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Discussion

The Measurement of Additional Losses in Induction Motors: Discussion about the Actually Achievable Uncertainty

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Abstract: In this paper, a discussion is presented concerning the combined uncertainty when measuring residual and additional losses in the efficiency evaluation of three-phase induction motors, by evaluating some experimental results obtained on a commercial motor. The IEC 60034-2-1 standard is considered, in comparison to a previous version of this standard requiring the estimation of residual losses instead of their measurement. A major goal is to investigate if the complex measurement method introduced in the present version of the standard is justified or not by processing the actually achievable uncertainty both in additional losses and in the overall efficiency measurement. Finally, some considerations are presented about additional issues concerning the classification of the tested motor, in comparison to the IE (International Efficiency) efficiency levels.

Keywords: IEC standards; induction motors; losses; power measurements; uncertainty

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1. Introduction

The efficiency measurement is a critical issue in the market of induction motors that concerns electric motor manufacturers, suppliers, consumers, and market surveillance authorities [1–3]. Efficiency can be either measured directly or determined indirectly. Due to the number of quantities to be measured when applying the indirect method, some critical issues can arise when estimating relative uncertainties. This analysis has implications both in terms of the measurement procedure and in terms of the instrumentation to be adopted [4–10]. In this paper, a summary of the evolution of the IEC standards, which has led to the current version of IEC 60034-2-1, is presented. Some remarks about the uncertainty are discussed; the contribution to the overall uncertainty in the efficiency measurements by evaluating separated losses is analyzed starting from experimental results obtained in the framework of a cooperation between the Department of Industrial and Information Engineering and Economics at the University of L'Aquila, and ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. It can be concluded that the complex measurement method introduced in the present version of the standard leads to uncertainty so high that the additional losses obtained are compatible with those obtained with assigned values, according to the simpler procedure in previous standards. The processing of the extended uncertainties in the efficiency measurement can lead to additional issues concerning the classification of the tested motors, in comparison to the IE efficiency levels. This paper is devoted to making a contribution to the discussion concerning induction motors' efficiency, especially for the benefit of motor manufacturers and surveillance authorities; in fact, both of them are interested in developing measurement procedures that are reliable and easy to execute. The main goal cannot be identified only as of the execution of testing according to a set of international standards, but it must be the correct processing of the efficiency along with its extended uncertainty, with actually achievable results. Of course, the more the measurement issues that are investigated before developing the measurement procedures and performing the tests, the fewer the legal issues that can be raised after the comparison of incompatible efficiency measurements.

2. Preliminary Remarks: Measurement Uncertainty

Generally, due to the instrumentation used, instability phenomena internal to the object under testing, and effects produced by external phenomena, the repetition of a measurement process provides a set of data that are close to each other, but not identical. It is, therefore, necessary to introduce criteria to discriminate if the different measurement results are equivalent or not. The concept of measurement uncertainty, introduced to provide a numeric estimation of the quality of the measurement, can be crucial in many cases [1,2].

Uncertainty is defined in the ISO/IEC Guide 99:2007, International vocabulary of metrology [3], as the "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used"; coherently, the measurement result is a "set of quantity values being attributed to a measurand together with any other available relevant information". To correctly evaluate the uncertainty in the measurement processes, the reference standard to be adopted is the ISO/IEC Guide 98-3:2008 (JCGM/WG1/100) Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995) [11].

As regards the measurement laboratories, the general requirements for the competence, impartiality, and coherent operation of laboratories are defined in the ISO/IEC 17025: 2017 [12] standard, which applies to all organizations that carry out laboratory activities and also to regulatory authorities and accreditation bodies. It states that "testing laboratories shall have and shall apply procedures for estimating the uncertainty of measurement".

In the following, u is the standard uncertainty, for which a coverage factor k of 1 is to be considered [11]; the extended uncertainty can be obtained from u by introducing larger values of k.

3. Efficiency Measurement for Induction Motors

The EC regulation 640/2009 [13] requires the measurement of the efficiency for induction motors as a surveillance task that is demanded of the different EU countries; toward this goal, induction motor manufacturers, as well as surveillance authorities, should carefully take into account various issues related to measurement aspects, as the instrumentation to be adopted and the expression of measurement uncertainty.

Different approaches to the measurement of efficiency can be considered, applying either direct or indirect methods.

To perform direct measurements of efficiency, the measurement of electrical input power is required, by acquiring voltage and current waveforms, as well as the measurement of rotational speed and output torque to process the mechanical power.

Otherwise, if no accurate measurement of torque is possible, the efficiency of induction motors can be evaluated indirectly; the indirect approach requires the measurement of electrical input power and the estimation of several losses' contributions, which lead to the evaluation of the output power. Usually, five kinds of losses are considered—losses in stator windings, losses in rotor windings, friction and windage losses, iron losses, and finally, additional losses (PLL). The choice between the direct or the indirect method depends on different aspects, such as the features of the motor to be tested, the available measurement apparatuses and laboratory facilities, and the accuracy target to be satisfied. Due to the number of quantities to be measured when applying the indirect method, it is necessary to carefully analyze some critical issues in order to estimate the relative uncertainties correctly. This analysis has implications both in terms of the measurement procedure and in terms of the instrumentation to be adopted.

