A Laboratory Assessment of In-Service Motor Efficiency Testing Methods

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Abstract - Determining in-service motor efficiencies is important to industries concerned with energy conservation and cost savings. However, non-intrusive efficiency measurements of installed motors can be difficult to obtain and even more difficult to verify. This paper describes an evaluation and comparison of twelve motor efficiency methods through laboratory testing to assess their accuracy and precision. Analysis of the methods and implementation procedures is discussed.

1. Introduction

It is estimated that more than 60% of the electrical energy being used in the U.S. is consumed by motors [1]. In addition, in 1992 the National Energy Policy Act (EPACT'92) was passed to promote increased industrial efficiency worldwide; this includes a provision that after October of 1997, all newly constructed motors must be high efficiency [2]. Note that motors running at full load most of the time will incur an annual energy cost far exceeding their initial price [3]. It is therefore essential for industries to ensure that their motors are operating in an effective and energy efficient manner. Fig. 1 illustrates how electric energy is distributed for various driven equipment [4].

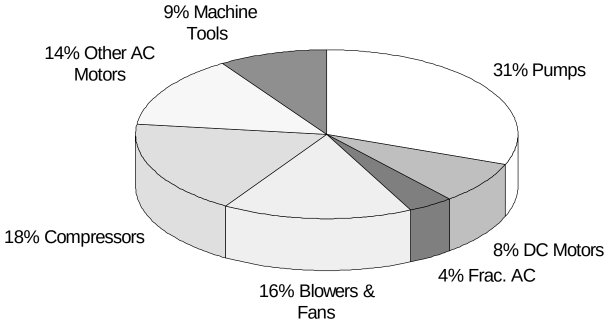

Fig. 1 Distribution of electric motor equipment.

The motor efficiency value, calculated as the ratio of the mechanical output to the electrical input, provides the basis for operating cost comparisons that could support replacing the motor with a more efficient unit offering a major reduction in operating cost. In order to determine the true motor operating efficiency, it is necessary to measure the electrical input power from the terminal voltages and currents and the mechanical output power from the shaft torque and speed. However, the mechanical output power of installed motors can be difficult to obtain in a non-intrusive manner, and even more difficult to verify [3,5-7].

In response to the need of estimating installed motor efficiencies, several different in-service testing methods and special measurement tools have been developed. In March of 1996, a team at the Oak Ridge National Laboratory (ORNL), under contract to the Bonneville Power Administration (BPA) and Pacific Gas and Electric (PG&E), reviewed 28 of these proposed "estimate methods" and evaluated them according to the invasiveness and cost of equipment [8,9]. Based on this review, the Washington State University Co-Operative Extension Energy Program (WSUCEEP), under contract with BPA and PG&E, subcontracted with the Motor Systems Resource Facility (MSRF) at Oregon State University (OSU) to test the 12 most promising in-service motor efficiency testing methods.

This paper discusses an impartial laboratory evaluation that has been conducted to assess the accuracy and precision of the final 12 methods. With the equipment available to the Motor Systems Resource Facility (MSRF) at OSU, the necessary measurements can be made with a high degree of accuracy and confidence by electric power analyzers and non-contact torque/speed transducers [10] in a manner similar to that employed by many motor manufacturers. The 12 in-service motor efficiency methods will be tested and the estimated efficiencies will be compared with the results of the laboratory baseline efficiencies found according to IEEE 112B. In addition, analysis of the methods and implementation procedures are discussed. From these results, the most appropriate method, or methods, for in-service motor efficiency estimation can be determined by the WSUCEEP team. This paper describes the test program and presents some of the preliminary findings.

2. In-Service Motor Efficiency Testing Methods

Table 1 Motor Efficiency Testing Methods

	Tests Required			
Motor Efficiency Testing Methods	No Load	Normal Load	Off	Speed Meas.
Dedicated Instruments				
V&B Option I	X	X	X	X
V&B Option II		X	X	X
Vectron (ECNZ)	X	X	X	X
MAS-1000	X	X	X	X
Software				
Esterline Angus	X	X	X	X
MM+ Power		X		
MM+ Current		X		
MM+ Slip		X		X
ORMEL96		X		X
Generic				
Standard Slip		X		X
O.H. Comp. Slip		X		X
Upper Bound Slip		X		X

Table 1 presents the 12 efficiency measurement methods recommended for testing at the MSRF. These represent nine different processes (with derivatives), three of which have specialized measurement equipment that is not already part of the system of sensors used in the IEEE 112B standard. Most of the methods involve different algorithms or computer programs to perform calculations on nameplate data and data gathered with generic instruments.

