MOTOR EFFICIENCY DETERMINATION: FROM TESTING LABORATORY TO PLANT INSTALLATION

Alan K. Wallace, SM IEEE
Oregon State University
wallace@ece.orst.edu

Ernesto J. Wiedenbrüg, M IEEE
Baker Instrument Company
ernesto@peakpeak.com

Abstract: IEEE 112 B has become the method of choice for laboratory environment efficiency testing. However, no strategy for low level intrusion testing of field applications has been able to achieve the same level of widespread acceptance. This paper compares the goals, techniques employed and key points of interest of the standardized IEEE 112 B laboratory test with a technique using minimum level of intrusion for field testing of induction motors. Development of the latter has been completed and is currently being tested.

Key words: Induction machines, Testing, Measurement, Measurement standards, Laboratories.

I. INTRODUCTION

The IEEE 112 B Standard is currently the baseline for laboratory testing of induction motors (IMs). It was designed to accurately measure the performance of IMs vs. load. As such it provides loss segregation and other performance values including operating temperature, power factor, speed and line currents as a function of load. The method was designed to be transportable, i.e. it is possible for evaluations performed in different facilities to yield very comparable results on the same motors, as demonstrated in “round robin” series of tests.

The level of intrusion that is required for performing an IEEE 112 B test is too high for field testing, since controllable voltage sources and controllable loads are required. These conditions are very rarely obtained in the field, hence IEEE 112 B does not represent an option for industrial site testing of IMs. However, there remains a need for knowledge of operating efficiency of machinery for proper plant management and good predictive maintenance programs in an industrial environment.

In an attempt to identify suitable field efficiency estimation methods, several techniques have been tested in a study conducted by Bonneville Power Administration (BPA) and Pacific Gas and Electric (PG&E). The first part of this study involved identification and assessment of expected accuracies [1]. The second part of the project entailed an extensive testing program at the Motor Systems Resource Facility (MSRF) Oregon State University, an EPRI/BPA funded laboratory [2-3]. The testing of those efficiency estimation methods investigated the level of intrusion they required, and their achieved level of accuracies. The deficiencies identified became the driving force in developing a new efficiency estimation method, with the intention of decreasing the level of intrusion, while increasing the accuracies of the predicted efficiencies.

This paper compares methodology, instrumentation, testing procedures and the information obtained using the laboratory IEEE 112 B method of measuring the motor efficiency with a viable field method. The first part of this paper describes the differences in the required instrumentation and physical setup of both methods. In the second part, the different questions faced by a laboratory test with regard to a field test are evaluated. The third part investigates the particular methods by which the efficiency results are obtained, as well as the theoretical background on which they are based.

II. REQUIRED INSTRUMENTATION

It has been mentioned that the methods compared in this paper are suitable for different environments. On one hand, a laboratory environment with advanced and substantial instrumentation, and with controllable loads and voltage conditions is required. On the other hand, any field testing program must severely limit any disruption of production before, during and after measurements. These two implementations differ widely in their physical setup. Typical examples are shown in the following figures.

A. IEEE 112 B

Fig. 1 is a schematic of a typical configuration for a test bed designed to perform IEEE 112 B tests. A micro-ohmmeter can be used to gather the stator resistances, and a controllable voltage source is needed to set balanced operating voltages from 125% down to roughly

10% of rated conditions. The electrical input has to be measured, either with true rms voltage, current and power transducers, or via instantaneous voltage and current transducers, the signals from which then can be used to calculate real power and power factor digitally. Torque and speed measurements are needed too, since the data required to calculate the results of a 112B test is input and output based. Ambient temperature sensing is also needed.

