International Standards for the Induction Motor Efficiency Evaluation: A Critical Analysis of the Stray-Load Loss Determination

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***Abstract*—Motor efficiency has to be measured or calculated in accordance with international standards. The most important standards are the IEEE 112-B, IEC 34-2, and JEC 3 . In this paper, a comparison of the measurement procedures defined by these international standards is reported, together with some comments on the prescribed methodologies. The comparison is based on experimental results obtained by tests on four general-purpose three-phase induction motors. The stray-load loss measurement represents a critical key for the correct evaluation of the motor efficiency. For this reason, a critical analysis of this type of losses has been performed. In particular, in order to understand which are the most critical quantities that influence their evaluation, the stray-load loss sensitivity to the measurement errors is analyzed. In the final part of the paper the temperature influence, on the conventional iron losses, is experimentally analyzed. The performed tests show that the temperature difference between the no-load test and the motor real operative conditions is not negligible.**

***Index Terms*—Efficiency, induction motors, international standards, stray-load losses.**

I. Introduction

IN THE ACTUAL electric energy market the energy saving policies are more and more important. In fact, cost and availability of the electric energy can vary in a complex manner. For these reasons, electric energy consumers are interested in using apparatuses with high efficiencies in order to reduce their electric consumption. It is important to observe that the induction motors can be considered as larger users of electrical energy. In the European Union, the electric motors used in the industrial field typically consume 60%–70% of the total absorbed electrical energy. In the commercial sector, this percentage is up to 35%. More information can be found in [1]. For these reasons, laws or protocols (such as the EPAC in the U.S. and the European Union and the CEMEP committee agreement in Europe [2], [3]) have been promulgated in order to define the efficiency class of the motors. For the industrial induction motors the European CEMEP protocol defines the following efficiency classes:

- Eff1 class: "high efficiency" motors;
- Eff2 class: "energy efficiency" motors;

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TABLE I
European CEMEP Efficiency Lower Limits

Rated power	4 kW	7.5 kW	11 kW	15 kW
Eff1 lower limit	88.3	90.1	91.0	91.8
Eff2 lower limit	84.2	87.0	88.4	89.4
Eff3 typical value	80.0	83.0	85.0	87.0

- Eff3 class: "standard efficiency" motors (motors now in production).

As an example, the Eff1 and Eff2, efficiency lower limits for the induction motors used in the performed tests are reported in Table I.

The producers provide the motor efficiency data on the basis of measurements and calculation procedures prescribed by international standards. In this paper, IEEE 112-B, IEC 34-2, and JEC 37 international standards [4], [5] are considered in order to evaluate the efficiency of four three-phase four-pole 380-V general-purpose induction motors of the same series. These standards recommend different measurement methods and calculation procedures, in particular, for the stray-load loss determination and the temperature corrections of the copper losses. As a consequence, it is possible that a motor can be labeled with different rated efficiency depending on the adopted international standard.

II. Motor Efficiency

The efficiency of an electric motor represents the machine energetic behavior during the conversion of the electric power in mechanical power. It is defined as

$$\eta = \frac{P_{\mathrm{Mechanical}}}{P_{\mathrm{Electrical}}} = \frac{P_{\mathrm{Mechanical}}}{P_{\mathrm{Mechanical}} + \sum \mathrm{Losses}} \qquad (1)$$

where $P_{\mathrm{Mechanical}}$ represents the output power at the motor shaft, and $P_{\mathrm{Electrical}}$ is the electric power absorbed from the main supply. The difference of these two powers is the total motor losses $\sum$ Losses. The $\sum$ Losses can be subdivided into

- stator and rotor Joule losses (P_{JS} and P_{JR});
- iron losses (P_{Iron});
- mechanical losses (P_{Mec});
- stray-load losses (P_{Stray}).

Hereafter, only the stray-load losses are analyzed, because they are directly related to the standard comparison arguments. More details on other loss contributions are reported in [6] and [7].

Stray-Load Losses: These losses are very difficult to model and to quantify. Although the stray-load losses have been the object of several studies and analysis, the phenomena that govern these losses are still under discussion, in particular, from the measurement point of view. The IEEE 112-B standard defines these losses as the difference between the total measured losses and the conventional losses, as reported in (2).

$$P_{\text{Stray}} = (P_{\text{Electrical}} - P_{\text{Mechanical}}) - P_{\text{Conventional}} \quad (2)$$

with

$$P_{\text{Conventional}} = (P_{\text{J}_\text{S}} + P_{\text{J}_\text{R}} + P_{\text{Iron}} + P_{\text{Mec}}). \quad (3)$$

In order to limit the stray-load losses, some possible solutions are represented by the rotor bar insulation (to limit the inter-bar leakage currents), by using a double-layer winding with low space harmonic contributions, by a reduction of the high-frequency flux variations in the motor teeth, etc. It is important to remark that a strong reduction of the stray-load losses can involve a not negligible motor efficiency increment.

III. International Standards for the Induction Motor Efficiency Measurements

The efficiency values provided by the manufacturers have to be determined in accordance with well-known international standards. The most important world references are as follows:

- IEEE 112—method B (U.S. standard);
- IEC 34-2 (European standard);
- JEC 37 (Japanese standard).