In the following, some remarks about the uncertainty are discussed, by stressing the contribution to the overall uncertainty in the efficiency measurements that can be obtained by evaluating separated losses, starting from experimental results.

The proposed results were obtained in the framework of cooperation between the Department of Industrial and Information Engineering and Economics of the University of L'Aquila, and ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. The main aim of this cooperation is the definition of measurement procedures for the correct measurement of efficiency in induction motors.

4. The Indirect Methods for Efficiency Measurement in IEC Standards: A Brief Review

To better understand some issues that will be discussed in this paper, it may be useful to summarize the evolution of IEC standards, which has led to the current version of IEC 60034-2-1 [14].

The IEC 60034-2 standard released in 1999 [15] provides that, generally, the guaranteed efficiency of a motor is that obtained with the determination of separate losses. In this standard, the indirect method is proposed as the preferred method for the efficiency evaluation of polyphase induction motors. In detail, the losses are to be processed separately by considering constant losses obtained with no-load tests at rated voltage values, and load and additional losses, which are obtained with variable load tests.

As a result of this indirect approach, the torque measurement is not prescribed in this version of the standard, which prescribes accuracy only for measuring electrical quantities.

In coherence with the method that was traditionally adopted for the measurement of efficiency in electrical motors, this version of the standard avoids requiring a measurement of output torque, since this was quite difficult in the past before the development of high-performance torque transducers [16]. The quantification of additional losses is to be done by estimation, conventionally as 0.5% rated input electrical power, by varying as the stator current squared. In the following, we will refer to this approach for comparison regarding the achievable uncertainties.

Some important efforts toward improving the measurement process and the efficiency evaluation can be found in IEC 60034-2-1 [17], released in 2007; the different approaches that can be adopted are classified qualitatively.

This statement is to be underlined: "Uncertainty, as used in this standard, is the uncertainty of determining a true efficiency. It reflects variations in the test procedure and the test equipment. Although uncertainty should be expressed as a numerical value, such a requirement needs sufficient testing to determine representative and comparative values. This standard uses the following relative uncertainty terms—"low" applies to efficiency determinations based solely upon test results;—"medium" applies to efficiency determinations based upon limited approximations;—"high" applies to efficiency determinations based upon assumptions." [17].

Moreover, another important sentence is: "It is difficult to establish specific rules for the determination of efficiency. The choice of the test to be made depends on the information required, the accuracy required, the type and size of the machine involved, and the available field test equipment (supply, load, or driving machine)."

Only for three-phase motors whose rated power is ≤1 kW and for all single-phase motors, the direct method is suggested as the preferred one.

For three-phase motors whose rated power is in the range of 1–150 kW, the preferred method for efficiency evaluation is the indirect one, in which a new approach for the additional load losses is proposed.

In 2014, the present version of IEC 60034-2-1 [14] was published, in which some further revisions were included. The test methods are now grouped into preferred methods and methods for field or routine tests. The preferred methods are presented as methods that allow low uncertainty; for a specific rating and type of machine, only one preferred method is currently defined. The requirements related to the instrumentation are detailed and refined. Furthermore, the description of all the tests required for each method is detailed, in the same sequence required for the execution of the test itself, with flow diagrams that graphically show the sequence of tests.

The first important innovation concerns the order in which each typology of tests is to be performed; the first to be done is the rated load test, then, in rapid sequence, the test at variable loads, and finally, the no-load test. In the previous versions, the load and no-load tests were considered practically independent: no-load tests were performed after making sure that the motor reached thermal equilibrium as a consequence of its no-load losses only. Usually, the reached frame temperature, under these conditions, is sensibly lower than that reached underrated conditions, with the undesired effect of underestimating the iron losses. In the present version, all tests must be performed on the machine after reaching equilibrium at rated load, resulting in a better estimate of the iron losses as well as friction and winding losses. Furthermore, another advantage is that the time required for the complete test is lower since it is not necessary to reach two distinct thermal balances, one for the no-load test and the second for the test at the rated load; the variable load test and the no-load test are performed immediately after the rated load test. Since the no-load test must be performed without applying additional torque to the motor, it is necessary to adopt a rapid mechanical decoupling system between the bench and the motor.

The second innovation concerns the measurement of winding resistances used to evaluate the stator losses in the variable load tests and no-load tests: for each load point, the average resistance must be calculated by interpolating the values measured at the beginning and the end of each test.

An important innovation was also introduced in the rated load test for measuring the electrical input power, which must be corrected considering the temperature of the coolant.

Finally, friction and windage losses are to be considered as a function of the slip in order to take into account the actual working condition during the variable load test.

As a general remark, an effort must be made to model the effects of many experimental parameters in the evaluation of the different typologies of losses. However, as it is well known in the field of instrumentation and measurements, if a quantity is indirectly measured as a function of n directly measured quantities, the combined uncertainty must be evaluated by taking into account the uncertainty of each measurement.