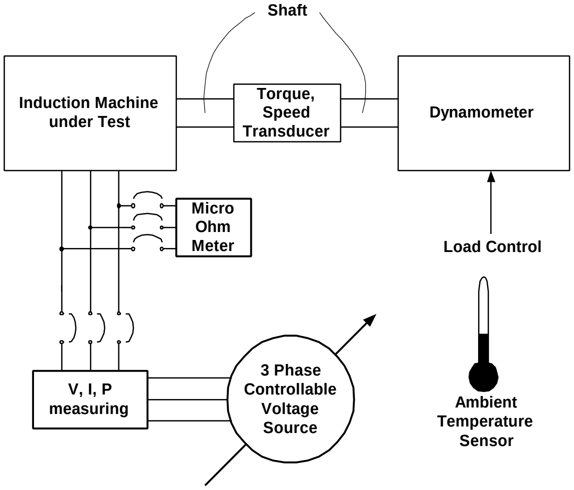

Figure 1: Physical setup of a test bed suitable for 112 B tests

B. Field efficiency testing:

Fig. 2 shows a typical configuration for the field application of a proposed efficiency estimator. Neither motor connection, nor operating condition have to be changed.

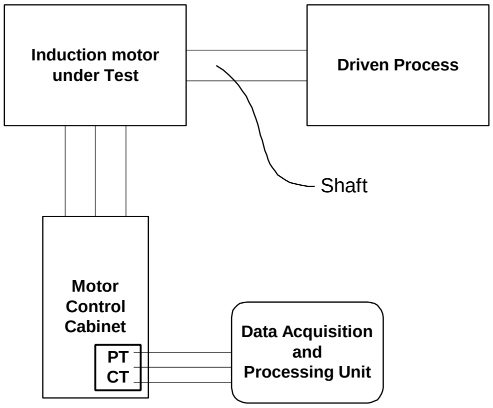

Figure 2: Typical implementation for the proposed field efficiency estimator

No sensors are required other than voltage and current monitoring, which, for cases other than in low voltage applications (smaller than 600V), should be connected on the low power side of voltage transformers (PT) and current transformers (CT). This may impose obvious restrictions for the resulting accuracy caused by these transformations. For low voltage applications, the connections are done at the motor control center, or at the terminals of the motor, depending on accessibility. No other special instrumentation is required for the physical setup, and no uncoupling is needed either. Output power is not measured as this technique is based on input power measurement and output power estimation.

III. DIFFERENCES IN SOUGHT INFORMATION

Both methods that are currently analyzed share the goal of efficiency measurement. However the difference in the environments in which the information is sought is the source of deep differences, not only in the setup and expected accuracy, but also in the set of questions that are asked by each method.

A. IEEE 112 B:

IEEE 112 B is a laboratory environment testing method, designed to have a maximum of accuracy and repeatability. According to [4], a well calibrated laboratory, with a well performed IEEE 112 B may reach overall accuracies within 1%. As with any loss segregation method, assumptions have to be made when separating the different losses. These assumptions are an integral part of the testing standard, ensuring portability. Since a laboratory is, by definition, a measurement environment, it permits both, a complex instrumentation setup and also the performance of tests at operating conditions other than the restricted options available in an industrial environment.

The method IEEE 112 B has been designed to characterize the capability of the motor under test, at rated voltage conditions and as a function of load for steady state operation. The standard describes acceptable unbalance conditions, and acceptable levels of harmonic distortions. These specifications demand a clean voltage supply, which translates into both, a best case and also a repeatable scenario. In order to achieve repeatability, all the calculations must be corrected to a base line ambient temperature, which has been chosen to be 40°C.

The tables with results from a 112B test (sample form provided as Appendix A) include the following information, printed for each of the six operating points (25%, 50%, 75%, 100%, 125% and 150%):

- Efficiency
- Power factor
- Speed

- Line currents.
- Loss segregation
- Operating stator temperature
- Total loss.
- Operating torque

The achieved information characterizes the capabilities of the tested motor, and describes the allocation of the losses into the classes of stator copper losses, core losses, friction and windage losses, rotor conductor losses and stray load losses. The loss segregation allows some insight into the tradeoffs chosen by the designer, and, in some instances, permit identification of abnormal loss distributions, which may point to possible motor damage.