In other countries one of the previous standards is generally adopted (i.e., the C390 Canadian standard makes reference to IEEE, and European countries not belonging to the European Union make reference to IEC). It is important to underline that the rated value of the motor efficiency depends on the standard followed, because each standard adopts different methodologies and measurement procedures [6], [8], [9]. A short analysis of these differences is reported in the following.

IEEE 112-method B: This standard is the most important in the industrial field because it is applicable to horizontal-axis polyphase squirrel-cage induction motors with power in the range 1–190 kW. Method B requires three tests. In particular, they are as follows.

- *Thermal test at the rated load*—The machine works at the rated load until the main motor temperatures (stator winding, stator lamination core, and external frame), measured each 30 min, do not change less than 1 °C. At the end of this test, the stator winding resistance has to be measured.
- *No-load test*—The motor, supplied with the rated voltage and frequency, runs without mechanical load until the bearings are stabilized (between two consecutive measures spaced out of 30 min, the input power not increases over 3%), then a variable voltage test is performed.
- *Variable-load test at rated conditions*—With the motor in steady-state thermal condition at rated load, the motor is loaded with six decreasing load torques (from 150% down to 25% of the rated torque). The winding temperature has to change not more than 10 °C with reference to the rated one.

Using these tests it is possible to determine all the motor loss contributions and to calculate the motor efficiency. Conventional iron losses (P_{Iron}) and mechanical losses (P_{Mec}) are evaluated by the no-load test. Through the load test the stator and rotor Joule losses (P_{Js} and P_{Jr}) are evaluated, whereas the stray-load losses are calculated by the variable-load test data using (2) and the other losses previously determined. The obtained stray-load losses are then plotted versus the squared load torque values. These values have to be smoothed using a linear regression. More consideration of the stray-load loss measurement procedures can be found in [4] and [7]. These standards require that the electrical quantities be measured with accuracy better than 0.2%, and with a 0.5% voltage stability and a 0.1% frequency tolerance. The absolute maximum speed error is 1 r/min. It is important to remember that the IEEE 112 standard reports other methods. These methods are applicable to particular sizes or types of motors (for example, Method A regards motors with a rated power less than 1 kW) or they prescribe tests and procedures different than the analyzed ones.

IEC 34-2: This standard provides several methods and procedures for the efficiency measurements in accordance with the type and the machine size, with the desired accuracy, etc. These methods can be subdivided into two categories.

- *Direct method*—The absorbed and provided power at the motor shaft are directly measured.
- *Indirect method*—The motor losses are measured by suitable tests and the efficiency is evaluated measuring the motor absorbed power.

The "indirect method" is suitable for a direct comparison with IEEE 112-Method B. For these reason, only this method will be considered in the following. The standard requirements are as follows:

- a conventional no-load test to measure the "constant losses" (sum of the iron and mechanical losses);
- the stator joule losses are evaluated using the winding resistance measured in dc and reported at the reference temperature (this temperature depends by the machine insulation class and, for this reason, it is independent of the real temperature reached during the load tests);
- the rotor joule losses are evaluated as the product of the rotor slip and the air-gap "transmitted power" (defined as $P_{\text{Electrical}} - P_{\text{JS}} - P_{\text{Iron}}$);
- the stray-load losses are considered as a function of the squared stator current and they are assumed at rated load condition equal to 0.5% of the absorbed power at rated load.

Using the previous loss definition, the efficiency is defined as

$$\eta = \frac{P_{\text{Electrical}} - \sum \text{Losses}}{P_{\text{Electrical}}}. \quad (4)$$

The standard imposes that all the electrical and the mechanical quantities have to be measured with accuracy better than 0.5%.

JEC 37: These standard is less restrictive of the USA and European ones. The efficiency evaluation through the Japanese standard can be considered as an indirect method. JEC 37 neglects

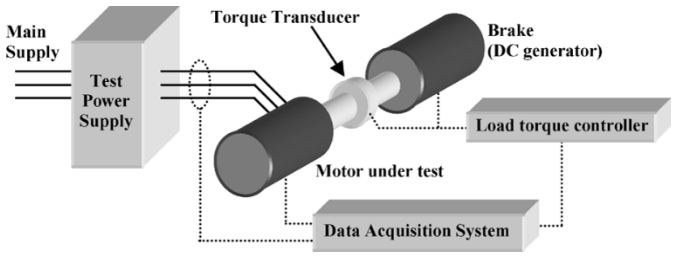

Fig. 1. Test bench layout.

the stray-load losses. For this reason, the obtained efficiencies are generally higher. Furthermore, no thermal correction of the joule losses is specified. Because it is very difficult to find the measurement procedures prescribed by the Japanese standard, it is reasonable to evaluate the machine efficiency using the results of the tests required by the other standards.

IV. Description of the Performed Tests

The tested induction motors are of the same series (380 V, 50 Hz, four poles) with rated power of 4, 7.5, 11, and 15 kW; they have been monitored by four thermal sensor. Two sensors are mounted on the end-winding connections; one is put in a stator slot and one is buried in the stator lamination core.

