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INCONSISTENCIES IN ELECTRIC MOTOR CERTIFICATION REQUIREMENTS

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ABSTRACT

The Final Rule on certification requirements for induction motors issued by the Department of Energy contains different assumptions for the compliance and the enforcement procedures. These differences may yield unexpected results under certain conditions. For example, at times, the enforcement procedure can support a higher nameplate rating for a motor lot than would be possible by an appropriate application of the compliance procedure and vice versa. This paper examines, in detail, the nature of the problem and gives several examples where the enforcement plan fails to achieve its intended purpose.

KEY WORDS

Electric Motors, Efficiency Standards, Energy Conservation, High Efficiency Motors

1. Introduction

About 60% of the electricity produced in industrialized countries is used to power motors. In these same countries, electricity demand is challenging generation capacity and is causing congestion in transmission and distribution systems. Solutions to this situation include:

1. The expansion of generation sources, both conventional and novel such as wind power,
2. The expansion of transmission and distribution systems,
3. The growing use of distributed generation to increase available power without transmission congestion on existing lines,
4. Improving load efficiency.

Because they are such a large fraction of the load, efforts to improve load efficiency often include efforts to improve motor efficiency. If a significant number of higher efficiency motors are to be introduced into the load mix, the buyers must have an incentive to purchase higher efficiency motors and a means to identify which motors have higher efficiency. The motivation is usually supplied by a combination of three factors. One is the desire to reduce operating costs. A higher efficiency motor can have a lower life cycle cost than a less efficient one. The second is a desire to attract customers by showing that a company is sensitive to environmental issues and a good neighbor. The third is governmental incentives that may be positive, e.g. tax incentives, or legal, e.g. regulations.

The technical issue, however, is the identification of higher efficiency motors. The metrology base exists so that a buyer can compare any two motors for the same load and identify the more efficient motor. Because of the large volume of sales, however this is not a practical approach in most cases. The approach used in the United States and most other countries is that the motor manufacturer labels a motor lot with an efficiency rating. The manufacturer then puts sufficient controls on the variability of incoming materials and the manufacturing process to have confidence that the entire lot is appropriately labeled. In the U.S., the historical procedure for this labeling process was a voluntary one, complying with a standard promulgated by the National Electrical Manufacturers Association [1]. On October 5, 1999, the Department of Energy (DOE) issued its Final Rule [2] on the implementation of the Energy Policy Act (EPAct) [3] establishing government specified testing procedures for the verification of the efficiency of induction motors, efficiency labeling requirements for induction motors, compliance certification requirements, and enforcement procedures. The publication of this Final Rule followed years of public debate on the various issues. During this time, industry groups (especially NEMA, National Electrical Manufacturers Association), energy conservation advocates, individual manufacturers, motor users, and private citizens had an opportunity to comment on the course of action that DOE had been proposing in various editions of its preliminary Proposed Rule [4]. The publication of DOE's Final Rule is the culmination of the U.S. Government's efforts to regulate induction motor efficiency dating back at least to the mid-1970s [5].

This paper shows that this rule, while providing enforceable procedures, does not necessarily permit the selection of more efficient motors by following the specified efficiency ratings. The problem can become worse as manufacturing quality control improves.

2. Background Information and Definition of the Problem

Prior to the late 1970s electric motors were not required to have a full-load efficiency value stamped on their nameplate. At that time, in response to rising energy costs, the motor industry adopted new voluntary NEMA standards regarding the method to follow in showing a full-load efficiency on the motor nameplate. These standards were quickly followed by all major manufacturers and proved useful for motor users in determining energy consumption. In 1992 the Department of Energy mandated that all integral horsepower induction motors of standard design meet specified minimum efficiency levels published in tables arranged by horsepower (up to 200 HP), motor speed, and motor enclosure type [3]. The law gave motor manufacturers five years to bring their production in compliance but specifically said that no motor, among the designs covered by the law, could be sold in the USA after the end of October 1997 if it did not meet the minimum efficiency mandated in the DOE tables.

It is safe to say that, at the time the law was enacted, a majority of induction motors sold in this country did not meet the mandated DOE efficiencies. Furthermore, a substantial portion of motors manufactured at the time had efficiencies so far below the minimum requirements that they could be brought into compliance only with a major redesign. It is a great credit to the motor industry that it was able, in the relatively short period of time of five years, to upgrade its production to the point of not only meeting the requirements of the law, but also introducing new motor lines that far exceeded them. This often required radical re-tooling and the adoption of new production methods, but by October 1997 the conversion had been accomplished.