2.1 Dedicated Instrument Methods

The Vogelsang & Benning (V&B) method I requires testing at three conditions: uncoupled, normally loaded and unpowered (off). A reflector must be attached to rotating equipment to allow the speed to be recorded. In Option II, testing is accomplished without uncoupling, and motor nameplate data is substituted, but the accuracy is assumed to be reduced.

The Vectron method was developed for the Electricity Corporation of New Zealand (ECNZ). It requires testing at a load <10% and a load > 50%, and unpowered. It also uses an optical tachometer based on an attached reflective strip. The manufacturer claims that the efficiency at full load conditions can be determined from testing at a load >50% but less than full load. The manufacturer also claims this method can correct for off nominal voltage conditions up to 5%.

The MAS-1000 method is based upon a tester developed by Niagara Instruments under the direction of Vern Nielsen who was one of the designers of the motor test platforms in the Ontario Hydro Technology Lab (OHT) in Toronto, Canada and in the Industrial Electrotechnology Laboratory (IEL) in Raleigh, NC. A magnetic reluctance speed sensor is used, although a strobe tachometer can be substituted if readings are manually entered, but the former is preferred. The system is based on an Intel 486 processor and the manufacturer claims that Motor Master Plus (MM+) software developed by the U.S. Department of Energy (DOE) could be loaded and used with the tester for additional convenience in motor systems management.

2.2 Software Methods

The Esterline Angus method requires only generic equipment and custom software. Tests are required while uncoupled, at normal load, and unpowered. Surface and ambient temperature are required.

The three Motor Master Plus (MM+) methods are based upon nameplate and normal load operation. They allow efficiency to be computed/estimated at the normal load. Electrical and/or speed readings are required at normal load. No uncoupled or unpowered readings are required.

The Oak Ridge Motor Efficiency and Load 96 (ORMEL96) method requires only nameplate information and a speed measurement. The speed can be taken with a strobe tachometer. A computer program is used to process the data.

2.3 Generic Methods

The three slip methods require only a speed reading and, in one case, a voltage reading. All readings are at normal load.

Note that the more accurate estimate methods require shaft speed measurements, some of which may be difficult to obtain in an industrial environment.

3. Laboratory Equipment and Testing

The baseline for the comparisons of the in-service testing methods outlined in Section 2, are determined from the MSRF laboratory dynamometer. At the input terminals, this consists of a power analyzer to measure the electrical quantities of voltage and current and, hence, calculate power and power factor. At the motor shaft the torque and speed were measured by the most appropriate of a range of mechanically interchangeable non-contact transducers.

Four different motors have been used for the evaluation (50 hp, 100 hp, 150 hp, and 300 hp). The 50 hp and 300 hp motors are “perfect” motors which are used for laboratory set-up calibration (see Appendix 1). The 150 hp motor has a rotor eccentricity problem. The 100 hp motor has deliberately introduceable defects of a “dropped” turn on any one of all three stator phases (i.e. a turn of a winding that can be deliberately disconnected from the circuit). The reason for introducing the defective motors is that some of the methods have built-in assumptions about performance characteristics that are approximations of “perfect” motor parameters. The dynamometer method should enable an assessment of the accuracies regardless of the condition of the motor.

The motors have been tested on the motor/dynamometer platform in the MSRF laboratory which is summarized in Appendix 2, and described in detail in a previous paper [10]. The load points where efficiency has been documented include 25%, 50%, 75%, and 100% of rating for the 300 hp motor. For the smaller and intermediate hp motors, additional load points were performed at 125% and 150% of rating, which were not possible on the 300 hp motor due to the initial rating limitations of the lab. Tests were also conducted during 10% over-voltage, 10% under-voltage, and 2% and 5% unbalanced voltage conditions for all the motors.

Thus, with four motors, one of which can be balanced or unbalanced turns per phase, each evaluated at five voltage conditions, with no-load, 25%, 50%, 75%, 100% (for 300 hp) plus 125% and 150% of rated load (for the 150 hp, 100 hp [in both configurations] and 50 hp) approximately 165 load points were determined and recorded.

