ASSESSING METHODS TO MEASURE MOTOR EFFICIENCY IN SITU

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Managing electric motor systems is one of the most important aspects of improving reliability and increasing energy efficiency in the industrial environment. Unfortunately, unknown performance data for existing motors often frustrates good motor systems management intentions. The foremost aspect of motor systems management is knowing when to retire an existing motor for a more efficient replacement. Software and information provided by U.S. Department of Energy's Motor Challenge Program make this an easy economic calculation only if certain facts about the motor system are known. The most elusive facts are the existing motor's efficiency and the shaft power demanded by the load.

Some experts claim accurate in situ measurement of motor efficiency and shaft power is not feasible while others disagree and promote certain devices and methods for this determination. With support of Pacific Gas and Electric Company and Bonneville Power Administration, the Oak Ridge National Laboratory (ORNL) addressed this controversy in a major literature review, evaluating and reporting on approximately thirty field methods for determining motors efficiency. Supported by the same sponsors, the Washington State University Energy Program (WSU) pursued further resolution of the controversy in the laboratory. WSU formed a partnership with the Oregon State University Motor Systems Resource Facility to evaluate the most promising devices and methods identified in the literature study. The sponsors expressed hoped that one or more methods could be found that would consistently determine efficiency with a deviation of less than 3% from accurately determined efficiency per IEEE 112B.

In December 1996, four motors, from 50 to 300 HP, underwent laboratory efficiency testing per IEEE methods 112A and B. Concurrent testing was conducted with all the efficiency measuring devices and methods under investigation. Three test motors were without measurable defects. By intention, a fourth motor had a documented defect typical of damaged or mis-repaired in-service motors, i.e. an asymmetrical air gap. One of the good motors, a 100 HP older machine, was rewound with a switchable dropped turn. This allowed us to rerun it with the switchable turn bypassed to simulate a fifth (and defective) motor. Each motor was tested at nominal conditions and at over/under and unbalanced voltage typical of a real industrial environment. Unbalance testing was conducted at 1% and 2.5% unbalance except on the 100 HP motor where it was conducted at 2% and 5% unbalance. The motors are summarized in Table 1.

Table 1. Description of Motors Tested

ID #	HP	Poles	Frame	Condition
1	300	4	T	Newer; Energy efficient inverter duty
2	50	2	T	Older; Never rewound
3	100	4	U	Older; Multiple rewind history
4	100	4	U	Same motor as above, but with one dropped turn
5	150	4	T	Older; Warped end bells causing poor rotor concentricity

An important evaluation criterion was invasiveness, because it was considered a major concern for any method. Methods, which could be accomplished without shutting the motor down, were considered to have low invasiveness. Actions requiring long downtime or interference with a motor's electrical or mechanical connections were considered invasive. Methods requiring the motor to be uncoupled and operated unloaded were deemed most invasive. A few methods that required shutting down the motor, but not uncoupling it, were considered intermediate in invasiveness. The methods are shown in Table 2, with columns progressing from least to most invasive test requirements.

Table 2. Invasiveness of Motor Test Methods

	Required Operating States (Least Invasive→→→Most Invasive)		
Motor Efficiency Testing Methods	**Normally Loaded**	**Off**	**Operating Uncoupled**
Dedicated Instruments			
Vogelsang & Benning Option I	☑	☑	☑
Vogelsang & Benning Option II	☑	☑	
ECNZ Vectron	☑	☑	☑
MAS-1000	☑	☑	☑
Software			
Esterline Angus MET	☑	☑	☑
MotorMaster+ Power	☑		
MotorMaster+ Current	☑		
MotorMaster+ Slip	☑		
ORMEL 96	☑	Option	
Hand Calculations			
Standard Slip	☑		
Ontario Hydro Comp. Slip	☑		
Upper Bound Slip	☑	Option	
Analytical Slip	☑	☑	☑

In this paper, methods are classified by means of calculation. Three of the evaluated methods involved "dedicated instruments". These require a special hardware device that is used both in recording electrical characteristics and in performing the associated calculations. Another class of methods is "software" because special software is used to calculate efficiency from data acquired with generic instruments, e.g. voltmeter, ammeter, tachometer, etc. The final calculation class is "hand calculation". No special hardware or software is required, but generic instrüments are still required to obtain input data for hand calculation.