B. Field efficiency testing:

The field efficiency testing method that is presented here does not share identical goals of investigation with IEEE 112B method. Since it is a field viable method, it is not a realistic option to perform a test on a motor with a similar level of intrusion and complex testing setup as is performed in a laboratory. This fact obviously translates into concessions that have to be made in terms of accuracy. Additionally, it can be proven difficult for some implementations to reach the motor that is to be tested, a submerged pump being a prime example.

The questions asked in industrial settings focus on the motor's actual performance under the conditions given that include voltage unbalances, harmonic distortions, over or under rated voltages, torque variations and actual ambient temperature conditions. Typically, the interest in whether the particular motor is actually performing according to expectations. The main issues to be identified in an industrial setting, are the following:

- Voltage condition
- Operating efficiency
- Operating mechanical power
- Operating speed
- Operating torque

1. Voltage condition:

With the knowledge of voltage condition it is possible to identify the maximum percentage of rated mechanical output, suggested by NEMA, for a particular supply unbalance [5]. Information on voltage symmetrical components should also be used. A substantial negative sequence component has a significant heating effect on the windings, reducing their life significantly. Additionally, total harmonic distortion, harmonic bar charts and crest factor information permit identifying further problems in the supply condition and allow for corrective actions, which is part of adequate preventive maintenance programs.

2. Operating efficiency:

Obviously, knowing the operating efficiency of a motor allows comparison with acceptable baseline efficiency numbers for that particular implementation. The rising cost of energy makes exchange of low performance machinery economically advantageous. Pay back periods clearly below a year are possible in many applications can now be identified.

3. Operating mechanical power:

The importance of knowing the operating power is twofold. First, knowing the power output of an IM enables comparison with its rating, allowing the identification of motor-load mismatches, which can waste large amounts of energy. Second, if field efficiency testing is performed as a part of plant maintenance, it is possible to build up historic files on performance of the load of any process. Sudden increase in requested load of any process which has not changed may point to problems with the process involved. This particular asset allows early identification of some problems in the mechanical systems driven by the motors, expanding predictive maintenance capabilities.

4. Operating speed:

The knowledge of operating speed can be used in conjunction with a history file. If the load driven did not change substantially since the last maintenance period, but the operating speed dropped, then closer attention has to be paid to the motor. It is possible that the motor rotor cage is showing degradations.

5. Operating Torque:

With the proposed method it is possible to calculate the operating torque, not only in a steady state, but also as a function of time. This feature allows for identification of electro-mechanical oscillations, which put undue stress on the mechanical components, as well as on the motor. Misalignments, bent shafts and coupling problems can be identified by experienced operators from the frequency spectrum of the torque signal.

IV. METHODS AND THEORETICAL BACKGROUND

While the IEEE 112 B method is based upon rms calculations and identification of particular losses of the motor, the field efficiency estimation method is a result of instantaneous signal processing.

A. IEEE 112 B:

1. Required Measurements

The set of measurements to be performed for a IEEE 112 B, if based on a setup similar to the one described in Fig. 1, are the following:

- Cold stator resistance
- Cold no load performance
- No load saturation characteristic
- Load operating data including hot stator resistance

The no load saturation test is performed with descending voltages. This process is performed in steps, so that there are at least ten voltage conditions available from the rated voltage conditions down to the lowest voltage, which are used to segregate friction and windage losses from core losses, as described in [6].

The load run consists of seven operating points. Standard are the uncoupled (no load), and the 25%, 50%, 75% and 100% operating points. Additionally two more operating points are required above 100% rated operation. Frequently 125% and 150% rated are chosen.