The tests have been performed using the test bench sketched in Fig. 1. The apparatus and instruments used in the tests are conformed to the IEEE 112-B standard requirements. In particular, the analyzed motors have been supplied with a 40-kVA static three-phase sinusoidal ac supply, which provides a sinusoidal waveform with a voltage total harmonic distortion less than 0.1%. The electrical quantities at the motor terminals have been measured with a three-phase digital power meter (Infratek 305A), whereas the torque transducer guarantees accuracy better than 0.2% of the rated torque value without hysteresis errors. In addition to the U.S. standard specifications, the following procedures have been adopted. At the end of the rated load test, the variable-load test has been performed in the following way. The six provided loads are applied in an alternate manner (with reference to the rated one) in order to keep constant the motor temperatures. In this way, the measurements are directly comparable from the thermal point of view. The motor temperature is more stable and it is possible to perform several measurements for each load torque. A high number of measurements, during this test, is extremely important in order to reduce the stochastic errors that may invalidate the stray-load loss determination.

V. Stray-Load Loss Measurement Results

Following the procedures reported in Sections III and IV, the stray-load losses have been measured and corrected as requested by the standards. In Figs. 2–5 the results for the four motors are shown. The "measured stray-load losses" are the stray-load losses, evaluated by the IEEE 112-B standard, before the compensation of the negative intersection with the stray-load loss axis [4]. It is possible to observe that the stray-load loss measurements are accurate with an excellent correlation factor.

It is important to underline that the correlation factor is very sensitive to the measurement accuracy. In particular, if a point is very far from the linear trend, some measurement errors are

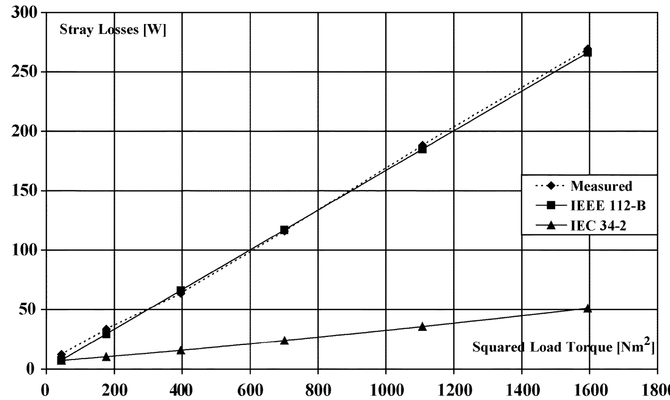

Fig. 2. Stray-load losses of the motor rated 4 kW.

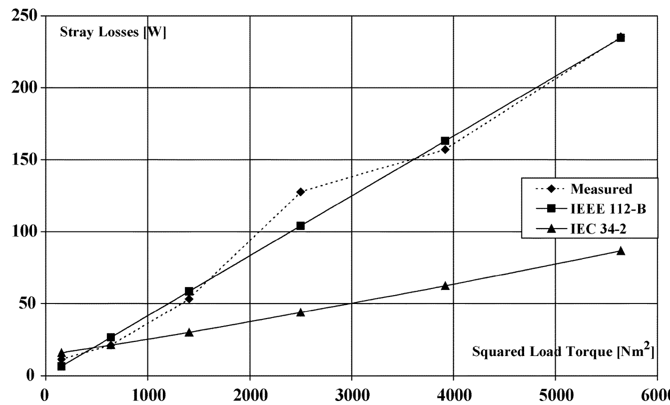

Fig. 3. Stray-load losses of the motor rated 7.5 kW.

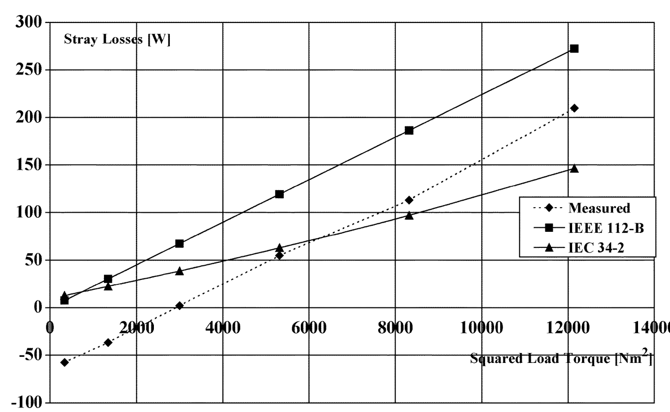

Fig. 4. Stray-load losses of the motor rated 11 kW.

certainly present. In other words, it is possible to consider the stray-load loss curve as a quality factor of the performed measurement. Fig. 2 shows that the measured stray-load losses are very close to the IEEE ones. Since the requested corrections are very small, the efficiency measured with IEEE 112-B is very close to the efficiency measured with the direct method (see Fig. 7). On the contrary, the IEC standard over estimates the motor efficiency because it considers a lower stray-load loss contribution. Same considerations can be made for the 7.5-kW motor (see Figs. 3 and 8).

For the 11-kW motor the trend of the measured stray-load losses is very close to a straight line, but a negative intercept of the regression line with the zero torque line appears (see Fig. 4).

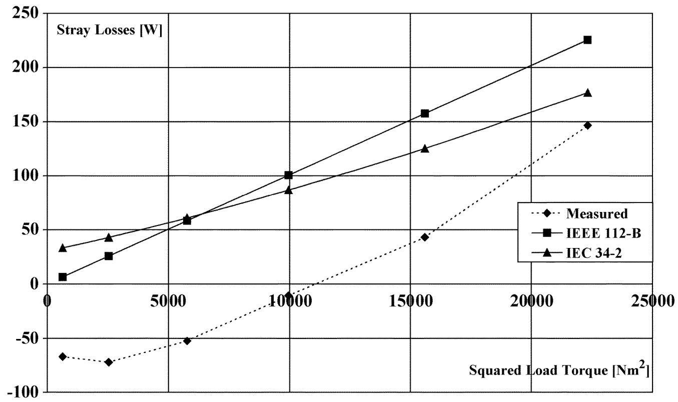

Fig. 5. Stray-load losses of the motor rated 15 kW.