DEDICATED INSTRUMENTS

Lab testing revealed that the more-invasive methods generally had the best accuracy. The three dedicated instruments were more invasive, and they performed better than other methods. The ECNZ Vectron gave some problems with its internal over-current protection circuitry, and this is believed to have corrupted its performance on the 50 HP motor. The manufacturer attributed this to a program error (now corrected) which had no effect at the voltage and frequency of its native New Zealand. The MAS-1000 performed well except it read quite high at low loads on the 300 HP motor. The manufacturer believes this to be a lab staff error caused by failure to reset the power range lower for the no-load test.

Disregarding the above two problem runs, the dedicated instruments were generally within 1-2% accuracy in the load range of typical operation. The Vogelsang and Benning instrument had an "Option II" operating alternative which bypassed the no-load test. This Option II, sometimes called the "Nameplate" option, paid for its convenience with somewhat lower precision. Greatest deviation for all methods was experienced with the old 100 HP rewound motor where low load efficiencies were understated by 2-5% with most methods and voltage conditions. However a subsequent rigorous IEEE 112B retest of this motor generated slightly lower efficiencies, closer to results obtained from the dedicated devices. The difference between the earlier and later lab results (using the same facilities) has not been explained. It appears most likely that there was a torque sensor calibration error in the original IEEE 112A test.

The ECNZ instrument had a software feature that lets it project efficiency at 100% load and nominal voltage conditions from test results obtained at part load and off nominal voltage. This seems to be an important feature for comparing existing motors to catalog motors that, of course, are rated at nominal conditions. We intended to evaluate this feature but erred by not retaining some essential segregated loss data calculated by the machine in the off-nominal runs.

User friendliness encompasses ergonomics, convenience, automatic features, and human error avoidance, detection, and annunciation. We found some opportunities for improved user friendliness in each of the three dedicated instruments, leading to the suggestions below. Most suggestions do not pertain to all three dedicated instruments.

- Eliminate separate laptop requirement. (MAS-1000)
- Eliminate separate milliohmeter requirement. (V&B)
- Ensure against nuisance overcurrent trips. (ECNZ)
- Find an alternative to battery-powered current transducers. (V&B)
- Establish auto-ranging or warning to ensure correct power range setting.
- Improve confusing storage and retrieval methods.
- Improve shaft speed sensors for easier use. (MAS-1000 and V&B)
- Enhance display quality (ECNZ)

SOFTWARE METHODS

All three MotorMaster+ methods are of low invasiveness. All three work by calculating load then looking up efficiency from tables based on enclosure, poles, and whether or not the motor is labeled energy efficient. Among the MotorMaster+ methods, the power method clearly was the best at determining load. The slip method sometimes missed badly in overload conditions and the current method sometimes missed badly below 50% load. For most motors and voltage conditions, all three tended to perform best around 75% to 100% load where they were usually within 3% of the lab-determined efficiency. All MotorMaster+ methods work by first computing load, then looking up an efficiency from tables organized by enclosure, horsepower, speed and load. This placed them at the greatest disadvantage with the older and damaged motors.

The low invasiveness basic ORMEL 96 method, developed by ORNL, is a computer program using nameplate data and only one measured value. The measured value is RPM, which must be obtained with high precision. ORMEL 96 also has an advanced procedure, which allows the user to adjust certain "tunable parameters". We found that the basic method worked for only one of our five diverse motors. For the other four, we had to receive some coaching from ORNL in tuning the parameters and make use of the winding resistances we had recorded. Obtaining winding resistance puts the method into the intermediate invasiveness level, although it is possible to use the advanced method with a default or "tuned" estimate of winding resistance.

Only the 150 HP motor could be computed on the first try by the basic ORMEL 96 method. The basic method predicted its efficiency within 2.5% of actual efficiency at all except the 25% load level where it was low by around 5%. The advanced method predicted within 2% at all but 25% load for the 300 HP motor. The advanced method was also well within 2% on the 50 HP motor except above 100% load where estimates were typically high by 3% or more. ORMEL 96 was considerably low on the 100 HP motor, both with and without the dropped turn. Dynamometer tests of that motor revealed that its real efficiency peaked much lower than most, i.e. around 50% load. The ORMEL 96 curve looked more like a conventional curve, tending to underestimate 25% load efficiency by about 10%. The IEEE 112B retest on this motor came in at a lower efficiency, such that ORMEL 96 was very close at full load but still underestimated by about 4% at 50% load. This motor had the greatest potential to stump ORMEL 96 because it was an old U-Frame machine with a history of several rewindings. It bore a replacement nameplate affixed by a rewind shop. ORMEL 96 relies heavily on nameplate data since it operates from a minimum of measured data.