To appreciate the degree of improvement achieved, one has to consider the net reduction of full-load losses for each motor design. Efficiency values of integral horsepower induction motors have always been generally 85% or higher, so that incremental improvements stated in terms of efficiency result in relatively small changes of that number. For example, a pre-1997 induction motor of 200 HP, 1800 rpm, totally enclosed fan-cooled design typically may have had an efficiency of 94.1%. This same motor, after October 1997 was required to have an efficiency of 95.0%, which is equivalent to about a 16% loss reduction. As stated above, most manufacturers after 1997 carried the redesign further on a strictly voluntary basis and offered a premium efficiency motor design of this same rating with a full-load efficiency of 95.8%, equivalent to an additional 17% loss reduction, or even 96.2% (25% loss reduction above what is mandated by DOE and 37% less losses than the pre-1997 design). Similar percentages of loss improvements were realized throughout the whole range of motors covered by the federal law.

It is clear from this example that shifting to higher efficiency motors could have a significant impact on the country's energy usage as well as electrical distribution infrastructure. Thus, in order to insure that motor manufacturers met the requirements of the law, the DOE also issued guidelines on how to decide whether the efficiency number stamped on a motor nameplate truly reflected the full-load motor performance. This resulted in the issuance of what came to be known as DOE's Final Rule [2].

DOE's Final Rule spells out the procedure a motor manufacturer has to follow to substantiate the efficiency value stamped on the nameplate of its motors and, in particular, to prove that its motors are manufactured in accordance with EPAct. The Final Rule specifically defines the following major items:

1. The testing procedure to be used for induction motors
2. The process to qualify a calculation method, if one is employed to calculate efficiency
3. The labeling requirements as to motor full-load efficiency
4. The method to decide what value of efficiency should be stamped on the nameplate (compliance procedure)
5. The procedure whereby DOE verifies that indeed the motors are correctly labeled (enforcement procedure)

For about two decades, integral horsepower, polyphase, single-speed, induction motors manufactured in the U.S. have had a nominal efficiency stamped on their nameplate in accordance with the requirements of the NEMA Standards [1], Section 12.59.2. The nameplate efficiency is chosen by the manufacturer of the motor from the allowed values of nominal efficiencies listed in Table 12-9 of [1]. The NEMA Standard requires that the average efficiency of a large population of motors of the same design shall not be less than the value of nominal efficiency chosen from this table and that no motor shall have an efficiency less than a minimum value associated to each nominal efficiency and also listed concurrently in Table 12-9 of [1]. A section of Table 12-9 is reported here for reference in Table 1.

Table 1. NEMA Nameplate Efficiencies (expressed in percent), partial tabulation taken from Table 12-9 of [1]

Nominal Efficiency	Minimum Efficiency Based on 20% Loss Difference
95.8	95.0
95.4	94.5
95.0	94.1
94.5	93.6
94.1	93.0
93.6	92.4
93.0	91.7

The labeling requirements of DOE's Final Rule are in agreement with this NEMA table and use the same values of nominal efficiencies. Although this much of this activity predates the adoption of Public Law 104.113 (National Technology Transfer and Advancement Act of 1995), the use of an industrial voluntary standard in a Federal Rule is consistent with that law.

3. DOE's Compliance Procedure

The section of DOE's Final Rule dealing with the compliance procedure is consistent with the approach specified in the NEMA standard. It prescribes that, taking a sample of n motors ($n \geq 5$) each with measured efficiencies X_i ($i = 1, 2, ..n$) and all of the same motor model for which the nameplate nominal efficiency, RE, had been selected, the average efficiency $\overline{X}$ of the sample be no less than the value obtained decreasing RE by an additional 5% of losses. RE is one of the efficiency values selected from those listed by NEMA in the first column of Table 1 (whenever possible, the symbols used in this paper are those of DOE's Final Rule). Furthermore, the minimum sample efficiency of the sample lot shall not be less than the value calculated decreasing RE by an additional 15% of losses. The DOE's compliance procedure is summarized in Figure 1.

A few observations are in order. First of all, one key feature to note in both the NEMA Standards and the DOE compliance procedure is that the nameplate efficiency is limited to one of a set of discrete values. While there are many practical advantages to this approach, e.g. providing some protection against the specification of insignificant differences, it is not statistically based. From a statistical sense, this procedure does not specify, assume, or rely on any particular underlying distribution, a mean, or a standard deviation.