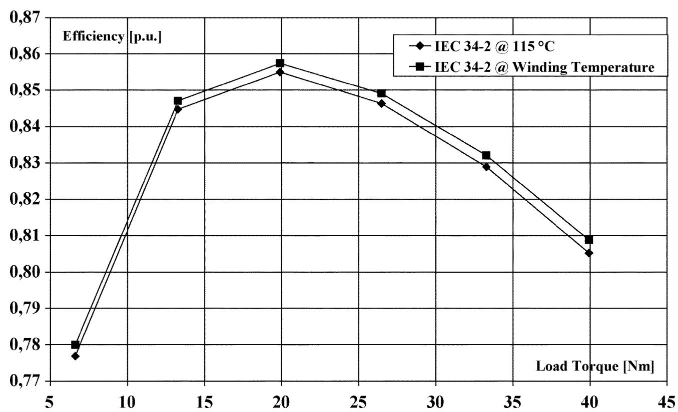

Fig. 6. Efficiency variation of the motor rated 4 kW due to the thermal corrections of the Joule losses.

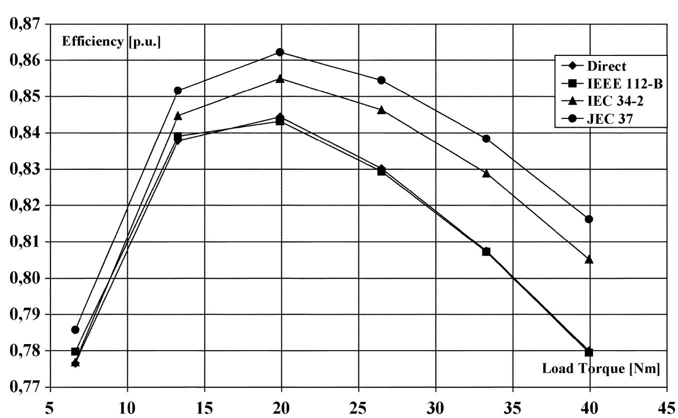

Fig. 7. Efficiency of the 4-kW motor.

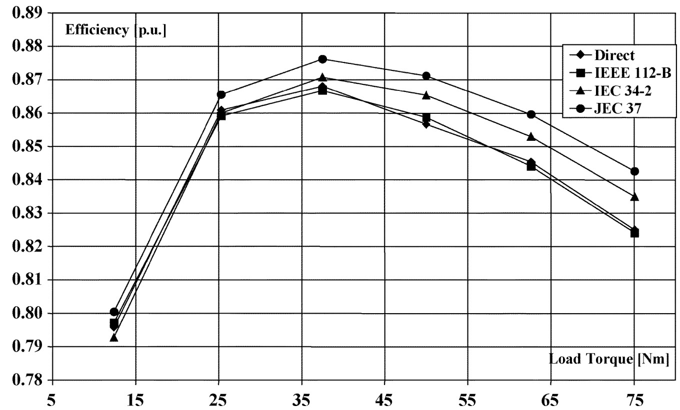

Fig. 8. Efficiency of the 7.5-kW motor.

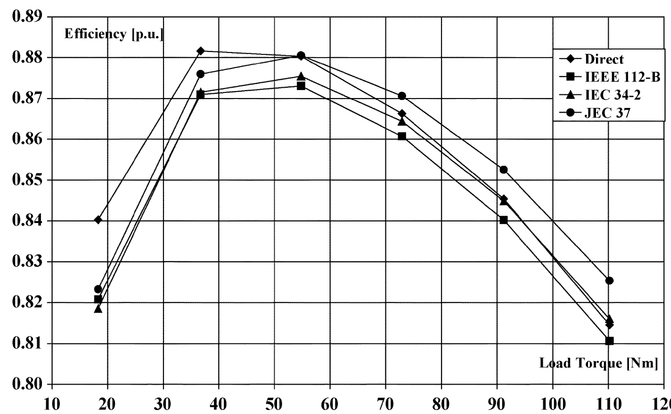

Fig. 9. Efficiency of the 11-kW motor.

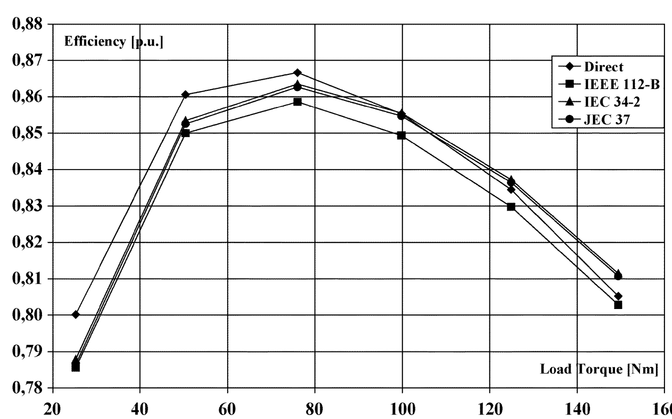

Fig. 10. Efficiency of the 15-kW motor.