Software methods also presented user friendliness problems. The Esterline Angus MET method is a rather old (1986) DOS program. It may have been "ahead of its time," because motor systems management was not as visible an issue when it was created. With reprogramming as a Windows application and appropriate pricing and marketing, MET could compete well with other methods. ORMEL 96 required much manipulation of tunable parameters to clear confusing error messages and yield a valid result. Most methods need better documentation or automatic defaults for coping with unavailable input data.

HAND CALCULATION METHODS

The standard slip method was atrocious. Errors of 10-15% were common and efficiencies ranged from 56% to 169%. The Ontario Hydro Compensated Slip Method was not much better. It adjusted the standard slip efficiency in the right direction to compensate for voltage discrepancies, but the standard slip method was extremely imprecise even at nominal voltage. The poor performance was not surprising because (mathematically) the results are extremely sensitive to the slightest error in either nameplate or measured speed, and NEMA standards allow a broad tolerance of ± 20% of slip rpm. Manufacturers typically round their nameplate speed to only the nearest 5 rpm.

The upper bound slip method is much more accurate than the standard slip method because it uses slip in a different way. It simply treats the measured percent slip as a partial measure of input power loss, which is theoretically valid. Though the upper bound slip method was better than standard slip, it systematically erred on the high side because slip only reflects *rotor* electrical losses. A small modification, suggested by ORNL, was to include stator winding losses determined from measured current and winding resistance. This might be characterized as an upper bound slip *and copper loss* method. It provided so much of an improvement that we used it in the analysis in lieu of the upper bound derived only from slip. Therefore, "upper bound method" in this paper refers to the slip plus copper loss method. The added winding resistance measurement places the method in the intermediate invasiveness classification.

Even with copper losses included, the upper bound method systematically erred on the high side. This error was less than three percent at full load at all voltage conditions. However, it tended to overestimate considerably more at lower loads where rotor and copper losses diminish and core, friction, and windage losses dominate. This led us to experiment with one more embellishment to the upper bound method, creating a new "analytical slip" method. We included no-load power as a loss category. Including no-load power accounted for friction, windage, and core losses and greatly improved accuracy at the lower loads. Indeed, accuracy of the method approaches that of the dedicated instruments. This accuracy improvement comes with a price. The no-load test requires uncoupling, which places the method in the more invasive category. The cost of a dedicated device is avoided, but a tachometer, milliohmeter, and wattmeter are required. The wattmeter must be capable of measuring full load power and no load power. No load power may be less than one percent of full load and it occurs at very low power factor, so a broad ranging instrument or instruments are necessary. Analytical slip was not sensitive to instrument error in this experiment because electrical readings were taken from the same lab sensors that provided input data to IEEE 112 testing.

PERFORMANCE PRESENTED BY METHOD

Many things affected the performance of the various methods when they were applied to the different motors under different voltage conditions. The tables and graphs that follow should not be considered in isolation from the comments that follow each. Table 3 presents the performance by accuracy and precision. Error is defined to mean the difference between the MSRF lab efficiency and the efficiency indicated by the method under test. For example, in a run, if lab efficiency were 95% and a method indicated 94%, that method would be reported to have a –1% error. These results are presented with columns respectively showing one standard deviation below mean error, mean error, and one standard deviation above mean error.