2. Data Processing

Operating temperature for the stator is calculated with the gathered data for each load point. The stator I^2r_s loss is calculated from the input currents at the different loads, and the average of the stator resistances. The power crossing the airgap is equal to the stator input power minus core loss and stator copper loss. The rotor I^2r loss is found by multiplying the power across the airgap with slip. Adding core loss, stator and rotor copper loss to friction and windage loss, results in the total conventional loss, also printed as a function of load. Stray load losses are obtained by subtracting the total conventional losses from the subtraction of input electrical power minus output mechanical power. A spreadsheet with results from a performed IEEE 112 B is shown in the Appendix A of this paper.

B. Field efficiency testing:

1. Required measurements

The measurements necessary for the field efficiency testing are very simple if compared to the IEEE 112 B method. Input currents and input voltages are the only quantities that need to be measured, but this data is required on an instantaneous basis for future calculations.

2. Data Processing

The field efficiency estimation method is based on an input output approach. Input power is calculated by the measured electrical input voltages and currents, while the mechanical output power is found by the multiplication of operating speed times torque.

Speed is found by looking at modulations which occur in the frequency spectrum of the measured input currents. These modulations are caused by inherent imperfections of the rotor, which is always going to be slightly out of round. These imperfections modulate the airgap size as a function of the speed, effectively varying the mutual and stray inductances of the equivalent circuit diagram. Reference [7] shows, in a single phase diagram model, how the speed dependent modulations of airgap size introduce side bands in the frequency domain of the stator currents, the position of which is used for very accurate speed extraction. Sidebands of typical stator currents can be seen in Fig. 3.

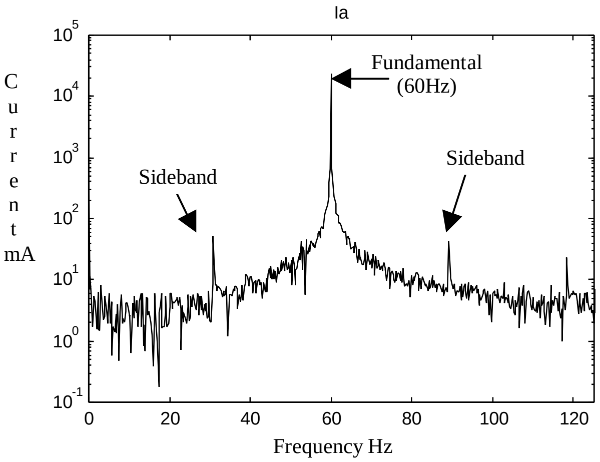

Figure 3: Stator current Spectrum of a 4-pole IM.

The torque calculations are based upon the set of equations that are commonly used in vector drive theory, in which the IM is modeled as a two axis machine in the *dq* domain. Torque can be calculated by the cross multiplication of the stator flux vector and the current vector [8].

Friction, windage and stray load losses also have to be estimated. However it has been found that these losses do not vary to a large extent from design to design, when compared among motors of similar rating and pole number. In this case, clearly, concessions are made with regards of accuracy when compared with the IEEE 112 B method. However, the accuracies achieved by this field method clearly exceed the operator's needs, permitting proper identification of the subjects of interest in the field previously mentioned. Extensive tests performed on a laboratory environment showed that the employed method of speed extraction reaches consistent accuracies within 1r/min, while the estimated torque predictions commonly achieve accuracies of 2% or better for 50% or higher loading. However, at lower loads such as 25%, the inaccuracies double.

Finally, if it was felt that more accurate measurements or loss segregation were required than could be provided by these field methods, then the only option available would be to send the motor to a laboratory, to perform an IEEE 112 B test on it.

V. CONCLUSIONS AND FUTURE WORK

This paper presents the differences when comparing laboratory testing of IMs to state of the art field testing. It is important to point out that the questions of interest for field personnel differ sharply from the questions asked to laboratories, and so do the requested accuracies of the results obtained.