In this case the stray-load loss corrections provided by the IEEE 112-B test method are quite evident. As a consequence, following the IEEE standard the machine efficiency is underestimated (see Fig. 9). The same considerations can be made for the 15-kW motor (see Figs. 5 and 10). For this motor the measured stray-load loss points present a consistent spread. In any case, the test still respects the validity conditions prescribed by the IEEE Standard. As a criticism of the IEC 34-2 standard, the use of conventional stray-load losses equal to 0.5% of the absorbed power at rated load (see Section III) is not correct in motors with rated power from 1 up to 90 kW, because the stray-load losses are strongly dependent on motor size [6], as confirmed by the obtained results. In particular, the stray-load losses evaluated following the IEC standard do not vanish when the load torque is zero. In fact, this standard requires that the stray-load losses have to be considered as a function of the squared stator current. As a consequence, due to the not negligible no-load current influence, the IEC standard underestimates the motor efficiencies when the motors run with low loads (see Section VII).

VI. Effects of the Joule Loss Thermal Corrections

The IEC 34-2 standard requires that the stator joule losses have to be calculated using the winding dc resistance reported at the reference temperature of the machine insulation class. This

TABLE II
MOTOR EFFICIENCY AT THE RATED LOAD AND EUROPEAN CEMEP LOWER LIMITS

	4 kW	7.5 kW	11 kW	15 kW
IEEE 112 – B	82.9	85.9	86.1	84.9
IEC 34-2	84.6	86.5	86.4	85.5
JEC 37	85.4	87.1	87.1	85.5
Direct Method	83.0	85.7	86.6	85.5
Eff2 lower limit	84.2	87.0	88.4	89.4
Eff1 lower limit	88.3	90.1	91.0	91.8

means that the obtained joule losses are not related to the real winding temperature reached during the load tests. As an example, for insulation Class F an over temperature of 115 °C has to be considered. As a consequence, these thermal corrections have negative effects on the motor efficiency if the real winding temperature is lower than the reference temperature, as shown in the case of the 4-kW motor (see Fig. 6).

VII. Motor Efficiency Results

Using the obtained stray-load losses and applying the thermal corrections requested by the standards, the machine efficiencies are evaluated. In Figs. 7–10 the efficiency versus load torque curves are shown. For 4- and 7.5-kW motors, the IEEE method provides motor efficiencies very close to the efficiency measured by the direct method. Following the IEC 34-2 or JEC 37 standards, the efficiency values are overestimated for each load (Figs. 7 and 8).

Figs. 9 and 10 highlight how the IEEE standard underestimates the efficiency of the 11- and 15-kW motors.

For all the motors, the JEC 37 standard overestimates the efficiency, in particular, for loads greater than the rated one.

With reference to the rated load, Table II shows the evaluated efficiency for the four motors together with the European CEMEP limits. It is possible to conclude that the efficiency class of the motor is strongly dependent on the standard followed. In fact, the 4-kW motor can be labeled Eff2 both for the IEC 34-2 standard and JEC 37 one, but it can be included in the Eff3 class using the IEEE 112-B standard. The 7.5-kW motor is in the Eff2 range for the Japanese standard, whereas the 11- and 15-kW motors have an Eff3 efficiency level with all the standards. As a final remark, IEEE 112-B can be considered the most accurate standard for the motor efficiency measurements, in particular, for the stray-load loss determination. The new European Standard IEC 61972, proposed in draft version in the recent months by the European Union, follows in a more detailed way IEEE 112-B, confirming its international validity in regard to the motor efficiency determination. Taking into account the class of motors used for this analysis, the measured efficiency could be influenced by variations in the manufacturing process. As an example, for small- and medium-sized motors with poured rotors bars, the inter-bar currents, which are enabled when the poured rotor conductor seeps between the rotor laminations, affect the efficiency.

An interesting question is whether these variations in efficiency are even more dominant than those that result from differences in the adopted standard. An answer to this question can be found in [10], where motors with oxidized and flamed rotors do not show efficiency variation using the IEEE 112-B standard.

VIII. Stray-Load Loss Sensitivity

As reported in Sections II and III, the stray-load losses are not directly measured but they have to be computed using the data obtained from the variable-load test. In order to understand which are the most critical quantities that influence the stray-load loss determination, an analysis of the method sensitivity at the measurement errors has been performed. The "sensitivity" is the mathematical relationship that describes how the variation of a performance (in this case the stray-load losses $P_{\rm Stray}$) depends on the variation of the parameters (x_i) that influence the performance. The expression of the sensitivity is shown in (5) and (6)

$$S_{x_\subset}^{P_{\rm Stray}} = \frac{\frac{dP_{\rm Stray}}{dx_i}}{\frac{P_{\rm Stray}}{x_i}} \tag{5}$$

$$\frac{dP_{\rm Stray}}{P_{\rm Stray}} = S_{x_i}^{P_{\rm Stray}} \cdot \frac{dx_i}{x_i}. \tag{6}$$

As an example of the use of (6), if $S_{x_i}^{P_{\rm Stray}} = 0.3$ and the x_i parameter changes of 1%, then the variation of the stray-load losses is equal to 0.3%. In other words, the instrumentation accuracy can be defined in accordance with the sensitivity values of the measured items. If the sensitivity at the x_i parameter is equal to 10 and an accuracy of the $P_{\rm Stray-}$ of 1% is wanted, then the x_i parameters have to be measured with an accuracy equal to or better than 0.1%.