Table 3. Percent Error of Selected Methods Relative to IEEE 112 A

Method	Low σ	Mean	High σ	Motors	Voltage
MAS-1000	0.31	1.23	2.15	1,2,5	All
V&B Opt I	-0.01	1.23	2.61	1,2,5	All
ECNZ Vectron	-0.37	1.05	1.74	1,5	All
ORMEL Adv.	-0.86	0.71	2.28	1,2	All
ORMEL Basic	-4.12	-2.03	0.06	5	All
E. Angus MET	-0.76	-0.03	0.83	1,2,5	All
MM+ Power	-1.22	1.39	4.00	1,2,5	All
MM+ Current	-2.46	6.06	14.59	1,2,5	All
MM+ Slip	-23.5	-6.94	9.63	1,2,5	All
V&B Opt II	-2.49	0.65	3.79	1,2,5	All
Analytical Slip	-0.43	1.05	2.53	1,2,5	All

Note that the ECNZ Vectron unit statistics were not reported on the 50 HP motor number 2. The lab staff struggled with a nuisance automatic over-current trip on the unit. After the data for that motor's load runs was displayed, it appeared that the ECNZ unit had lost its reference to the no-load data, creating excessively high low-load efficiency readings. Those runs were omitted for the ECNZ, but it should be noted that this might exaggerate the comparative precision of the ECNZ because motor number 2 had the greatest range of efficiency by load and greatest divergence of efficiency among the methods under evaluation. A similar problem occurred with the MAS-1000 unit for unknown reasons on the 300 HP motor number 1. Motor number 1 was very efficient with flat load curves and all methods tended to diverge very little from lab efficiency. Even with the problem, the performance of the MAS-1000 as displayed in Table 1 is better when motor number 1 remains included. For both these methods it could not be retraced exactly why no-load reference data appeared to have been lost. The manufacturers have speculated that there was a keyboard error committed by lab staff.

The 100 HP motor that constitutes motors number 3 and 4 was omitted from Table 3. This was done because of a discrepancy with the lab IEEE 112 method A versus method B data. Table 4 is presented to show how the methods performed relative to IEEE 112 method B for all five motors. Table 4 is for nominal voltage only since that was the only condition for which method B was run.

Table 4. Percent Error of Selected Methods Relative to IEEE 112 B

Method	Low σ	Mean	High σ	Motors	Voltage
MAS-1000	0.31	1.11	1.90	1,2,3,4,5	Nominal
&B Opt I	-0.22	1.05	2.32	1,2,3,4,5	Nominal
ECNZ Vectron	-1.42	0.44	2.30	1,3,4,5	Nominal
ORMEL Adv.	-3.44	-0.75	1.94	1,2,3,4	Nominal
ORMEL Basic	-4.83	-2.27	0.30	3,5	Nominal
E. Angus MET	-0.90	-0.10	0.70	1,2,3,4,5	Nominal
MM+ Power	-2.66	0.81	4.23	1,2,3,4,5	Nominal
MM+ Current	-2.59	0.89	4.36	1,2,3,4,5	Nominal
MM+ Slip	-3.25	0.48	4.20	1,2,3,4,5	Nominal
V&B Opt II	-2.19	2.06	6.31	1,2,3,4,5	Nominal
Analytical Slip	-0.49	0.84	2.17	1,2,3,4,5	Nominal

The motors were remounted on the test stand and torque sensors were recalibrated for the method B test. The results were virtually identical except on the 100 HP motor for which the method B results tended to be 2-4% lower than for the method A runs. The reason for this discrepancy has not been determined, but evidence points toward a probable torque sensor calibration error during the original method A runs. All the methods being evaluated performed closer to the IEEE 112 method B curves for that motor. If there was a torque accuracy problem with method A, it would have affected all voltage conditions on the 100 HP motor. Method B was only performed at nominal voltage conditions since its loss segregation aspects are not compatible with the voltage deviations applied to simulate the typical field environment.