So, the goal of reaching a more accurate estimation of losses and efficiency can be hindered by the increasing of the combined uncertainty during the measurement process. This is a major weakness in some of the international standards, where the measurement uncertainty is overlooked or only slightly considered.

5. The Case of the Uncertainty Propagation in the Estimation of Additional Losses

This work analyzes the evaluation of additional losses, with the relative combined uncertainty. The objective is to identify the most suitable measurement methods, taking into account the realistic value of uncertainty that can be reached when a large number of intermediate measurement results must be processed to obtain the final result.

Figure 1 describes the indirect method for evaluating the efficiency in three-phase induction motors, starting from the present version of IEC 60034-2-1 [14].

As shown in the diagram, the additional losses must be processed almost at the end of the entire procedure. In detail, the additional losses are measured starting from the residual losses P_{Lr} obtained from the input power by subtracting the losses:

$$P_{Lr} = P_1 - P_2 - P_{s,\theta} - P_{r,\theta} - P_{fw} - P_{fe} \tag{1}$$

where P_1 is the input electric power without corrections, P_2 is the output mechanical power, $P_{s,\theta}$ are the stator winding losses, $P_{\rho,\theta}$ are the rotor winding losses, P_{fe} is the iron loss, and P_{fw} is the friction and windage loss referring to the actual rotor slip.

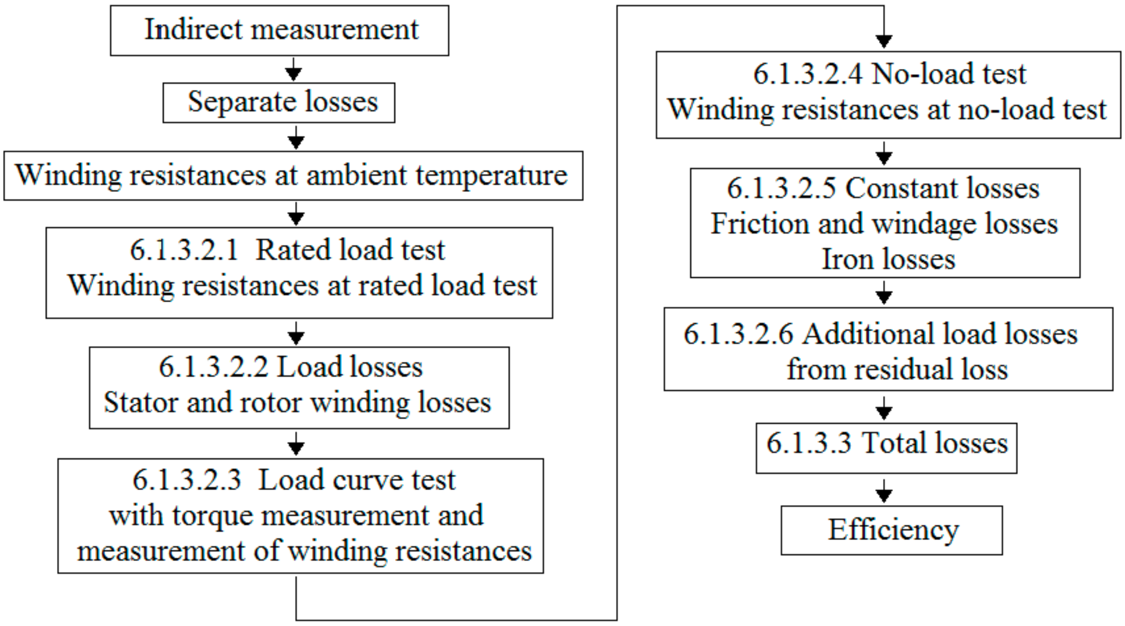

Figure 1. The procedure for the indirect evaluation of efficiency, with the measurement of total losses; the numbering refers to the paragraphs of IEC 60034-2-1 in which the tests are described.

It should first be noted that (1) is a subtraction whose result P_{Lr} is about two orders of magnitude lower than P_1 and P_2; as it is known from uncertainty assessment theory when a quantity is obtained with a subtraction, some critical problems can appear in terms of combined uncertainty. With a metrological approach, if a quantity y is not measurable directly, but a relationship $y = f(x_1, \ldots, x_N)$ can be formulated by considering a number N of directly measurable quantities x_i, which is independent, the combined standard uncertainty of y is defined as:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i)} \tag{2}$$

where $u(x_i)$ are the uncertainties related to the measured quantities x_i.

The combined uncertainty related to (1) can be expressed as:

$$u_c(P_{Lr}) = \sqrt{u^2(P_1) + u^2(P_2) + u^2(P_{s,\theta}) + u^2(P_{r,\theta}) + u^2\left(P_{fw}\right) + u^2\left(P_{fe}\right)} \tag{3}$$

Besides, if the relative combined uncertainty is to be considered, the expression is:

$$u_{Rc}(P_{Lr}) = \frac{\sqrt{u^2(P_1) + u^2(P_2) + u^2(P_{s,\theta}) + u^2(P_{r,\theta}) + u^2\left(P_{fw}\right) + u^2\left(P_{fe}\right)}}{P_1 - P_2 - P_{s,\theta} - P_{r,\theta} - P_{fw} - P_{fe}} \tag{4}$$

To better analyze the effects of the propagation of uncertainty in the case under examination, some experimental data are analyzed below. These data were measured by carrying out a complete characterization of several induction motors as part of applied research activity in collaboration with ENEA, dedicated to the development of a structure and to the test procedures for measuring induction motor efficiency according to IEC and ISO standards [3,11,12].

