Analysing Different Efficiency Evaluation Methods For Induction Motors

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Abstract: **Induction motors are the most commonly used machine in industry because of their robust nature. Energy management of induction motor is relevant as they form the bulk segment in industry. So online monitoring and efficiency estimation of the existing induction motors play a vital role in energy management. The air gap torque (AGT) method is a well established technique for determining the efficiency of an induction motor, since it is known to be highly accurate Unlike testing motor efficiency in a laboratory, certain methods given in IEEE Standard 112 cannot be used for motor efficiency evaluations in the field. For example, it is difficult to load a motor in the field with a dynamometer when the motor is already coupled to driven equipment. The motor efficiency field evaluation faces a different environment from that for which IEEE Standard 112 is chiefly written. A field evaluation method consists of one or several basic methods. This paper separates and compares the basic methods according to their physical natures.**

Keywords: **Accuracy, comparison, efficiency, field evaluation, IEEE Standard 112, induction motors, methods.**

I. INTRODUCTION

Industry remains the biggest consumer of commercial energy and its share in the overall consumption is 49%. Induction motors are widely used in industry as essential prime movers. They are commonly used in manufacturing, transportation, petrochemical, mining, power systems and so on due to their reliability, simplicity of construction and high overload capability.

There have been many articles concerning energy efficiency of induction motors [1]. In general, an energy efficiency improvement program includes development of a motor management plan that focuses on development of a plant motor inventory and an evaluation of motor performance for large or critical motors. The evaluation of motors focuses on the operating efficiency and motor load to identify energy efficiency gains and possible reliability improvements. This requires a reliable method for assessing motor performance in the field.

There are many methods pertinent to field efficiency evaluation in the literature, and new methods are appearing every year. and is available from the Bonneville Power Administration Printing Office.

A field evaluation method can consist of a single basic method or can be built using a combination of different basic methods. This paper separates and compares the basic methods according to their theoretical basis and error sources. This may help field engineers select or establish an efficiency evaluation method suited to their need.

The basic methods are as follows:
1. nameplate method;
2. slip method;
3. current method;
4. statistical method;
5. equivalent circuit method;
6. segregated loss method;
7. airgap torque method;
8. shaft torque method.

An example illustrating a combination of different basic methods is a modified version of the slip method established in conjunction with nameplate information and built-in statistical data. If applied properly, this combined effort normally improves the accuracy of the efficiency evaluation for a targeted group of motors. Regardless of how complex the combination is, the nature of each basic method affects the overall accuracy of the combination.

All methods calculate efficiency according to the definition of:

$$\text{Efficiency} = \frac{(\text{Shaft output power})}{(\text{Electrical input power to drive system})}$$

(1)

The shaft output power is the input power minus the losses. How to assess losses and evaluate output power gives rise to fundamental differences among the various methods. Consequently, the accuracies of methods are different.

The degree of intrusiveness of a field evaluation method is determined by what data are required to be measured in the field and the difficulty of performing the measurements. One or more of the following measurements may be involved:

1. nameplate reading;
2. speed measured by optotachometer;
3. currents measured by clamp-on transducer;
4. voltages measurement;
5. input power measurement;
6. stator winding resistance reading;
7. winding temperature data;
8. no-load data measured with uncoupled shaft;
9. shaft torque measurement.

The data may be acquired in the format of rms meter readings or digitally sampled waveforms.

The cost associated with the labor, material, and downtime for implementing safety requirements for data collections can be used as a gauge to weigh intrusiveness. For example, using an optical tachometer for rotating speed measurement normally has a lower intrusion level than a voltage measurement, since it requires making connections in a terminal box. Intrusiveness can vary from plant to plant. For the same example, if the voltage transducer is permanently installed and wired to proper connectors, the intrusiveness is significantly lower.

Planning may also affect intrusiveness. If a decoupled noload test is required and the motor power supply is available during scheduled downtime, it may be possible to conduct this kind of test without affecting production. If, however, the data are to be taken during production time, the cost and intrusion level would be very high.

II. PHYSICAL NATURES OF BASIC METHODS

In this section, the physical basis of each basic method is described in terms of how the efficiency is obtained and of the potential errors associated with it.

A. Nameplate Method

The least intrusive field evaluation method is to obtain motor information from the nameplate. In this method, it is assumed that the efficiency of the motor is constant and equal to the nameplate value. This works best when the efficiency–load curve is fairly flat, so that the full-load efficiency is applicable for most load conditions.