Secondly, the DOE compliance procedure allows the sample mean to fall below the value of RE by the equivalent of an additional 5% loss. In this sense, it is more lenient than the NEMA Standards, although in requiring a maximum 15% loss deviation from RE for the minimum sample efficiency it is tighter than NEMA. As observed previously, the minimum values of the NEMA chart (right column of Table 1) are based on a 20% loss deviation from RE.

Thirdly, there is no requirement for an upper limit to the efficiency: in principle, if there were an incentive to do so, a manufacturer could select a rating of RE even if the mean of his population exceeded the next higher value of allowed efficiencies.

Therefore, RE is not, either in principle or in practice, the mean of the distribution but a benchmark used to define the greatest lower bound for what that mean may be (item 4 in Figure 1). The compliance procedure is based on an operational definition that provides the purchaser with a prescriptive description of the meaning of the nameplate efficiency rating.

1. Test a sample of n motors ($n \geq 5$) obtaining efficiencies X_i ($i = 1, 2, .. n$).
2. Compute the sample mean:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

3. Identify the minimum sample efficiency X_{min} :

$$X_{min} = \min(X_i)$$

4. Letting RE = nameplate nominal efficiency, both conditions below must be verified

$$\overline{X} \geq \frac{100}{1 + 1.05\left(\frac{100}{RE} - 1\right)}$$

and

$$X_{min} \geq \frac{100}{1 + 1.15\left(\frac{100}{RE} - 1\right)}$$

Figure 1. Outline of DOE's Compliance Plan

4. DOE's Enforcement Procedure

According to DOE's Final Rule, the Secretary of Energy may order the testing of any motor design covered by the law to verify that it is in compliance with EPAct: this is the enforcement section of the Final Rule. The DOE sampling plan for enforcement testing [2] is summarized here in Figure 2 for convenience.

The DOE section on the enforcement procedure follows a different approach than the compliance procedure. The enforcement plan imposes specific statistical assumptions that were not required to be present in the base lot of motors meeting the compliance procedures. At the operational level, this results in centering the plan around the use of the t distribution, as can be seen in Figure 2. Key assumptions for the valid application of the t distribution are that the underlying distribution from which the samples are drawn is distributed normally and that the mean of the underlying distribution is known. In the practical situations to which the DOE Rule is applied it is unlikely that either of these situations is realized.

On the contrary, as already noted, the underlying distribution is not required to be normal to meet the compliance procedure. This lack of harmony between the compliance and enforcement procedures can be expected to result, in and of itself, in potential conflicts between the two.

In addition, there is a fundamental weakness in the DOE's sampling plan for enforcement testing. The equation in step 5 of Figure 2 applies the statistics of the t distribution using RE as the distribution mean. As pointed out above, RE is not a mean but a rating for a machine lot.

The statistical assumptions for enforcement lead to some counterintuitive results. For example, it can be shown that for any given set of values of nominal efficiency RE, sample average $\overline{X}_1$, and sample size n_1, there is an interval of values for the sample standard deviation S_1 that guarantees that the sample meets the DOE enforcement test. From the equations shown in steps 4, 5, and 6 of DOE's enforcement plan (Fig. 2) we can derive a first condition for S_1, to assure passage of our sample, as follows:

$$\overline{X}_1 \geq RE - t \cdot \frac{S_1}{\sqrt{n_1}} \quad (1)$$

$$S_1 \geq \frac{\sqrt{n_1}}{t}\left(RE - \overline{X}_1\right) \quad (2)$$

From the equations in step 7 of DOE's enforcement plan (Fig. 2), we can derive a second condition for the sample standard deviation. Let for convenience

$$A = \frac{(120 - 0.2RE)}{RE(20 - 0.2RE)} \quad (3)$$

then we obtain

$$\left(t \cdot S_1 \cdot A\right)^2 \leq n_1 \quad (4)$$

$$S_1 \leq \frac{\sqrt{n_1}}{t \cdot A} \quad (5)$$

Combining both conditions, we find the interval for S_1 that assures that our sample will pass DOE's enforcement test:

$$\frac{\sqrt{n_1}}{t}\left(RE - \overline{X}_1\right) \leq S_1 \leq \frac{\sqrt{n_1}}{t \cdot A} \quad (6)$$

As long as S_1 falls in the interval shown above, the sample is sure to pass the enforcement test.