Firstly, we tested a 5.5 kW three-phase induction motor, whose rated values are: 2 poles, 380–420 V, delta-connected, 10.7 A, 2900 rpm @ 50 Hz, PF of 0.88, IE2 efficiency. The measurement results reported in Tables 1–3 were obtained by meticulously applying the requirements in [14] and using instrumentation fully compliant with the accuracy class in [13] or higher. Motor shell and cooling air temperatures were acquired with a Fluke 61 IR thermometer and a Fluke 971 Temperature Humidity, respectively.

Table 1. Experimental results: input power, output power, and stator winding losses with uncertainties.

Load	P_1 [W]	$u_c(P_1)$ [W]	P_2 [W]	$u_c(P_2)$ [W]	$P_{s,\theta}$ [W]	$u_c(P_{s,\theta})$ [W]
25%	7657	5.69	6723.19	0.42	63.34	0.09
50%	6924	5.58	6121.79	0.64	104.38	0.15
75%	6209	5.47	5532.83	0.88	166.00	0.23
100%	4509	3.16	4050.14	1.18	274.95	0.37
115%	3132	3.98	2782.19	1.31	330.24	0.43
125%	1691	2.80	1631.16	1.43	395.68	0.50

Table 2. Experimental results: rotor winding losses, friction and windage losses, and iron losses with uncertainties.

Load	$P_{r,\theta}$ [W]	$u_c(P_{r,\theta})$ [W]	P_{fw} [W]	$u_c(P_{fw})$ [W]	P_{fe} [W]	$u_c(P_{fe})$ [W]
25%	14.55	10.74	70.80	1.33	126.81	3.87
50%	45.58	20.63	69.67	1.31	124.52	3.81
75%	98.77	29.77	68.38	1.29	121.98	3.72
100%	188.55	40.65	66.81	1.26	119.01	3.63
115%	229.44	45.12	66.30	1.25	118.29	3.61
125%	288.97	49.53	65.44	1.23	116.87	3.57

Table 3. Experimental results: residual losses with uncertainties.

Load	P_{Lr} [W]	$u_c(P_{Lr})$ [W]	$u_{Rc}(P_{Lr})$
25%	−15.67	11.83	75.49%
50%	4.64	21.41	461.42%
75%	3.72	30.20	811.83%
100%	26.84	41.21	153.54%
115%	57.94	45.65	78.79%
125%	66.84	50.01	74.82%

The stator windings' resistance was measured with the Chauvin Arnoux CA 6255 micro-ohmmeter. An API COM 21 kW test bench, with energy recovery and field orientation control techniques, was used to load the motor under testing at the required percentages of rated power in the variable load tests; torque and speed measurements were performed with a Magtrol Vibro-Meter TM 108 torque and speed transducer.

A PROVA Tachometer RM-1000 was adopted during the no-load test to measure the rotation speed. A three-phase voltage induction regulator ISGEV RT 250 MB 4, allowing output voltages in the range of 20–770 Vrms and output currents in the range of 0–100 Arms, was used to guarantee the required voltages. The electrical quantity measurements for the evaluation of RMS values of voltage, current and electrical input power were obtained with a Yokogawa WT1800, allowing an active power accuracy at 50 Hz of +/−(0.1% of measured values + 0.2% of the range). The relative measurement uncertainties were processed with an Excel application by Yokogawa [18]. Torque and speed signals were acquired by the WT1800, equipped with the engine option.

Analyzing Table 2, it can be noticed that the least accurate measurements are those related to rotor winding losses. Table 3 shows that the results obtained for residual losses are influenced by a combined uncertainty that can reach 800% of the central value, and in one case, the central value is negative, which is a clear nonsense result. This confirms the previously mentioned problems related to indirect measurements obtained by subtraction.

It must be considered that these data refer to standard uncertainty and combined uncertainty with a confidence level of approximately 68%, which is too low for realistic measurement approaches. If extended uncertainties are to be considered, a coverage factor k of 2 or 3 must be adopted to obtain confidence levels of 95% and 99%, respectively [11]. Therefore, the criticality of the values in Table 3 is shown even more. To reduce the effects of measurement errors, the standard establishes a linear regression analysis of residual losses, expressed as a function of the square of load torque, according to the relationship:

$$P_{Lr} = A \cdot T^2 + B \tag{5}$$

where T is the torque measured in the variable load test. A and B are to be obtained by considering at least six load points, and using the following relations:

$$A = \frac{N \cdot \sum_{i=1}^{N} \left(P_{Lri} \cdot T_i^2 \right) - \sum_{i=1}^{N} P_{Lri} \cdot \sum_{i=1}^{N} T_i^2}{N \cdot \sum_{i=1}^{N} T_i^4 - \left(\sum_{i=1}^{N} T_i^2 \right)^2} \tag{6}$$

$$B = \frac{\sum_{i=1}^{N} P_{Lri}}{N} - A \cdot \frac{\sum_{i=1}^{N} T_i^2}{N} \tag{7}$$