The typical load factor of industrial motors is around 75% [19]. Using typical efficiency-versus-load curves for motors having various poles and horsepower ratings, we can evaluate the potential accuracy of the nameplate method. As indicated
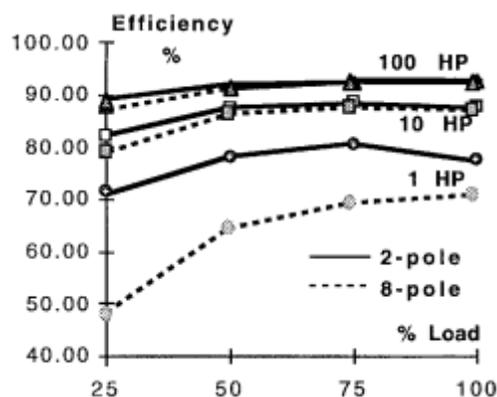

Fig. 1.Typical efficiency-versus-load curves.

In Fig. 1, the efficiency is not a strong function of load for a two-pole motor between 50% and 100% of load. However, the efficiency of an eight-pole, 1-hp motor shows a marked decline over that load range. Hence, the nameplate method may be applicable for some motors, but could result in substantial inaccuracies for other motor types.

With this nameplate method, three additional problems may occur. First, the nameplate data may be given according to a method other than IEEE Standard 112 Method B. Second, the motor may have been rewound. Third, the field environment pertinent to the voltage unbalance and harmonics content may be different from that for which the nameplate data is derived.

Certain engineers suggest that, after each rewinding to the same horsepower and same number of poles, a two percentage points reduction of efficiency should be considered. However, a different opinion indicates that the efficiency should not be reduced if the rewinding follows Electrical Apparatus Service Association (EASA) standards.

The field environment pertinent to the voltage unbalance and harmonics content is commonly worse than that from which the nameplate data are derived.

The worst situation for a field efficiency evaluation using the nameplate method is that having a less than 10-hp lowspeed rewound motor that was not repaired according to EASA Standards. The motor has data stamped on the nameplate that is not given according to IEEE Standard 112 Method B and is operated under a polluted supply (voltage unbalance or harmonic distortion). The efficiency can easily be off ten percentage points from the nameplate efficiency. However, the bottom line is that a nameplate method is better than no field evaluation at all.

B. Slip Method

This method presumes that the percentage of load is closely proportional to the percentage of the ratio of measured slip to full-load slip. The shaft output power is, thus, approximated using the following relationship:

$$(\text{Shaft Output Power}) = \frac{(\text{Measured Slip})}{(\text{Rated Slip})}(\text{Rated Output Power})$$

$$(2)$$

Where slip is a function of motor speed given by the ratio of the difference of synchronous speed and motor speed to the synchronous speed. Motor speed can be measured by an optical tachometer, which has a low intrusion level. Input power must also be measured,which has a higher degree of intrusion.

The slip method can be an improvement over a pure nameplate method, especially when the motor-efficiency-versusload curve is not flat. Any method that uses slip to estimate percentage of load is related to the slip method.

Once the shaft output power is known, one may use a typical efficiency-versus-load curve specifically for standard-, high-, or in-between-efficiency motors, similar to the one shown in Fig. 1, to assess efficiency. Alternatively, one may combine the basic slip method with other additional measurements, such as the input power, which has a higher degree of intrusion, to obtain efficiency through (1).

NEMA MG-1 Section 12.46 [14] states that variation from the nameplate speed of ac integral horsepower induction motors shall not exceed 20% of the difference between synchronous speed and rated speed when measured at rated voltage, frequency, and load and with an $^\square$ ambient temperature of 25C. This means that the nameplate slip can be 20% inaccurate when the motor is operating in the field, thus introducing significant inaccuracies in (2).

The no-load speed of induction motors is always close to the synchronous speed. Subsequently, the projection of a light load through the basic slip method is relatively more accurate than the projection of a heavy load.

C. Current Method

This method presumes that the percentage of load is closely proportional to the percentage of the ratio of measured current to full-load current. The shaft output power is, thus, approximated using the following relationship:

$$(\text{Shaft Output Power}) = \frac{I}{I_{fl}} \cdot (\text{Rated Output Power})$$

(4)

Where I_{fl} is the nameplate full load current and I is the measured current.