The x_i parameters that influence the stray-load losses are as follows:

- absorbed electrical power $(P_{\rm Electrical})$;
- the load torque $(T_{\rm LOAD})$;
- the stator current $(I_{\rm S})$;
- the rotor speed (n);
- the stator winding temperature $(t_{\rm SW})$.

In order to simplify the calculations, it is assumed that only one parameter can change at the same time. In other words, only one measurement error has been considered for each measure. Using (2), it is possible to relate the stray-load losses to the previous five parameters, as shown in (7)

$$P_{\rm Stray} = \frac{n}{n_0} \cdot P_{\rm Electrical} - T_{\rm Load} \cdot \frac{2 \cdot \pi \cdot n}{60} - 3 \cdot R_0 \cdot \frac{(t_{\rm SW} + 234.5)}{(t_0 + 234.5)} \cdot I_{\rm S}^2 \cdot \frac{n}{n_0} - P_{\rm Iron} \cdot \frac{n}{n_0} - P_{\rm Mec} \tag{7}$$

where n_0 is the synchronous speed, and R_0 is the stator winding resistance measured at a temperature of t_0 (°C). Equation (7) allows us to evaluate the following quantities:

$$S_{P_{\rm Electrical}}^{P_{\rm Stray}} \quad S_{T_{\rm Load}}^{P_{\rm Stray}} \quad S_{I_S}^{P_{\rm Stray}} \quad S_{n}^{P_{\rm Stray}}, \quad S_{t_{\rm SW}}^{P_{\rm Stray}}.$$

It is important to remark that the iron losses and the mechanical losses have to be considered constant in the stray-load loss calculation.

As an example, the stray-load loss sensitivity at the absorbed electrical power results in

$$S_{P_{\rm Electrical}}^{P_{\rm Stray}} = \frac{n}{n_0} \cdot \frac{P_{\rm Electrical}}{P_{\rm Stray}}. \tag{8}$$

TABLE III
STRAY-LOAD LOSS SENSITIVITY FOR THE 4-kW MOTOR

		Load Torque/Rated Load Torque [p.u.]					
		0.25	0.5	0.75	1.00	1.25	1.50
P_{Stray}	[W]	12.2	33.6	63.6	116.1	188.3	269.5
$S^{P_{Stray}}_{P_{Electrical}}$	[p.u.]	107.2	70.8	54.4	39.3	30.4	25.5
$S^{P_{Stray}}_{T_{Load}}$	[p.u.]	-84.2	-60.7	-47.5	-34.2	-26.12	-21.5
$S^{P_{Stray}}_{I_S}$	[p.u.]	-15.8	-8.15	-6.52	-5.37	-4.86	-4.77
$S^{P_{Stray}}_{n}$	[p.u.]	5.20	2.53	1.81	1.44	1.27	1.19
$S^{P_{Stray}}_{t_{SW}}$	[p.u.]	-2.34	-1.21	-0.97	-0.80	-0.72	-0.71

TABLE IV
STRAY-LOAD LOSS SENSITIVITY FOR THE 15-kW MOTOR

		Load Torque/Rated Load Torque [p.u.]					
		0.25	0.5	0.75	1.00	1.25	1.50
P_{Stray}	[W]	-67.1	-72.3	-52.5	-10.9	43.0	146.6
$S^{P_{Stray}}_{P_{Electrical}}$	[p.u.]	-72.3	-121	-243	-1508	473	165
$S^{P_{Stray}}_{T_{Load}}$	[p.u.]	58.5	107	219	1360	-424	-146
$S^{P_{Stray}}_{I_S}$	[p.u.]	12.8	15.2	29.3	198	-71.0	-28.7
$S^{P_{Stray}}_{n}$	[p.u.]	-0.53	-0.42	-0.95	-8.38	3.38	1.70
$S^{P_{Stray}}_{t_{SW}}$	[p.u.]	2.51	2.97	5.73	38.7	-13.9	-5.63

For each motor, the stray-load loss sensibilities have been calculated for each measurement point considered in the variable-load test. The stray-load loss sensitivity values for the 4-kW and the 15-kW motors are, respectively, reported in Tables III and IV.

The 7.5- and 11-kW motors results are respectively similar to the 4- and 15-kW ones. A negative value of the sensitivity means that an error in excess of the parameter produces a diminution of the stray-load losses. The tables show that the sensitivity values can be very high, in particular, when the measured stray-load losses are close to zero. In this condition, the errors are very high, even if highly accurate instrumentation is used. Table III and Table IV show that the sensitivity values are not constant with reference to load torque value.