(6) and (7) are meaningful when P_{Lri} and T_i are correlated; the checking of these important conditions requires the evaluation of the correlation factor γ, according to the definition in [14]:

$$\gamma = \frac{N \cdot \sum_{i=1}^{N} \left(P_{Lri} \cdot T_i^2 \right) - \sum_{i=1}^{N} P_{Lri} \cdot \sum_{i=1}^{N} T_i^2}{\sqrt{\left[N \cdot \sum_{i=1}^{N} \left(T_i^2 \right)^2 - \left(\sum_{i=1}^{N} T_i^2 \right)^2 \right] \cdot \left[N \cdot \sum_{i=1}^{N} P_{Lri}^2 - \left(\sum_{i=1}^{N} P_{Lri} \right)^2 \right]}} \tag{8}$$

In case of issues during the measurement process, γ could be lower than 0.95 [14]; in this case, the operator is recommended to remove the worst measurement point from (5), and it is asked to process the regression again. If the new value of γ is ≥0.95, this new regression is acceptable; otherwise, the measurement results are not satisfactory, and the whole measurement process is repeated, also investigating the possible causes of the issues that have involved low-accuracy results.

Given the value of A, for $\gamma \geq 0.95$, the additional losses P_{LL} against the torque T of each load point are:

$$P_{LL}(T) = A \cdot T^2 \tag{9}$$

The evaluation of factor A requires the evaluation of its combined uncertainty; this can be obtained by taking into account the previous statements concerning the combined uncertainty, but also introducing some corrections required for correlated quantities, such as P_{Lri} and T_i [19].

For correlated quantities, the combined uncertainty is:

$$\begin{aligned} u_c(y) &= \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \left(\frac{\partial f}{\partial x_i} \right) \cdot \left(\frac{\partial f}{\partial x_j} \right) \cdot u\left(x_i, x_j \right)} \\ &= \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 \cdot u^2(x_i) + 2 \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial x_i} \right) \cdot \left(\frac{\partial f}{\partial x_j} \right) \cdot u\left(x_i, x_j \right)} \end{aligned} \tag{10}$$

The parameter $u(x_i, x_j)$ is the covariance of x_i and x_j, $Cov(x_i, x_j)$; if a correlation coefficient $r\left(x_i, x_j\right)$ is introduced:

$$r\left(x_i, x_j\right) = \frac{u\left(x_i,\ x_j\right)}{u(x_i) \cdot u\left(x_j\right)} \tag{11}$$

Substituting (5) in (2), the final expression is obtained:

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)\cdot\left(\frac{\partial f}{\partial x_j}\right)\cdot u\left(x_i, x_j\right)} = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2\cdot u^2(x_i) + 2\cdot\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\frac{\partial f}{\partial x_i}\right)\cdot\left(\frac{\partial f}{\partial x_j}\right)\cdot u(x_i)\cdot u\left(x_j\right)\cdot r\left(x_i, x_j\right)} \quad (12)$$

The uncertainty of A is:

$$u_c(A) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial A}{\partial P_{Lri}}\right)^2\cdot u^2(P_{Lri}) + \sum_{i=1}^{N}\left(\frac{\partial A}{\partial T_i}\right)^2\cdot u^2(T_i) + 2\cdot\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\frac{\partial A}{\partial P_{Lri}}\right)\cdot\left(\frac{\partial A}{\partial T_j}\right)\cdot u(P_{Lri})\cdot u\left(T_j\right)\cdot r\left(P_{Lri}, T_j\right)} \quad (13)$$

where the correlation factor $r(P_{Lri}, T_i)$ for P_{Lri} and T_i is:

$$r\left(P_{Lri}, T_j\right) = \frac{u\left(P_{Lri}\cdot T_j\right)}{u(P_{Lri})\cdot u\left(T_j\right)} \quad (14)$$

where $u(P_{Lri}, T_j)$ is the covariance of P_{Lr} and T.

The uncertainty in the measurement of the additional losses P_{LL} is:

$$u_c(P_{LL}) = \sqrt{T^4\cdot u_c^2(A) + (2\cdot A\cdot T)^2\cdot u^2(T)} \quad (15)$$

Table 4 shows the results for the additional losses and for the associated combined uncertainty. Concerning the residual losses, a value of the correlation factor γ equal to 0.97 was reached. This value is slightly lower than the desired 0.98 but can be considered satisfactory, considering the complexity of the measurement procedure; therefore, no point must be removed from the linear regression. A value of 0.1676 W/(Nm)^2 for A was obtained, with combined uncertainty $u_c(A)$ equal to 0.0854 W/(Nm)^2.

Table 4. Experimental results—additional losses with uncertainties according to [5].

