February or March 1993. The data were checked at installation and removal to verify that the monitor had functioned properly and all of the data were present.

Satisfying the criteria of the sampling protocol resulted in monitoring of 229 motors at 30 sites. Of those motors, 25 did not run during the monitoring period, and data from an additional 30 could not be used. The reasons data for these motors could not be used were:

- An error occurred during installation or programming and was not detected because the motor was not running at start up
- Power to the monitor was disconnected during the monitoring period
- The monitor failed after installation and verification
- The monitored data showed clearly erroneous readings at some points during the monitoring period.

Infrequently, motors selected for monitoring could not be monitored when the installation occurred for one of the following reasons:

- Unforeseen site conditions
- Motor had recently failed
- Equipment was down for maintenance.

Data Analysis

Measurements from a total of 193 motors were used in the analysis. Peak coincident, annual average, and maximum load factors were calculated for each of these. Adjustments for weather- or production-dependence were necessary for only 13 motors. For motors not in use during the monitoring period (seasonal motors, backups, and intermittently operated motors) it was decided to estimate load factors using data from similar applications (in some cases the backup motor's twin), rather than introduce a systematic bias by excluding them. A total of 19 such motors were analyzed; an additional 12 motors were excluded from the analysis because their loading could not be reliably estimated. In the few instances where several hours of data were bad or missing, the missing data were interpolated from the data in the preceding and subsequent hours.

Results

Table 2 shows the results of the measurements and analysis. The annual average load factor of 0.64±0.05 was lower than expected.[4,5] Because motor efficiency curves are relatively flat down to about 50% load, most of the underloading can be attributed to lower than rated shaft loads, rather than decreases in efficiency. The average load factors vary considerably across motors, from less than 0.1 to more than 1.5. It is likely that variations within function classes would be smaller, and that load factor is somewhat correlated with motor function, although no analysis was done to test this because the sample size was too small.

Ultimately, in an effort to simplify the motor evaluation, only the average factor was used in the evaluation of demand impact. The argument for making this simplification was bolstered by the fact that the uncertainties of the coincident load factors computed using either method overlapped with those of the average load factor.

Load variation throughout the 24-hour monitoring period was observed to be small for perhaps two-thirds of the motors. Although minimum load factor was not calculated, the spread between average, coincident, and maximum load factors for a given stratum is significant, however, and is due to variation with time of day in the remaining third of the sample.

The mean maximum load factor is 0.74±0.06. Given the data recording interval of one hour, it would be unreasonable to infer that motors are, on average, a third too large, because it is likely that higher loads would be observed for shorter intervals.[6] The number does, however, provide a conservative estimate of peak load for use in adjusting engineering estimates of savings for VSDs performed assuming peak loads of 100%; the higher the estimate of maximum motor loading, the higher the savings.

The sample, representative of the population, was comprised predominantly of industrial facilities of varying sizes with a small number of hospitals and offices buildings. Only a small portion of motors analyzed (3%) were

Table 2. Measured Load Factors

Motor Size Stratum	Number of Motors n	N	Load Factor: Peak Coincident Winter	Peak Coincident Summer	Annual Average	Average Maximum
S	58	2,502	0.669	0.719	0.663	0.783
M	59	896	0.612	0.629	0.584	0.643
L	76	378	0.665	0.672	0.624	0.698
Total/Mean	193	3,776	0.66±0.06	0.69±0.06	0.64±0.05	0.74±0.06

controlled by VSDs. Motors on HVAC fans and pumps also constituted a relatively small portion of the sample (12%), and most of these were constant volume, with no load variation. Weather, a predictable load determinant, therefore affects load variation for few of the installed motors. Other unpredictable determinants, such as production levels, influence motor loading. Most motors ran continuously during the monitoring period.

Conclusion

Average load factor (64%) was high enough to be explained by lower than rated loading at the motor shaft, but low enough that the impact of reduced efficiency on motor savings estimates should be considered. Because the improvement in efficiency of energy efficient motors over standard motors increases as load decreases (i.e., their efficiency curves don't drop off as quickly), savings estimates that assume nameplate efficiency (such as that used by this utility, exemplified in Equation 3) may be low.[7] This indicator of average motor loading was significantly lower than previously used engineering assumptions, and resulted in reduced estimates of savings.