Furthermore, with the same load torque, the sensitivity values for the 4- and 7.5-kW motors are in the following order:

$$\left|S^{P_{\text{Stray}}}_{P_{\text{Electrical}}}\right| > \left|S^{P_{\text{Stray}}}_{T_{\text{Load}}}\right| > \left|S^{P_{\text{Stray}}}_{I_S}\right| > \left|S^{P_{\text{Stray}}}_{n}\right| > \left|S^{P_{\text{Stray}}}_{t_{\text{SW}}}\right|$$

on the contrary, for the 11- and 15-kW motors the sensitivity values are in the following order:

$$\left|S^{P_{\text{Stray}}}_{P_{\text{Electrical}}}\right| > \left|S^{P_{\text{Stray}}}_{T_{\text{Load}}}\right| > \left|S^{P_{\text{Stray}}}_{I_S}\right| > \left|S^{P_{\text{Stray}}}_{t_{\text{SW}}}\right| > \left|S^{P_{\text{Stray}}}_{n}\right|.$$

This difference is due to the fact that, for the machines under study, the bigger motors have steady-state winding temperatures higher than the smaller ones. In any case, the measurement items that involve high-sensitivity values have to be carefully measured. The performed analysis shows that the absorbed electrical power, the load torque, and the stator current have to be measured with very high accuracy. In addition, the sensitivity analysis can be used as a first aid for searching errors which can be done during the test measurements. As a final remark, it is possible to conclude that the performed sensitivity analysis puts into evidence that an accurate prediction of the stray-load losses by the IEEE 112-B procedure is very difficult to carry out, even if the instrumentation used matches the standard requirements. In order to improve the accuracy and the repeatability of the stray-load loss evaluations, it is recommended to perform many measurements for each load torque applied at the motor during the variable-load test and to average the results.

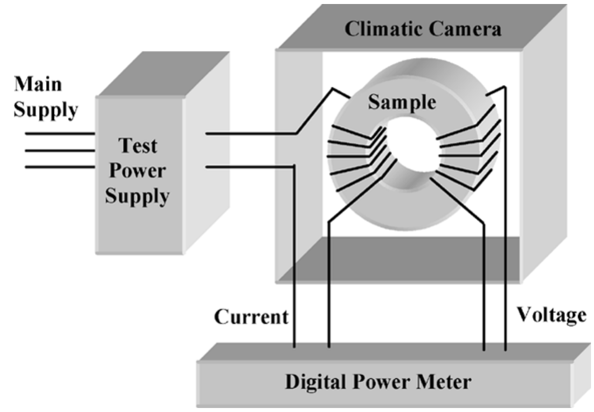

Fig. 11. Test bench used for the specific losses measurements.

IX. TEMPERATURE EFFECTS ON IRON LOSSES

The iron losses contribution is requested to calculate the motor efficiency and to perform the motor loss segregation. All the considered international standards adopt the conventional iron losses measured by the no-load test. It is important to remark that the iron core temperature measured in the variable-load test is much higher than the same one measured in the no-load test. In this section, the authors want to evaluate the temperature effects on the iron losses and how these effects influence the stray-load losses and the motor efficiency. Experimental tests performed in a climatic camera on a toroidal sample, realized with the same magnetic material used for the motor construction, have been used to extrapolate as the conventional motor iron losses change between the prescribed no-load test and the motor real operative conditions. The test bench layout is sketched in Fig. 11. The magnetic material specific losses are determined as in the conventional Epstein frame test. In Fig. 12 the specific iron losses (P_{Spec}) versus the flux density measured on toroidal sample at 0 °C, 25 °C, and 75 °C are shown. This figure highlights that when the temperature increases there is a sensible iron losses decrement. In particular, due to the increase of the stator lamination electrical resistance, an eddy-currents decrement is expected. In Fig. 13, the specific iron losses measured on toroidal sample versus the temperature, for a flux density of 1 and 1.5 T, are reported.

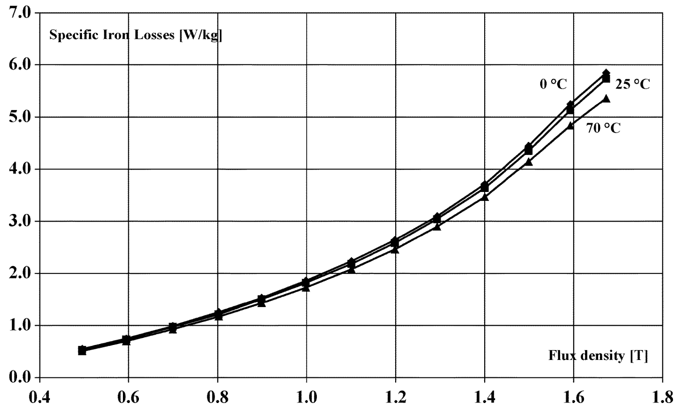

Fig. 12. Specific iron losses versus the flux density (reference temperatures: 0 °C, 25 °C, and 75 °C).

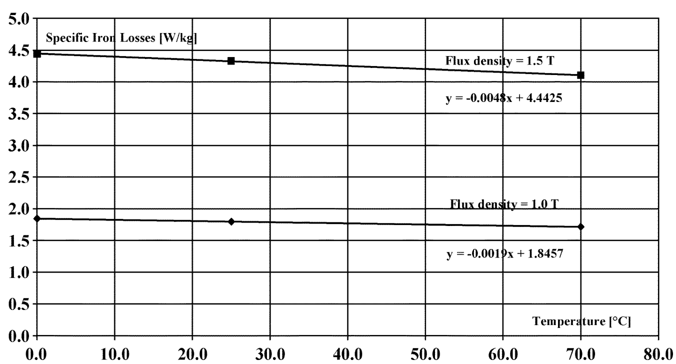

Fig. 13. Specific iron losses versus temperature with flux densities of 1.0 and 1.5 T.