Load	P_{LL} [W]	$u(P_{LL})$ [W]	$u_{Rc}(P_{LL})$
25%	3.548	1.809	50.99%
50%	13.509	6.918	51.21%
75%	29.214	14.878	50.93%
100%	55.374	28.282	51.07%
115%	68.414	34.839	50.92%
125%	83.378	42.458	50.92%

The relative combined uncertainty is around 50%, which is a better value than the uncertainty obtained for residual losses. If a coverage factor k equal to 2 or 3 is considered, an extended uncertainty of 102% or 156% is obtained, respectively. Such a large uncertainty seems to go in the opposite direction to that illustrated in the standard, whose objective is to define the procedures for “low uncertainty”.

A comparison with the results obtained according to the previous version of the standard 60034-2 [8] is useful; in this version, the additional losses at full load are equal to 0.5% of the nominal power input P_1, and in the variable load test they are:

$$P^*_{LL}(I) = 0.005\cdot P_1\left(\frac{I^2}{I_n^2}\right) \quad (16)$$

For the considered induction motor, rated P_1 is 6523.59 W. In Table 5, the additional losses, according to (16) are presented. The obtained combined uncertainty is smaller than in Table 5 because it depends only on the accuracy of the RMS current measurement.

Table 5. Experimental results—additional losses with uncertainties according to [6].

Load	I [A]	$u(I)$ [A]	P^{*}_{LL} [W]	$u_c(P^{*}_{LL})$ [W]	$u_{Rc}(P^{*}_{LL})$
25%	4.99	0.002	7.094	0.006	0.085%
50%	6.39	0.002	11.633	0.007	0.060%
75%	8.04	0.002	18.416	0.009	0.049%
100%	10.32	0.004	30.342	0.023	0.076%
115%	11.31	0.004	36.443	0.026	0.071%
125%	12.38	0.004	43.665	0.028	0.064%

The question is: are the measurement results for the additional losses P_{LL} and P^{*}_{LL} compatible, from a metrological point of view? The answer is to be determined by considering the graph shown in Figure 2, in which it is clear that the P^{*}_{LL} values are inside the confidence interval of P_{LL} even if the coverage factor k is 2. The extended accuracy of P^{*}_{LL} is not graphically appreciable.

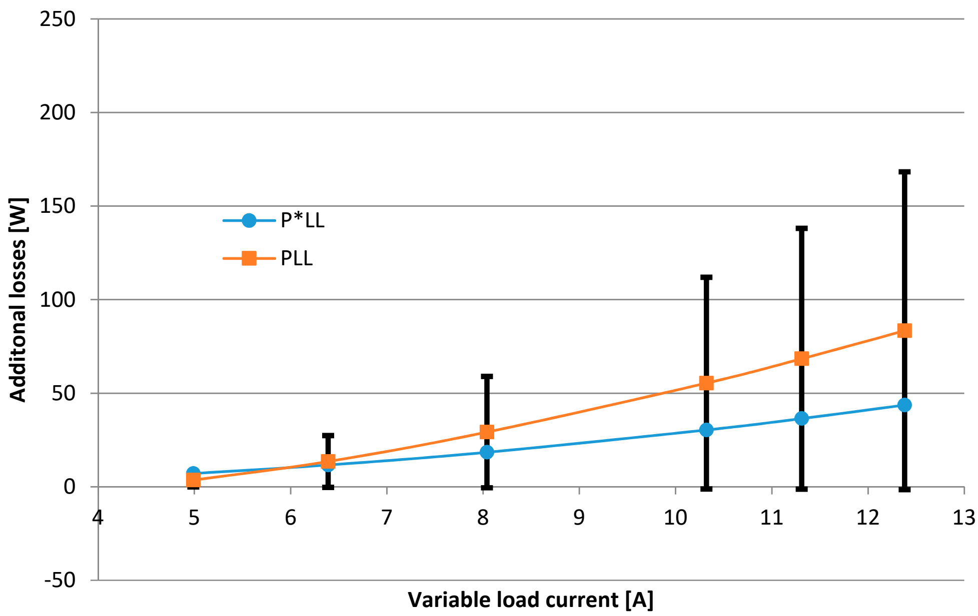

Figure 2. Comparison among the additional losses, with the extended uncertainties.

It can be stated that, from a metrological point of view, measuring additional losses in this version of the standard [14] does not increase the level of information on this quantity, compared to the previous approach, which is easier to implement. The results obtained with the two methods are compatible because of the large uncertainty due to the adopted method, which implements a subtraction for the evaluation of a small quantity.

The main issue is that in this standard, as in other standards concerning measurement procedures, the quantification of accuracy is commonly neglected since the achievement of "low" uncertainty is briefly relegated to the adoption of instrumentation, allowing a defined accuracy level for the directly measurable quantities. The latter are not considered targets for the maximum combined uncertainty for the derived quantities. In this standard, there is only one check for the quality of the performed measurements; the evaluation of the correlation factor at the end of the process. If it is less than 0.95, the measurements must be repeated. This approach is not correct because it does not help operators to identify problems. It is our opinion that specific requirements must be introduced for the extended accuracy of each type of loss, in order to support operators in correcting problems that can be connected both to the performance of correct measurements and to the subsequent data processing.