Fig. 2(a) shows a circle diagram of an induction motor. For small integral horsepower motors the no-load current may not be greatly reduced from the full-load current. Fig. 2(b) shows a source of error when (3) is used to assess the shaft output power; the assumed load-versus-current curve used by (3) is further apart from the actual curve at light loads. This is opposite to what the basic slip method is relatively good for. The load is normally overestimated.

The expression of shaft output power defined by (4) requires that the no-load current I_{nl} be known. This may increase the intrusiveness substantially when a no-load test is required:

$$(\text{Shaft Output Power}) = \frac{(I - I_{nl})}{(I_{fl} - I_{nl})} (\text{Rated Output Power})$$

(4)

Fig. 3 shows that the load evaluation is normally underestimated when (4) is used. The average of the two approaches of (3) and (4) may give a more accurate shaft output power.

NEMA MG-1, Section 12.47, states that, when operated at rated voltage, rated frequency, and rated horsepower output, the input in amperes shall not vary from the nameplate value by more than 10%. This is another source of errors for the current methods.

Motor current measured by a clamp-on probe corresponds to a relatively low level of intrusiveness. The insulation of motor leads and terminals is not disturbed. The measured current is used to estimate the load of a motor. The simple current method does not require a no-load current value.

Just as with the slip method, to obtain efficiency one will have to either use typical efficiency-versus-load curves or measure input power.

D. Statistical Method

Empirical equations are set up to use minimal numbers of measured data for input power and efficiency estimations. Usually, application of this method is restricted to the group of motors for which empirical equations were derived.

If the statistical results are not used for the group of motors that the empirical equations are based on, significant errors in the efficiency estimation are likely.

The statistical results can be quite different for the same variable. A good example is the stray load loss estimation. NEMA MG1 [14], paragraph 20.52, states that, if stray load loss is not measured, the value of stray load loss at rated load shall be assumed to be 1.2% of the rated output for motors rated less than 2500 hp and 0.9% for motors rated 2500 hp and greater. IEEE Standard 112 [10, Sec. 5.4.4], gives different assumed stray load loss values for motors rated less than 2500 hp. They are as follows:

1) 1-125hp=1.8%

2) 126–500hp = 1.5%; 3) 501–2499 hp = 1.2%.

(5)

Additionally, certain non-U.S. standards use 0.5% of rated output as the stray load loss at rated load.

The statistical approach is commonly used with other basic methods. For instance, Ontario Hydro 1 has published a segregated loss method that simplifies IEEE Standard 112 Method E1 much further. As pointed out in this study, it is not always possible to interrupt a process long enough to decouple a motor from its load and conduct a no-load test. The study suggests that one way around this obstacle is to assume a value for the combined windage, friction, and core losses. This method suggests that these combined losses be set to 3.5% of input rated power. The stray load losses are estimated based on the IEEE Standard 112 standard assumed values.

This method can be simplified even further by using assumed values for rated power factor. Approximations can also be made for the temperature rise of the winding, and the winding resistance can even be estimated by measuring the line-to-line resistance taken from the circuit breaker and subtracting the estimated cable resistance. The only other measurements required are power into the motor and motor speed.

E. Equivalent Circuit Method

Efficiency assessed through an equivalent circuit method is based on the impedance values of an equivalent circuit, shown in Fig. 4. The circuit represents the fundamental portion of a complex equivalent circuit shown by Alger in [5, Fig. 9.6]. The six impedances are stator resistance r_1, stator leakage reactance x_1, magnetizing reactance x_m, core-loss resistance r_o, rotor leakage reactance x_2, and rotor resistance r_2. The slip affects the load of the equivalent circuit.

The advantage of the equivalent circuit method is that the performance of a motor can be predicted at any load when the impedance values are known. On the other hand, the impedance values can change a great deal when the motor speed varies between standstill and no load, due to deep bar
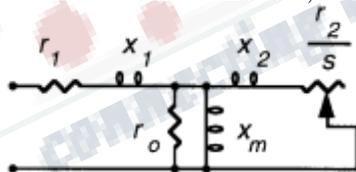

Fig. 4.A six-impedance equivalent circuit. Effects and magnetic saturation. There are different approaches for obtaining the impedance values.

When the six-impedance equivalent circuit is used, all the losses other than the friction and windage loss that are not represented by the stator copper, rotor copper, and no-load core-loss resistances, are grouped together in a collective loss named stray-load loss.