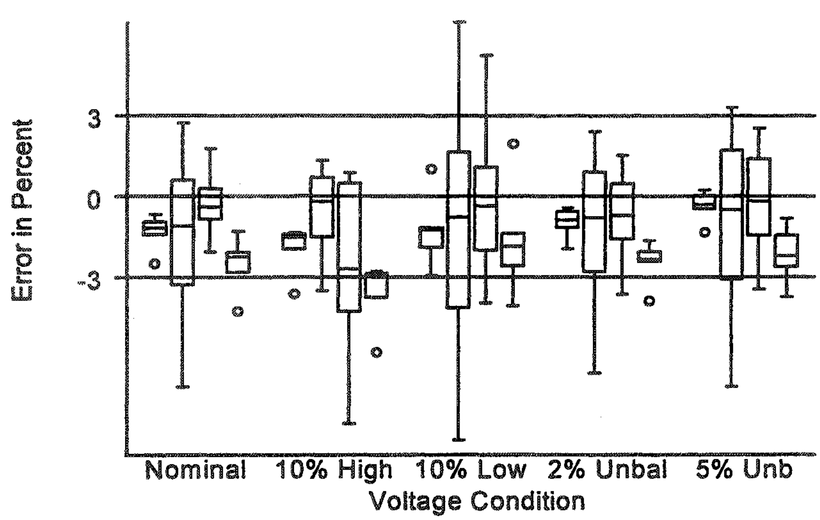
The Esterline Angus MET is conspicuous for its good performance in both Tables 3 and 4. While this certainly speaks well for the method, it must be noted that it has an advantage over the dedicated instruments in this experiment. Since the Esterline Angus MET is a software method, its inputs came from the same current, speed, voltage, micro-ohmmeter, and wattmeter sensors used by the lab for its IEEE 112 method. Any error in any of these reading should generally tend to move the Esterline Angus efficiency in the same direction as lab IEEE 112 A or B efficiency. In order to get good performance from this method in the field, precise instruments must be used. It is especially important to ensure that the wattmeter used for the no-load test is capable of reading accurately at very low power factor.

The results for analytical slip were obtained using cold resistance values and without accounting for stray load losses. Its performance, shown in Tables 3 and 4, is encouraging for a simple and low cost method. However analytical slip along with all the methods, other than the dedicated instruments, had the same immunity to sensor errors as did the Esterline Angus MET in this experiment. That is a reason to cautiously regard the good performance of the analytical slip method. Also, the analytical slip method probably would err more if no-load power were recorded under other voltage conditions than those that occur in service. This could happen if the motor had no-load power documented in the repair shop at carefully maintained nominal voltage and loaded data was taken when plant voltage was off nominal. The dedicated instruments and Esterline Angus MET software internally adjust no-load power based on the voltage actually recorded at the time of no-load test. A review of the no-load power of motors in this test suggests that this is not trivial. The sensitivity of no-load power to changes in voltage conditions varied considerably by motor.

EFFECTS OF OFF-NOMINAL VOLTAGE

One of the surprises in this research was that the efficiency determining methods were not significantly thwarted by the off-nominal voltage conditions. All the methods seemed to match lab values about as well at off voltage conditions as at nominal conditions. An example of this is shown in the Figure 1 box plot for the 100 HP motor #3 with symmetrical turns. Figure 1 shows four anonymous methods applied to each of five different voltage conditions. The vertical boxes span the distribution of each method's errors over the load range from 25% to 150%. Each box encloses the 25 percentile to 75 percentile band of errors. The distribution is typical for all the motors.

Figure 1. Distribution of Errors by Voltage Conditions; 100 HP Rewound U-Frame Motor



Although the *error* in methods' versus lab efficiency was not significantly effected by voltage, the actual efficiency was. For example, at low voltage, curves shifted toward lower efficiency at high load and higher efficiency at lower load.

CONCLUSIONS

Determining motor efficiency is not easy. Nonetheless, several existing methods and dedicated instruments estimated in-situ efficiency well enough to support economic decisions. The off-voltage conditions did not subvert results as much as we had expected. However, performance of the different methods varied by the motor under test, revealing that developers need to tune their designs for better accuracy with older, rewound, and/or damaged motors. For most methods, the best correlation with lab-determined efficiency was for the new energy efficient 300 HP motor. With the diverse veteran motors the methods diverged more, not only from lab efficiency, but also from each other.

The most accurate methods were more invasive, requiring shutdown and uncoupling. However, with a structured motor systems management program, these procedures could be accomplished conveniently at different times with the results combined later to compute efficiency. For example, winding resistance could be measured and recorded at the receiving inspection of new and repaired motors. No-load power consumption could be accomplished either at the repair shop or during initial or post-repair installation. Performance under load could be recorded any time the motor is installed and operating at normal load.

We believe that all methods can benefit from more validation studies with a diversity of typical veteran motors (i.e. other than new, efficient, and healthy motors). Where divergence occurs, case studies should pursue the causes of divergence. Several methods perform well enough that their adoption should be encouraged. However, the need to keep the techniques simple and user friendly for use in the industrial environment should not be forgotten. Field demonstration and testing (with feedback to developers) is needed. This will expand the practice of in situ efficiency testing, while supporting improvements in user friendliness.