6. Effects on the Efficiency Measurements

For the evaluation of efficiency, it is necessary to investigate whether, by replacing measured additional losses with estimated additional losses, with the corresponding combined uncertainty, the two efficiencies are compatible.

For the indirect method, the efficiency is defined as:

$$\eta = 1 - \frac{P_{s,\theta} + P_{r,\theta} + P_{fw} + P_{fe} + P_{LL}}{P_1} \tag{17}$$

Meanwhile, the combined uncertainty $u_c(\eta)$ is:

$$u_c(\eta) = \sqrt{\left(\frac{\partial\eta}{\partial P_1}\right)^2 \cdot u(P_1)^2 + \left(\frac{\partial\eta}{\partial P_{s,\theta}}\right)^2 \cdot u(P_{s,\theta})^2 + \left(\frac{\partial\eta}{\partial P_{r,\theta}}\right)^2 \cdot u(P_{r,\theta})^2 + \left(\frac{\partial\eta}{\partial P_{fw}}\right)^2 \cdot u\left(P_{fw}\right)^2 + \left(\frac{\partial\eta}{\partial P_{fe}}\right)^2 \cdot u\left(P_{fe}\right)^2 + \left(\frac{\partial\eta}{\partial P_{LL}}\right)^2 \cdot u(P_{LL})^2} \tag{18}$$

from which:

$$u_c(\eta) = \sqrt{\left(\frac{P_{s,\theta}+P_{r,\theta}+P_{fw}+P_{fe}+P_{LL}}{P_1^2}\right)^2 \cdot u(P_1)^2 + \left(-\frac{1}{P_1}\right)^2 \cdot \left(u(P_{s,\theta})^2 + u(P_{r,\theta})^2 + u\left(P_{fw}\right)^2 + u\left(P_{fe}\right)^2 + u(P_{LL})^2\right)} \tag{19}$$

With the indirect method, the total losses are 705.405 W, the efficiency η^1 is 0.8870, and $u_c\left(\eta^1\right)$ is 0.0079; by replacing the additional losses with estimated ones processed with the method in (16), the total losses are 680.210 W, the efficiency η^2 is 0.8910, and $u_c\left(\eta^2\right)$ is 0.0066. The corrected input power is 6242.68 W, with a combined uncertainty $u_c(P_1)$ equal to 41.032 W.

To investigate if the two efficiencies are compatible, in Figure 3, the central values with the combined uncertainty ranges are presented. Even with a coverage factor of k = 1, the measurements are compatible, so the estimated additional losses could be adopted without affecting the correctness of the efficiency measurement.

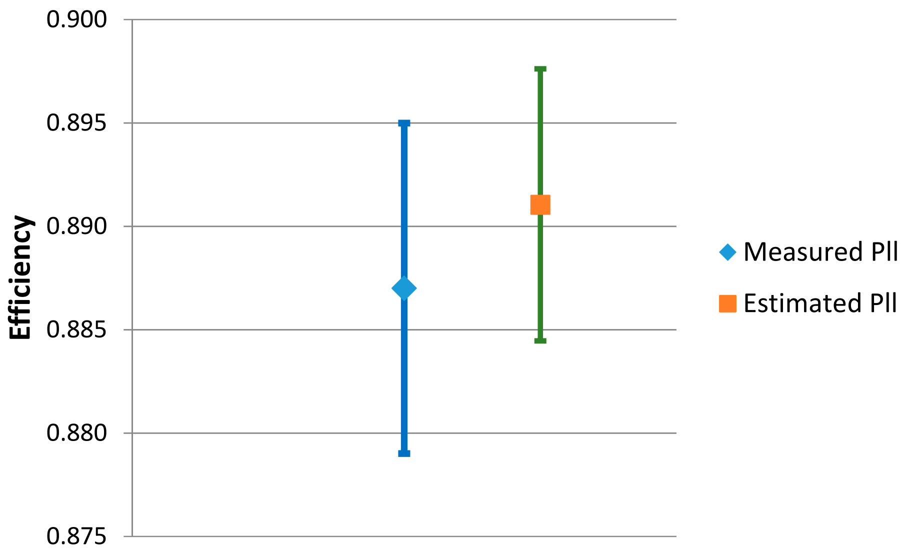

Figure 3. Comparison between the experimental efficiencies, with combined uncertainties.

For a three-phase induction motor with two poles and 5.5 kW of the rated power, the minimum efficiency values defined in IEC/EN 60034-30-1:2014 [20], based on the test methods specified in IEC 60034-2-1:2014 [14], are: (i) for IE1, 0.847; (ii) for IE2, 0.870; (iii) for IE3, 0.892; and (iv) for IE4, 0.909.

The tested motor rated efficiency is IE2; the motor has been correctly classified. If we consider Figure 4, in which a coverage factor of k = 2 is applied, in comparison with the IE efficiency for the size of the motor, it is not excluded that the motor could also be rated as IE3; for k = 3, the same motor could also be rated as IE4 (Figure 5).