The IEEE Standard 112 Method F is an example of an equivalent circuit method. It is not a useful field test for efficiency. As is true for Method E, its additional removed-rotor and reverse-rotation tests to directly measure the

fundamental frequency and high-frequency stray-load losses are too invasive and user unfriendly. Therefore, we will restrict our attention to Method F1.

The basic Method F1 requires an impedance test and the complete no-load variable-voltage test. The version of Method F1 believed more suited to field use requires volts, watts, amperes, slip, stator winding temperature, or stator winding resistance to be measured at two values of voltage while operating at no load. In one case, measurements are made at rated voltage while operating at no load. In the other case, measurements are made while operating at no load, with voltage reduced until slip is equal to that obtained at the normal operating load. Once these measurements are made, an iterative procedure is used to determine the parameters of the equivalent circuit.. Although this method is expected to be quite accurate, it is still considered to be too intrusive for routine field use.

A no-load test provides data for determination of magnetizing reactance and core, friction, and windage loss resistance. A low-frequency locked-rotor test gives values for stator and rotor reactances and resistances. Simplified methods without conducting locked-rotor and no-load tests are possible.

Slip is an important parameter for the load calculation. The performance of an electric motor, at least with regard to efficiency, can be calculated from its equivalent electric circuit. Equivalent circuit methods permit one to compute estimates of the efficiency of the motor when it is operating at loads other than those at which measurements were made.

Two low-intrusion approaches can be followed to determine the values of the augmented seven components in the equivalent circuit. Both rely on the motor's nameplate data and NEMA standards. The first approach requires the measurement of stator resistance (r_1) at rated load temperature. The second approach estimates r_1 using generic relationships based on the number of poles, horsepower rating, and rated line voltage of the motor. The second approach does not require any measurements specific to the motor of interest; all motors with the same nameplate data will be found to have the same equivalent circuit. Consequently, their efficiency in the field will be estimated differently only if their speed is different.

Another example of the equivalent circuit method for field efficiency evaluations is "Ontario Hydro's Simplified Method F1." It is described in [1].

F. Segregated Loss Method

The segregated loss method estimates the magnitudes of the five losses, namely, stator copper loss, rotor copper loss, core loss, stray-load loss, and friction and wind age loss. The shaft output power is the input power minus the losses. Some of the methods in this category are quite complicated and intrusive, while others rely on empirical factors to estimate the losses.

There are quite a number of available methods that are based on the evaluations of the five losses. One good example is the IEEE Standard 112 Method E. A literal interpretation of Method E is not a useful field test for efficiency. Its additional removed-rotor and reverse-rotation tests used to directly measure the fundamental-frequency and high-frequency strayload losses are not practical for field efficiency evaluation. Therefore, attention will be restricted to Method E1. Even a literal interpretation of Method E1 would be impractical for field use, because it requires a variable load and a variablevoltage power supply. Method E1 specifies an assumed value for stray-load losses at rated load. The repeatability of Method E1 is improved by requiring the adjustment of all resistance and slip measurements to a specified temperature.

However, in many available methods, the principle of segregating motor losses into five losses remains the same as that used in Method E1. Statistical methods are always used in conjunction with the segregated loss method to simplify the procedures required by Method E1. Once the voltage, current, power, and speed data have been collected, the algorithms provided in IEEE Standard 112 are used to calculate the individual component losses.

Commercial devices are available for measuring the efficiency of installed motors based on a modified version of IEEE Standard 112 Method E1. These also require a measurement of power in, winding resistance, and speed. There are also various empirical methods that use approximations of the various losses to develop an overall loss estimate.

G. Airgap Torque Method

The airgap torque method uses the product of airgap torque and rotor speed as the airgap mechanical power for efficiency evaluation. The more sophisticated airgap torque method developed at ORNL uses current and voltage waveforms as input data. The waveform data acquired can also be used for defect detections [7] on cracked rotor bars, stator turn-to-turn shorts, and for evaluation of harmonic contents of voltage and current. The efficiency is calculated as follows.