For most of the sample, motor load did not vary significantly over the course of a day. The mean maximum load factor of 0.74 indicates that on average, motors are probably oversized more than safety margins would require. Because relatively long recording intervals were used here, however, the result is inconclusive and is certainly an underestimate. In any case, these motors are not, on average, so oversized that the benefits of efficiency gains would outweigh operational concerns in decisions to downsize. The wide range of average load factors does indicate, however, that some motors are grossly undersized or oversized, an issue that should be addressed. Grossly oversizing a motor results in significantly greater equipment cost (including that for a larger VSD, if required) and operating cost due to poor efficiency; grossly undersizing a motor can obviously result in failure.

Caution should be used in applying the results of this study to other utility service territories; a different mix of motor function (e.g., more heavily commercial than industrial) would be likely to exhibit different loading characteristics.

Epilogue

In 1994, the utility performed an extension of the study reported above (Savage 1994). The results, only recently available, will be summarized in brief.

The recent study, drawing on the population of motors installed through the utility's programs in 1993, employed an improved two-stage or cluster sample design. Sites were randomly drawn from within three site strata of equal estimated demand savings, then motors were randomly drawn from three motor size strata of equal savings (0 - 10 HP, 15-30 HP, >30 HP). Additional information from rebate applications was incorporated to better facilitate on-site identification of selected motors, as the motor sampling protocol used in the original study had proved difficult to implement. The study was also expanded to include survey and verification of all motors at a site, more frequent data recording (five minute intervals),[8] two-week runtime logging for a subsample of motors, as well as operator interviews covering rewinding and replacement practices; the findings of those portions of the study, however, are beyond the scope of this discussion.

The results of the study are presented in Table 3. Since the summer coincident demand period (11 a.m. - 3 p.m.) differed slightly than that used for the original study, and because coincident results for the new data were quite close to the annual average results, coincident data for the two years were not combined. Surprisingly, the average

Table 3. Measured Load Factors, 1992 & 1993 Results Combined

Motor Size Stratum	Number of Motors n	N	Load Factor Annual Average	Average Maximum
S	85	5,146	0.638	0.767
M	93	1,895	0.572	0.647
L	95	855	0.621	0.709
Total/Mean	273	7,896	0.62±0.04	0.73±0.05

maximum of the more frequent data was lower than that of the original data recorded hourly. To combine data for the calculation of maximum load factor, these new five minute data were not used directly but were aggregated to hourly averages. In summary, with the inclusion of the new data, the load factors decreased slightly, and were accompanied by the expected decreases in uncertainty associated with the larger sample size.

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Endnotes

1. This can be attributed to the rather tight distribution of part-load measurements in the data used and the relatively large sample sizes.

2. Due to time constraints, this protocol proved cumbersome, and has been modified for subsequent evaluation, as discussed later in this paper.

3. For weather-dependent loads, adjustment factors were calculated for each hour of the day in a representative day for each month by estimating the change in motor load as a function of normal outside temperature for the given hour. The procedure is documented in greater detail in the complete report (Savage 1993). For production- or occupancy- dependent loads, adjustment factors were estimated according to the type of load and the control system used (if any). Adjustment factors do not account for changes in run time, because a change in run time does not affect load factor.

4. Previous utility estimates of load factor were around 0.75, although there was no basis for this number other than engineering judgement and general knowledge of sizing practices.

5. Uncertainties were determined using a 90% confidence interval. Uncertainties in the hourly measurements and variances in the mean load factors for each motor were not propagated through to the overall uncertainties.

6. It should be noted that with standard motor sizing increments, simply choosing a motor one size larger can typically result in 20% to 50% oversizing.

7. There are other aspects of actual motor performance that may significantly affect savings, such as reduced slip and increased power factor in efficient motors. These topics are subjects of continuing research by this utility, but are beyond the scope of this paper.

8. Although a recording interval as short as five minutes was thought to improve estimates of average motor oversizing, the results would still not be valid for individual motors in certain process applications where repetitive maximum loads might last only a few seconds, e.g., injection molding machines.

References

Savage Engineering, Inc. 1993. *Motor Performance Study.* Project Report 93-1045 to New England Power Service Company.

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