While the laboratory environment is faced with the challenge of achieving supreme accuracies and transportable data, the main challenge in the field resides in balancing the tradeoff between low intrusion measurements and achievable accuracies within that particular premise. At the same time, while the laboratory environment seeks to quantify the capabilities of a particular motor, the field is interested in the performance of that motor under particular given conditions. Consequently the methods tend to complement each other's scope.

Laboratory testing of the presented method has been performed at the MSRF, and the obtained data is currently being evaluated. It is planned to publish these results, comparing with the results obtained in the report [3], which investigated the efficiency estimation methods identified in [1].

Alpha and beta testing sites are currently being identified for testing the field efficiency estimator approach that has been presented in this paper. The results obtained from field testing of this method will be published as soon as the data is available.

VI. REFERENCES:

[1] J. S. Hsu, J. D. Kueck, M. Olszewski, D. A. Casada, P. J. Otaduy, L. M. Tolbert, *'Comparison of Induction Motor Field Efficiency Evaluation Methods'*, IEEE IAS Proceedings 1996 vol. 1, pp. 703-712.

[2] A. Wallace, A. von Jouanne, E. Wiedenbrüg, J. Douglass, C. Wohlgemuth, G. Wainwright, *'A Laboratory Assessment of In-Service Motor Efficiency Testing Methods'*, IEEE IEMDC Proceedings 1997, WC 1.7-1.

[3] John G. Douglass, *'Efficacy of Methods for Estimating In-Service Motor Efficiency'*, Washington State University, Cooperative Extension Energy Program, June 1997.

[4] EASA Technical Manual, © 1996, pp. 8-15, 8-16.

[5] NEMA *'Motors and Generators'*, MG 1, Part 14, page 8.

[6] IEEE *'Standard Test Procedure for Polyphase Induction Motors and Generators'*, IEEE Std 112.

[7] Ernesto J. Wiedenbrüg, Alan K. Wallace, *'Steady State Speed Extraction for Induction Machines Analyzing Instantaneous Stator Current Signatures'*, IEEE PES, Electrical Manufacturing Coil Winding Association 1998.

[8] Krause, Wasynczuk, Sudhoff, *'Analysis of Electrical Machinery'*, IEEE Press, New York, 1995, pp. 169-177.

APPENDIX A:

Type: Design: Frame: hp:
Freq: Volts: Synch. r/min: Serial No:
Deg C Temp Rise: Model No: Phase:

Stator Winding Resistance Between Terminals				@		deg C	
Specified Temperature for Resistance Correction (ts) =				deg C			
Item	Load, in % rated						
1	Ambient Temperature, in C						
2	(tt) Stator Winding Temperature, in C						
3	Slip, in /min						
4	Speed, in r/min						
5	Line-to-Line Voltage, in V						
6	Line Current, in A						
7	Stator Power, in W						
8	Core Loss, in W						
9	Stator I^2*R Loss, In W, at (tt) C						
10	Power Across Air Gap, in W						
11	Rotor I^2*R Loss, in W						
12	Friction and Windage Loss, in W						
13	Total Conventional Loss, in W						
14	Torque, in Nm						
15	Dynamometer Correction, in Nm						
16	Corrected Torque, in Nm						
17	Shaft Power, in W						
18	Apparent Total Loss, in W						
19	Stray-Load Loss, in W						
Int.	Slope	Corr. Factor				Del. Pt.	
20	Stator I^2*R Loss, in W, at (ts) C						
21	Corrected Power Across Air Gap, in W						
22	Corrected Slip, in r/min						
23	Corrected Speed, in r/min						
24	Rotor I^2*R Loss, in W, at (ts) C						
25	Corrected Stray-Load Loss, in W						
26	Corrected Total Loss, in W						
27	Corrected Shaft Power, in W						
28	Shaft Power, in hp						
29	Efficiency, in %						
30	Power Factor, in %						

Summary of Characteristics

Load, in % of rated						
Power Factor, in %						
Efficiency, in %						
Speed, in r/min						
Line Current, in A						