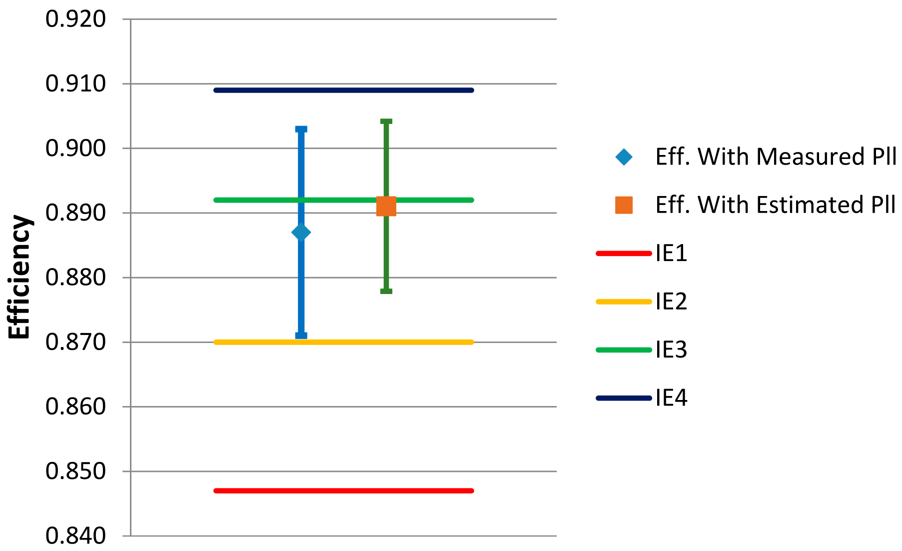

Figure 4. Comparison between the experimental efficiencies, with extended uncertainties coverage factor 2, and IE efficiency levels.

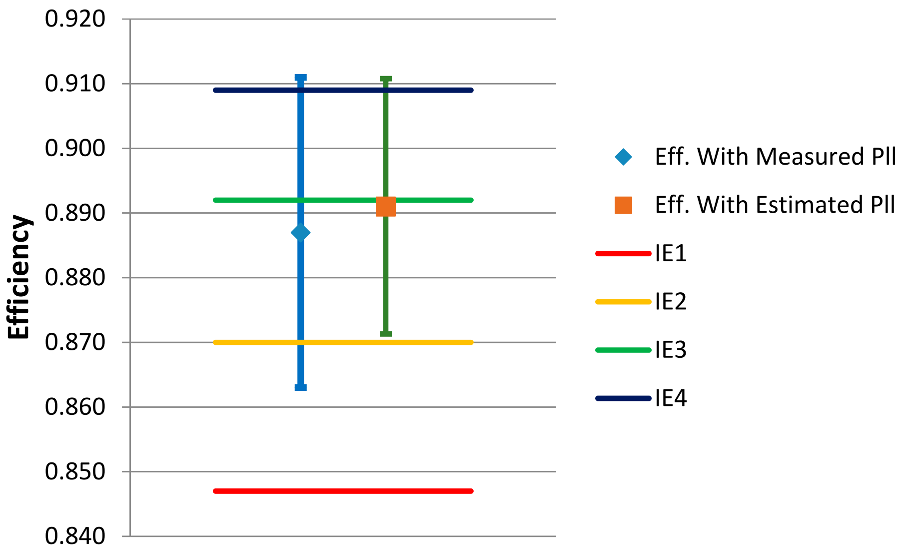

Figure 5. Comparison between the experimental efficiencies, with an extended uncertainties coverage factor of 3, and IE efficiency levels.

The two different measurement methods lead to the same IE efficiency rating of the tested motor. It should be emphasized that the extended accuracy required for standard measurements should be discussed together with the definition of efficiency classes. In other words, if the difference between the two IE classes is lower than the realistic extended uncertainty, which is actually obtainable according to the standards, it is very difficult to classify the motor univocally. Therefore, legal issues could also arise in the event of experimental control of the IE classification of the engine declared by the manufacturers, according to the surveillance that each EU country is invited to carry out [13].

7. Conclusions

In every experimental test, especially in efficiency measurements, the measurement uncertainty of the results must be processed and declared. In this paper, a discussion is presented concerning the combined uncertainty in measuring residual and additional losses in the efficiency evaluation of three-phase induction motors.

With the support of experimental results obtained on a commercial motor, the combined uncertainties obtainable according to a previous version and the current version of the IEC 60034-2-1 standard are elaborated, obtaining fully compatible results.

It can be concluded that the complex measurement method introduced in the present version of the standard may not be justified, because its uncertainty is so large that the additional losses obtained are compatible with those obtained with assigned values, according to the previous and simpler procedure.

This issue is present whenever a measurement result is not considered as a set of quantity values, but only as a single value. The paradoxical effect is that when moving toward a more accurate estimation of an experimental quantity, the uncertainty increases due to the combined effects of an increasing number of new quantities, each of them having its own uncertainty.

Finally, the processing of extended uncertainties in the measurement of efficiency can lead to additional issues concerning the classification of the tested motor, in comparison to the IE efficiency levels. If the difference between two contiguous IE levels is lower than the extended uncertainty, the same motor could be classified as conforming to both the considered levels.

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