While the concept that there may be a maximum permissible standard deviation is intuitive, the concept of the minimum value is cause for suspicion. As long as the sample mean $\overline{X}_1$ exceeds the nominal efficiency RE there is no difficulty since the standard deviation is always non-negative. The problem arises when $\overline{X}_1$ is less than RE but still larger than the value of RE decreased by the equivalent of 5% additional losses. This would qualify the lot

1. Test a sample of n_1 motors ($n_1 \geq 5$) obtaining efficiencies X_i.
2. Compute the sample mean

$$\overline{X}_1 = \frac{1}{n_1}\sum_{i=1}^{n_1} X_i$$

3. Compute the sample standard deviation:

$$S_1 = \sqrt{\frac{1}{n_1 - 1}\sum_{i=1}^{n_1}\left(X_i - \overline{X}_1\right)^2}$$

4. Compute the standard error of the mean:

$$SE\left(\overline{X}_1\right) = \frac{S_1}{\sqrt{n_1}}$$

5. Compute the lower control limit (RE = nameplate nominal efficiency, $t = 2.5^{th}$ percentile of the t distribution for sample size n_1 yielding 97.5% confidence level for one-tailed t-test):

$$LCL_1 = RE - t \cdot SE\left(\overline{X}_1\right)$$

6. Compare:

$$\overline{X}_1 < LCL_1 \rightarrow \text{noncompliance : stop test}$$
$$\overline{X}_1 \geq LCL_1 \rightarrow \text{continue with step 7}$$

7. Compute the recommended sample size and compare:

$$n = \left[\frac{tS_1(120 - 0.2RE)}{RE(20 - 0.2RE)}\right]^2$$

$$n \leq n_1 \rightarrow \text{in compliance : stop test}$$
$$n > n_1 \rightarrow \text{noncompliance : continue with step 8}$$

8. Compute n_2 = smallest integer equal to or greater than $n - n_1$ but not greater than $20 - n_1$. Test n_2 additional motors and repeat step 2 with expanded sample:

$$\overline{X}_2 = \frac{1}{n_1 + n_2}\sum_{i=1}^{n_1+n_2} X_i$$

9. Using the same S_1 as found in step 3 above, repeat step 4 for expanded sample:

$$SE\left(\overline{X}_2\right) = \frac{S_1}{\sqrt{n_1 + n_2}}$$

10. Using the same t as in step 5 repeat step 5 for the expanded sample and decide on compliance:

$$LCL_2 = RE - t \cdot SE\left(\overline{X}_2\right)$$

$$\overline{X}_2 < LCL_2 \rightarrow \text{noncompliance : stop test}$$
$$\overline{X}_2 \geq LCL_2 \rightarrow \text{compliance stop test}$$

11. If the above results in a determination of noncompliance, the manufacturer has the option of expanding the sample size (but not to more than 20 units) in steps, repeating for each expanded new sample the same procedure outlined in steps 8, 9, and 10 above.

Figure 2. DOE's Sampling Plan for Enforcement Testing (the symbols are those used in DOE's Final Rule)

under DOE's compliance procedure. However, if the same lot were also the result of excellent manufacturing methods, its standard deviation could be smaller than the minimum required by equation (6) above and, thus, the lot would fail the enforcement procedure. While it is easy to generate concrete examples to verify this point, it is sufficient to note that, if the production methods were indeed ideal ($S_1 = 0$), the lot would never pass.

This example shows that due to the different assumptions in the two tests, it is possible for a motor lot to pass DOE's compliance but not DOE's enforcement plan. This is troubling to a manufacturer that produces motors in a well run plant and labels them correctly in full respect of DOE's compliance procedure. It would also be troubling to a buyer who chose to use the DOE enforcement procedure to test compliance. The converse also may occur, namely that a motor lot may not pass the compliance procedure but instead be approved under the enforcement procedure.

To see how this occurs, imagine a motor production method that is not in good control, so that some units may be well above the required RE while others are definitely substandard and the motor lot should not be labeled with the chosen value of RE since it fails the compliance criteria. Precisely because of this, however, the standard deviation of the lot will be large enough to satisfy the minimum condition of equation (6) and the same lot, that should have been rejected under compliance, will be accepted under the enforcement procedure for that chosen value of RE. An example of this situation is given in Table 2 where a hypothetical set of test data obtained under the enforcement procedure is reported. In this and all other examples, it is assumed that the nameplate efficiency is RE = 95% corresponding to a minimum efficiency of 94.1%. After the initial five tests, it is determined that an additional test is needed. This additional test results in the worst efficiency of the lot but its inclusion allows the lot to pass.