The input power of a three-phase induction motor is the average summation of products of the instantaneous phase voltages v_a, v_b, v_c and phase currents $i_a, i_b,$ and i_c:

$$\text{Power} = \frac{\int_0^{\text{period}} (v_a i_a + v_b i_b + v_c i_c)\, dt}{(\text{period})}. \quad (5)$$

The airgap torque equation is

Where is the line

$$\text{Torque } [\text{N} \cdot \text{m}] = \frac{P}{2 \cdot \sqrt{3}}$$

$$\cdot \left\{ \begin{array}{l} (i_A - i_B) \cdot \int [v_{CA} - R(i_C - i_A)]\, dt \\ -(i_C - i_A) \cdot \int [v_{AB} - R(i_A - i_B)]\, dt \end{array} \right\} \quad (6)$$

P is the number of poles, i_A, I_B, and i_C currents, and R is half of the line-to-line resistance value. The efficiency yields

$$\eta = \frac{\left[\begin{array}{l} (\text{Air gap torque}) \cdot 2\pi \cdot \frac{(rpm)}{60} \\ -(\text{Friction windage loss}) - (\text{stray loss}) \end{array} \right]}{(\text{Input power})}. \quad (7)$$

When the balanced power supply contains negligible harmonics, various modified versions based on Method E1 of IEEE Standard 112 [10] can be quite accurate for conventional induction motor field efficiency evaluations. The waveforms acquired by the airgap torque method may be used to calculate the power and harmonic content in detail. However, this is not the most important difference between the airgap torque method and Method E. The fundamental difference between these two methods is as follows.

Some engineers may have an unrealistic expectation concerning Method E and suggest that, under any load situation of a motor, the losses produced by the negative fields associated with unbalanced supply voltages and harmonics are included in the no-load loss. These negative sequence fields are not changed at either full load or no load, because the speed difference between full load and no load is small. Consequently, the slip is practically unchanged, and the negative sequence impedance, as well as the negative sequence currents, remain the same. Under any load, the loss associated with the negative sequence fields is the same as this loss at no load.

This expectation is not correct for motors operating in the field. In the real world, the supply has an impedance. The motor terminal voltages do change some as the load varies. Table II shows the tested fundamental-frequency voltages and currents of the positive- and negative-sequence components under an unbalanced supply. When the load goes up and further upsets the voltage balance, the negative-sequence voltage increases. The varied ratios of negative-sequence voltages to currents indicate that the negative sequence impedance is not a constant. It goes up when the negative-sequence current goes down. For a small negative-sequence current, a higher negative-sequence impedance occurs. This is caused by the no saturated tips of the rotor teeth. The tested data clearly show that the no-load negative-sequence current of 4.2 A is significantly smaller than the negative-sequence current of 13.7 A at full load. The no-

load loss does not cover most of the negative-sequence losses when the motor is loaded.

In Method E, the input power is used as the base to subtract various losses for the output power. The load-dependent negative-sequence losses that are not included in the no-load loss increase the input power. Subsequently, the output power is evaluated to be higher. On the contrary, the air gap torque method uses the air gap torque power, not the input power, as the starting point of loss subtraction for the output power evaluation.

The losses associated with negative-sequence currents are calculated for each load. The air gap torque method recognizes the sign difference between the torque and the corresponding input power. For example, the input power of the fundamental negative-sequence voltage and currents is positive, but the air gap torque is negative. After the air gap torque power is found, one subtracts the estimated stray-load loss and the no-load air gap torque power that includes the friction and wind age loss and the core loss to find the output power.

For three-phase four-lead motors, two line voltages and three line currents need to be measured for airgap torque calculations [2]. For three-phase three-lead motors, waveforms of two line voltages and two line currents are required.

TABLE I
EFFICIENCIES OF DIFFERENT METHODS

	A	B	C	D	E	F	G
1	Output Power	Load Test	Current Method	New Current Method	Modified Current Method	Slip Method	Air Gap Torque Method
2	0	0	0	0	0	0	0
3	867.31	24.8	33.9	13.67	21.78	72.46	29.06
4	1559.39	80.38	52.3	45.3	50.8	82.91	79.74
5	1921.6	85.7	50.02	54.9	52.86	76.6	82.76
6	2051.01	85.45	54.02	56.91	55.16	75.96	82.64
7	2147.06	82.61	57.16	56.8	56.98	74.24	81.25
8	2507.78	85.8	55.23	60.69	57.95	69.78	84.29
9	2697.08	87.5	66.73	67.26	66.99	73.12	86.79
10	2854.92	90.34	67.05	70.22	68.63	78.05	88.36
11	3027.76	91.2	71.49	74.17	71.8	80.75	90.54
12	3205.07	88.8	72.97	75.05	74.4	76.6	87.25
13	3425.74	90.1	74.89	78.15	77.12	76.2	88.18
14	3505.66	88.5	75.06	84.45	82.77	83.69	86.88
15							

H. Shaft Torque Method

Regardless of how sophisticated a method is, it remains difficult to assess all the stray-load losses accurately in the field. The most straightforward method is to measure the output power directly from the shaft, without any need to calculate losses. The shaft torque method offers the most accurate field efficiency evaluation method. It is also highly intrusive.