TABLE V
TEMPERATURE EFFECTS ON THE IRON LOSSES

	Motor Rated Power [kW]			
	4	7.5	11	15
$T_{NO-LOAD}$ [°C]	25	25	25	25
T_{LOAD} [°C]	63.5	81.8	66.8	100.2
ΔP_{SPEC} [%]	-4.28	-6.31	-4.64	-8.35
$P_{IRON\ NO-LOAD}$ [W]	122	216	303	461
$P_{IRON\ LOAD}$ [W]	117	203	289	423

It is possible to observe the linear behavior of the phenomena. In order to extrapolate the data obtained for the toroidal sample to the motors, the following considerations are made.

- The average stator flux density is assumed to be equal to 1.5 T.
- The real stator core temperature is measured.
- The same percentage variation of the $P_{\rm Spec}$ measured for the torridly core is applied to conventional iron losses measured in the no-load test.

The results applied to the motors are reported in Table V. It is quite evident that if the temperature effects are taken into account, an iron loss reduction from 4% up to 8% can be obtained.

Hereafter, only the results for the 15-kW motor are presented because its steady-state iron temperature during the thermal tests is the most high. In any case, for the other motors the same considerations are also valid. As shown in Fig. 14, the values of $P_{\rm Stray}$ evaluated following the IEEE 112-B procedure do not change because this standard requires that the intercept with the zero torque line of the regression line has to be considered zero (to note that in Fig. 14 the two regression lines are parallel). On the contrary, the motor efficiency changes in a significant manner when the iron losses are corrected using the real stator core temperature, as shown in Fig. 15. At the rated load, the overall motor efficiency improves by 0.2% by IEEE 112-B and by 0.3% by IEC 34-2. This efficiency improvement seems to be negligible, but it can be very interesting when the motor efficiency class has to be defined. On the base of the obtained results, it is possible to conclude that the motor efficiency values depend in a significant manner on the real iron temperature.

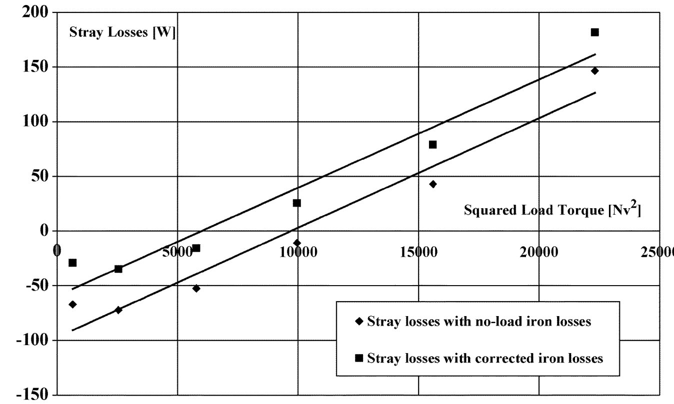

Fig. 14. Stray-load loss variation due to temperature corrections of the iron losses for the 15-kW motor.

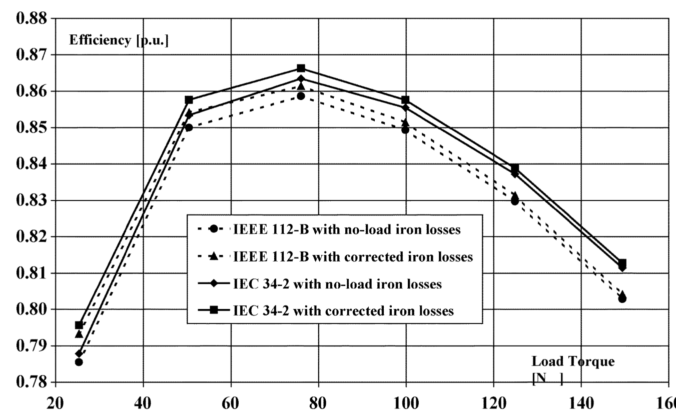

Fig. 15. Efficiency variation due to temperature corrections of the iron losses for the 15-kW motor.

X. CONCLUSION

In this paper the IEEE 112-B, IEC 34-2, and JEC 37 international standards for induction motor efficiency evaluation were considered. The differences in the prescribed procedures of each standard have been discussed. The experimental tests performed on four induction motors of the same series have put into evidence that the rated efficiency of the machine depends on the standard followed. Some criticisms of the prescribed standard methodologies have been reported, such as the variable-load test requested for the stray-load loss calculation and the thermal corrections of the stator joule losses. On the basis of the presented results, IEEE 112-B can be considered the most suitable standard for the stray-load loss measurements and, as a consequence, for the motor efficiency evaluation. In general, IEC 34-2 and JEC 37 overestimate the motor efficiency because they define, instead of measuring, the stray-load losses.

An accurate stray-load loss evaluation is mandatory to obtain significant motor efficiency values. The stray-load loss measurements are not simple to perform and they are strongly influenced by the measurement errors. In order to understand which are the most critical quantities that influence the stray-load losses, a sensitivity analysis devoted to parameter variations has been performed. The obtained results shown that the absorbed electrical power, the load torque, and the stators currents are the quantities which have to be measured with very high accuracy. In the final part of the paper the temperature influence on the conventional iron losses was taken into account, through experimental tests performed in a climatic camera on a toroidal sample realized with the same magnetic material used for the motor construction. The obtained data have been used to predict the iron losses variation between the no-load test and the real operative condition of the motors. Besides the international standard methodologies, it is the authors' opinion that for a correct motor efficiency evaluation the real iron temperature and the corresponding correct iron losses should be taken into account.

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