The practical implication of this data set is that a manufacturer that followed correctly the compliance procedure would mark this lot with an efficiency of 94.1%. Because of the enforcement procedure, a marking of the lot with an efficiency of 95.0% would instead be accepted under DOE's enforcement criteria. Thus, the enforcement plan would support a higher efficiency than the compliance plan.

A more radical variation on this theme is the case where motors of two different designs, one meeting the labeling requirements of RE = 95% and one being much inferior, have been intermixed (Table 3). Interestingly, this sample would qualify the whole population of motors for passing under DOE's enforcement rule even though 60% of it is made up of markedly inferior units.

The ones above are but three classes of cases where the conflict between compliance and enforcement is high-

Table 2. Application of DOE's Enforcement Plan to a Hypothetical Sample 1 (efficiencies in percent)

Sample #	Sample Eff. Data	Sample Mean X1	Min. S1	Sample Std. Dev S1	Max. S1	Std Dev. of Mean SE(X1)	Nominal F.L. Eff. RE	Lower Ctrl. Lim. LCL1	Minimum Sample n	Acceptance Tests	Action
1	93.60 94.00 94.20 95.10 95.40	94.46	0.43	0.760	0.758	0.34	95.00	94.06	5.03	94.46>94.06 5.03>5	More test
1A	93.60 94.00 94.20 95.10 95.40 93.10	94.23	0.68	0.76	0.83	0.31	95.00	94.14	NA	94.23>94.14	Accept

Table 3. Application of DOE's Enforcement Plan to Some Hypothetical Sample 2: Example of Bimodal Distribution (efficiencies in percent)

Sample #	Sample Eff. Data	Sample Mean X1	Min. S1	Sample Std. Dev S1	Max. S1	Std Dev. of Mean SE(X1)	Nominal F.L. Eff. RE	Lower Ctrl. Lim. LCL1	Minimum Sample n	Acceptance Tests	Action
2	93.60 93.60 93.70 95.00 95.00	94.18	0.66	0.75	0.76	0.34	95.00	94.07	4.90	94.18>94.07 4.90<5	Accept

Table 4. Application of DOE's Enforcement Plan to Hypothetical Samples 3 and 4: Example of How the Enforcement Plan Rejects a Better Lot but Passes an Inferior One (efficiencies in percent)

Sample #	Sample Eff. Data	Sample Mean X1	Min. S1	Sample Std. Dev S1	Max. S1	Std Dev. of Mean SE(X1)	Nominal F.L. Eff. RE	Lower Ctrl. Lim. LCL1	Minimum Sample n	Acceptance Tests	Action
3	94.80 94.90 95.00 94.90 94.80	94.88	0.10	0.08	0.76	0.04	95.00	94.90	0.06	94.88<94.90	Reject
4	94.40 94.90 95.00 94.90 94.80	94.80	0.16	0.23	0.76	0.10	95.00	94.71	0.48	94.80>94.71 0.48<5	Accept

lighted. As was said in connection with equation (6), there is a whole continuum of possible test data capable of generating similar discrepancies. Not only is there conflict between the two procedures, there is also internal inconsistency within the enforcement test plan proper. Table 4 shows how two samples with identical efficiency values except one, both passing the compliance test, are discriminated by the enforcement test: oddly, the inferior sample passes enforcement while the better sample does not.

5. Conclusions

It is well recognized that any statistically based test has some probability of rejecting a good lot or accepting a bad one [6]. The aim, of course, is to minimize the likelihood of either of these two outcomes. It must be emphasized, however, that the design of a statistical test is not the issue in this situation. The problems identified here are due to two major causes:

1. The approaches used in defining the compliance and enforcement procedures are not congruent
2. The statistics used in the enforcement procedure is incorrectly applied

As a result of this, the key implications that have been identified are the following:

a. In some cases the enforcement procedure will tolerate a higher nameplate efficiency than the compliance procedure.
b. In some cases the enforcement procedure will reject lots whose efficiency was correctly specified under the compliance procedure.
c. In some cases the enforcement procedure will pass inferior lots and reject better ones.

This means that neither the manufacturer nor the buyer can have confidence that the procurement and installation of motors with higher nameplate efficiencies will produce a reduced demand on the electrical distribution system for the same amount of work done.

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