4. Preliminary Findings

The initial results of the test program are very mixed in their findings. In some cases the correlation between laboratory test data and efficiency estimations is good but, depending upon the level of accuracy sought, these tend to be exceptions rather than a general rule. An example of the best correlations obtained for each of the three motors (300 hp, 100 hp, and 50 hp) is shown in Fig. 2: it should be emphasized here that it is not the same estimation method for these three examples that produces the best correlation. As a general trend, however, it appears that the estimation methods perform better with the larger motors than the smaller ones, and with new motors rather than repaired ones. A far more thorough investigation will be completed by WSUCEEP to isolate these specific details.

Fig. 3 provides comparable data for the 100 hp motor with balanced windings operating for three different voltage conditions (rated balanced, 10% overvoltage balanced, and rated 5% unbalanced). As only the data for one motor is being presented here a significantly expanded scale is possible. For some purposes the correlation for all three conditions may be adequate. Again it is emphasized that the best correlation, as presented in Fig. 3, is not for the same estimation method for all three conditions. However, in general the correlation for balanced operation, and 5% unbalanced operation appear better than for the 10% overvoltage operation.

5. Conclusion

With the increased emphasis on energy/cost savings, it is important for industries to be able to conduct motor efficiency measurements in the field. In this paper, 12 in-service motor efficiency methods have been presented and tested in the Motor Systems Resource Facility at Oregon State University to assess their accuracy and precision. From these results, the most appropriate means for in-service motor efficiency estimation can be determined. Note that the required tolerance for the efficiency estimate varies with the application, i.e. for a plant operator to be within 3% would be acceptable, whereas a manufacturer or rewind shop may need the efficiency estimate to be within 1%.

In some cases the findings of the efficiency estimation studies indicate that the correlation with test data is somewhat irregular and an instrument, or generic method, may perform better for some motors than for others. This obviously presents a dilemma for users at present but indicates that the estimation techniques have potential to give adequate indication with more development or refinement. However, the need to keep the techniques simple and user friendly, for use in an industrial environment, should not be forgotten. In summary, the findings of this study reinforce the opinions of Reference [3], entitled, “Finding True Power Output Isn’t Easy”. Although the results are promising enough to indicate that reliable efficiency estimation methods can be developed.

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References

[1] A. D. Little, Inc. “Efficiency standards in commercial and industrial electric motors and equipment”, Contract CO-04-50127-00, Case #78537, Jan. 1976.

[2] United States House of Representatives, “Energy Policy Act of 1992”, report 102-1018.

[3] R. L. Nailen, “Finding true power output isn’t easy”, *Electrical Apparatus*, Feb. 1994.

[4] A. Bonnett, “An Update on AC Induction Motor Efficiency”, IEEE Trans. on IA, Vol. 30, No. 5, Sept./Oct. 1994, pp. 1362-1372.

[5] C. Becnel, J. Kilgore, E. Merrill, “Determining Motor Efficiency by Field Testing”, IEEE Trans. on IA, Vol. 23, No. 3, May/June 1987, pp. 440-443.

[6] P. Cummings, W. Bowers, W. Martiny, “Induction Motor Efficiency Test Methods”, IEEE Trans. on IA, Vol. 17, No. 3, May/June 1981, pp. 253-272.

[7] S. Chen, S. Yeh, “Opmimal Efficiency Analysis of Induction Motors Fed by Variable-Voltage and Variable-Frequency Source”, IEEE Trans. on Energy Conversion, Vol. 7, No. 3, Sept. 1992, pp. 537-543.

[8] J. Kueck, J. Gray, R. Driver, J. Hsu, “Assessment of available Methods for evaluating in-service motor efficiency”, Oak Ridge National Laboratory report, ORNL/TM-13237 (3-96).

[9] J. Hsu, J. Kueck, M. Olzewski, D. Casada, P. Otaduy, L. Tolbert, “Comparison of Induction Motor Field Efficiency Evaluation Methods”, IEEE IAS Conf. 1996.

[10] A. K. Wallace, T. E. Rollman, “High Efficiency Testing Laboratory for Motors, Drives, & Generators”, PEVD96 Conf. Proc., pp. 220-225.