A custom-built torque coupling may be used to replace the existing coupling. Torque signals can be obtained through slip rings. Laser and telemetry technologies may also be used without going through slip rings for signal noise reductions. Many different ways have been proposed (see the reference section of [1]). The accuracy of this method depends on the
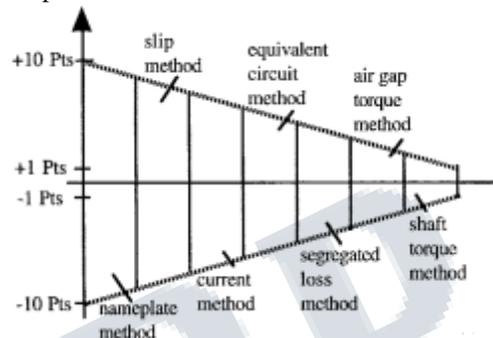

Fig. 5. Efficiency anticipated potential accuracies versus basic elements for loads between full and half load. (Additional equipment accuracy tolerances need to be added to those shown in this figure.)

quality of the torque sensors, the signal noise, and the shaft alignment of the motor and its load. Downtime is required for preparing and replacing the shaft torque coupling.
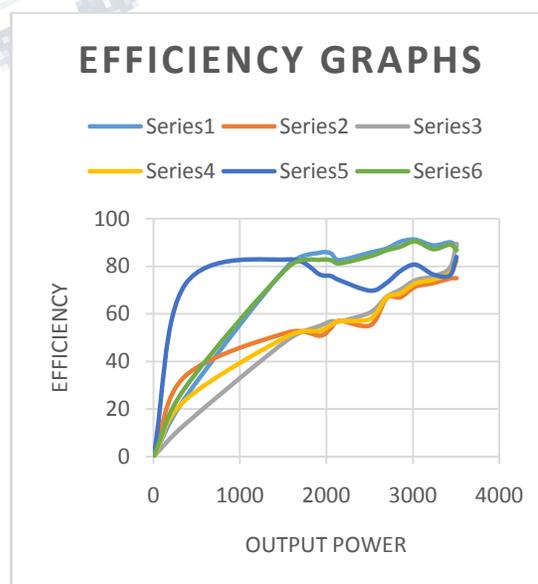
The Nameplate Equivalent Circuit Method, which has a very low level of intrusiveness (only a measurement of speed is required), but relies on statistical data heavily, gives good results for loads above 50%. It is suitable for a targeted group of motors.

Series 1: load test method
Series 2: current method

Series 3: new current method
Series 4: modified current method
Series 5: slip method
Series 6: air gap torque method

III. CONCLUSIONS

1) A field efficiency evaluation method can be built on different basic methods, such as equivalent circuit with empirical parameters. This combined approach normally improves the accuracy and reduces intrusiveness of efficiency evaluation for a targeted group of motors. Regardless how complex the combination is, the nature of each basic method affects the combination.

2) This paper compares the physical natures (i.e., theoretical bases and error sources) of basic methods contained in various available field efficiency evaluation methods.

3) The basic methods are nameplate method, slip method, current method, statistical method, segregated loss method, equivalent circuit method, airgap torque method, and shaft torque method.

4) The intrusiveness or cost and accuracy are the major considerations for selecting a field efficiency evaluation method. Users want a lower intrusive method under a given accuracy requirement.

5) The least intrusive and least accurate method is the nameplate method. The most intrusive and most accurate basic method is the shaft torque method. Accuracy evaluation in this paper is based on published opinions rather than on rigorous statistical exercises.

6) The average load factor of motors operating in the field is around 75%. Reexamination of the chosen method and the measurements should be conducted when the difference between the evaluated efficiency and the nameplate efficiency is greater than ten percentage points.

7) The sophisticated version of the airgap torque method can have a certain advantage over the segregated loss method when the unbalance and harmonic content of the supply system are not negligible.

8) The shaft torque method does not rely on any assumed loss, such as the stray-load loss, but is very intrusive.

9) Statistical approaches can be very effective. A good example is the Nameplate Equivalent Circuit Method. For a targeted group of motors, it provides a significant improvement in accuracy over the slip method, with no increase in intrusiveness.

10) Statistical approaches can also be damaging when they are not used for the targeted group of motors. A good example is the poor result of slip and current methods shown in Fig. 6.

11) We hope that this paper may help field engineers to select or to establish a proper efficiency evaluation method by understanding the different basic methods, their theoretical foundations, and error sources.

REFERENCES

[1] J. D. Kueck, M. Olszewski, D. A. Casada, J. S. Hsu, P. J. Otaduy, and L. M. Tolbert, "Assessment of methods for estimating motor efficiency and load under field conditions," Lockheed Martin Energy Research Corp., Oak Ridge, TN, Rep. ORNL/TM-13165, Jan. 1996.

[2] J. S. Hsu and P. L. Sorenson, "Field assessment of induction motor efficiency through air-gap torque," *IEEE Trans. Energy Conversion,* vol. 11, pp. 489–494, Sept. 1996.

[3] *High Efficiency Motor Selection Handbook,* Bonneville Power Administration (BPA), Portland, OR, 1990, p. 21.

[4] W. D. Biesemeyer and J. Jowett, "Facts and fiction of HVAC motor measuring for energy savings," Arizona Department of Commerce, Energy Office, Phoenix, AZ, Biesemeyer #116, 1994.

[5] P. L. Alger, *The Nature of Induction Machines.* New York: Gordon and Breach, 1965.

[6] J. S. Hsu, H. H. Woodson, and W. F. Weldon, "Possible errors in measurement of air-gap torque pulsations of induction motors," *IEEE Trans. Energy Conversion,* vol. 7, pp. 202–208, Mar. 1992.

[7] J. S. Hsu, "Monitoring of defects in induction motors through air-gap torque observation," *IEEE Trans. Ind. Applicat.,* vol. 31, pp. 1016–1021, Sept./Oct. 1995.

[8] C. L. Becnel *et al.,* "Determining motor efficiency by field testing," *IEEE Trans. Ind. Applicat.,* vol. IA-23, pp. 440–443, May/June 1987.

[9] A. H. Bonnett, "An update on ac induction motor efficiency," *IEEE Trans. Ind. Applicat.,* vol. 30, pp. 1362–1372, Sept./Oct. 1994.

[10] *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators,* IEEE Standard 112-1991, 1991.

[11] H. E. Jordan and A. Gattozzi, "Efficiency Testing of Induction Machines," in *Conf. Rec. IEEE-IAS Annu. Meeting,* Cleveland, OH, Sept. 30–Oct. 5, 1979, pp. 284–289.

[12] R. E. Oesterlei, "Motor efficiency test methods—Apple and oranges?," *Power Transmission Design,* vol. 22, no. 5, pp. 41–43, May 1980.

[13] P. G. Cummings, W. D. Bowers, and W. J. Martiny, "Induction motor efficiency test methods," *IEEE Trans. Ind. Applicat.*, vol. IA-17, pp. 253–272, May/June 1981.

[14] *NEMA Standards Publication No. MG1,* National Electrical Manufacturers Association (NEMA), Washington, D.C., 1993.

[15] *Motor Master, Version 2.1.,* 98504-3165.K, Washington State Energy Office, Olympia, WA.

[16] R. L. Nailen, "Can field tests prove motor efficiency?," in *Conf. Rec. IEEE 1&CPS Tech. Conf.,* Baltimore, MD, May 2–5, 1988, pp. 110–116.

[17] J. S. Hsu, P. J. Otaduy, and J. D. Kueck, "Efficiency and reliability assessments of retrofitted high-efficiency motors," in *Conf. Rec. IEEEIAS Annu. Meeting,* Lake Buena Vista, FL, Oct. 8–12, 1995, pp. 2745–2751.

[18] J. S. Hsu and B. P. Scoggins, "Field test of motor efficiency and load changes through air-gap torque," *IEEE Trans. Energy Conversion,* vol. 10, pp. 471–477, Sept. 1995.

[19] "Understanding AC motor efficiency," Electrical Apparatus Service Association, St. Louis, MO.

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