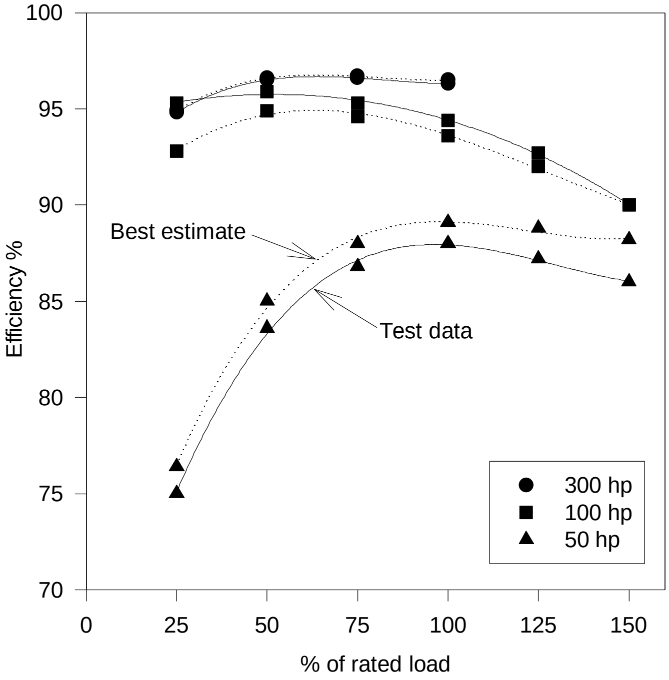

Fig. 2 Comparison of test data and best estimates for three motors at rated, balanced voltage.

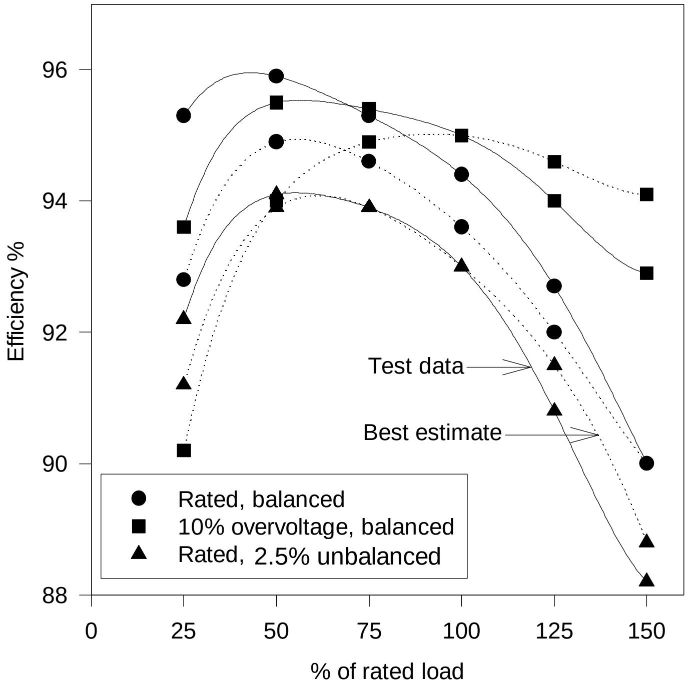

Fig. 3 Comparisons of test data and best estimates for 100 hp motor.

Appendix 1

Table 2. “Perfect” Test Motors

	Motor #1	Motor #2	Motor #3
Rating, hp	300	100	50
Speed, r/min	1780	1770	3550
Full-Load Current (A)	332	121.5	61.5
Line Volt. (V)	460	440	460
Nom. Eff. (%)	95.8	NA	NA
Nom. PF (%)	88.0	NA	NA

Appendix 2
Motor/Dynamometer Platform in MSRF Laboratory

Four Quadrant Dynamometer Converter

- Motor or Generator action
- Vector control for full load testing over entire speed range
- Programmable Torque and Speed Modes
    1. Steady state
    2. Torque vs. Speed profiles
    3. Torque vs. time profiles
    4. Speed vs. time profiles

Able to test devices up to 300 hp

- Motors
- Generators
- Converters and Controllers
- Instrumentation

Fully regenerative system

- Meets IEEE 519
- Dynamometer >95% efficient at rated load

Input power

- 750 KVA supply
- 0 to 600 VAC
- 3 phase, balanced or unbalanced

Mechanical specifications

- 300 hp
- 15,000 in-lb torque
- 0 to 4000 rpm
- Bi-directional rotation
- Full load testing over entire speed range