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RESEARCH ARTICLE

Assessment of iec 60034-2-1 in determining induction machine efficiency

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ABSTRACT

This paper evaluates the efficiency of induction machines and measurement uncertainties arising from applying two editions of the International Electrotechnical Commission (IEC) testing standard in industry. Machine testing standards vary in methodology, procedure and required instrumentation accuracy, therefore leading to significant discrepancies in the experimentally determined efficiency for the same induction machine tested to different standards as well as by different testing personnel. Five new induction machines with ratings between 7.5 and 150 kW are carefully tested using IEC 60034-2 (old edition), 60034-2-1 (new edition) and Institute of Electrical and Electronics Engineers (IEEE) standard 112 method B which is used as a benchmark. Furthermore, a 30 kW calorimeter is employed to validate power loss measurements and a realistic uncertainty estimation (RUE) is adopted to assess associated measurement uncertainties in power losses and efficiency, and then to assess the standard methods. Experimental results and uncertainty analysis confirm that IEC 60034-2-1 standard has improved over its previous version in defining a set of higher instrumentation accuracy, a more detailed testing procedure and more accurate models for core loss and particularly stray load loss (SLL). Overall, calorimetric methods justify the effectiveness of IEC 60034-2-1 in terms of providing reliable power losses and efficiency. Finally the need for a unified international induction machine testing standard is highlighted. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS
calorimetry; efficiency; IEC; IEEE standards; induction machines; loss measurement

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1. INTRODUCTION

Induction machines are acknowledged to be the 'workhorse of industry': both in terms of fixed speed and variable speed applications. In the European Union, electrical machines used in industry consume approximately 60–70% of the total electrical supply [1]. The majority of these are induction machine drives of some kind. Because of this, an accurate knowledge of machine efficiency is highly desired by both machine manufacturers and end-users if they are to evaluate potential energy savings and environmental benefits.

To produce a highly efficient machine is one thing but to label it with a correct efficiency figure on its nameplate is quite another. This is because that the measured efficiency can be significantly affected by the testing method used and by the test personnel who conduct the practical measurements. Both of course are prone to measurement uncertainty. Sometimes the measured efficiency can differ by 2–3% between different testing methods or between different testing personnel [2,3]. These discrepancies represent an enormous energy gap when induction machines are considered in the context of global population and operating duty. Without a correct (or at least consistent) determination of machine efficiency, it would be difficult to make meaningful improvements in machine design, or for the marketplace to favour those manufacturers who produce high-efficiency induction machines.

In regard to testing standards, the Institute of Electrical and Electronics Engineers (IEEE) 112 [4] has long been recognised as a reliable standard which provides several methods to estimate machine efficiency. However, the most accurate of these methods (i.e. method B) requires high-precision instruments and intrusive load connection; thus, limiting its use in field conditions. The International

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Electrotechnical Commission (IEC) standard 60034-2 [5] (hereafter referred to as the old IEC standard) has been widely used in industry, especially within Europe. The standard is relatively easy and economic to implement and does not critically rely upon high-precision measuring instruments for comparing the efficiency of different machines. Nonetheless, it has been criticised for decades, partly due to its specification of low instrumental accuracy, but mainly, for its invalid allocation of stray load losses (SLLs). In September 2007, a new standard IEC 60034-2-1 [6] (hereafter referred to as the new IEC standard) was published. This is thought to be a refinement of IEC 60034-2. However, its effectiveness is in need of experimental validation.

This paper investigates the major modifications made in the new IEC edition. Firstly, the paper outlines the analytical methods used to assess machine losses and efficiency; and then compares both editions with the aid of a practical case study. By investigating the major measurement uncertainties and assessing their relative influences on loss and efficiency calculations using a perturbation-based realistic uncertainty estimation (RUE) technique, the overall accuracy of these loss and efficiency calculations, with respect to the standard, can be obtained.

For the case study, a test rig was set up to directly measure machine power losses using the methods defined by the standards. Five new general-purpose three-phase induction machines rated at 7.5, 30, 75, 110 and 150 kW were carefully tested to both IEC standards and IEEE 112-B; the latter being used as a benchmark. Besides, a high-precision 30 kW calorimeter [7] was employed to independently test a 30 kW induction machine for validation purposes.

2. TESTING STANDARDS

2.1. International Electrotechnical Commission (IEC) 60034-2 (Old IEC standard)

It is well understood that measurement accuracy vitally depends on the accuracy of the measuring instruments used. Therefore, because the old IEC standard has relatively loose accuracy specifications (Table I), then by implication, it is not expected to yield very accurate results.

However, the most heated debate surrounding the old standard arises out of its prediction of SLLs. Instead of direct measurement as suggested in IEEE 112-B, the old IEC standard recognises the experimental difficulty of measuring the SLL and, thus, nominally allocates 0.5% of input power to the SLL at rated condition. For other load points, SLLs are assumed to vary as the square of the stator current. The problem is that this level of SLLs is atypically low for most small machines (below 150 kW) and this approach had been questioned by many authors in the past [8–13]. In the authors' previous study on 23 new induction machines rated between 5.5 and 225 kW, the ratios of SLL to input power were found to be within the range of 0.1–1.8%. This can be seen in Figure 1, where the SLLs indeed vary remarkably from one machine to another even though some of the machines are similarly rated. Obviously, for this group of 23 new products, the old IEC standard underestimates the magnitude of SLLs in most cases.

Table I. Instrumental accuracy and efficiency uncertainty (±%).

Parameter	Old IEC std	New IEC std	IEEE 112-B
Power	1	0.2	0.2
Voltage	1	0.2	0.2
Current	1	0.2	0.2
Torque	1	0.2	0.2
Speed	1	0.1	0.1
Frequency	1	0.1	0.1
Resistance	0.5	0.2	0.2
Temperature (°C)	2	1	1
Instr. transformer	1	0.2	0.2
Error in eff. (MUE)	1.3	0.34	0.31
Error in eff. (RUE)	0.72	0.19	0.17

Furthermore, when the stator I^2R loss is calculated by this standard, the measured stator winding resistance is corrected, depending upon the machine's insulation class, to a reference temperature of 75°C for Class A and Class E, 95°C for Class B, 115°C for Class F and 130°C for Class H. It is clear that this correction does not necessarily relate to the temperature the stator winding will achieve under normal operating condition. For instance, if an induction machine runs cooler than assumed, the stator joule loss by this method would be overestimated.

These downsides have been improved in the new edition of the IEC standard.

2.2. International Electrotechnical Commission (IEC) 60034-2-1 (New IEC standard)

In the new IEC standard, the instrumentation accuracy has been raised (Table I). The standard defines the same

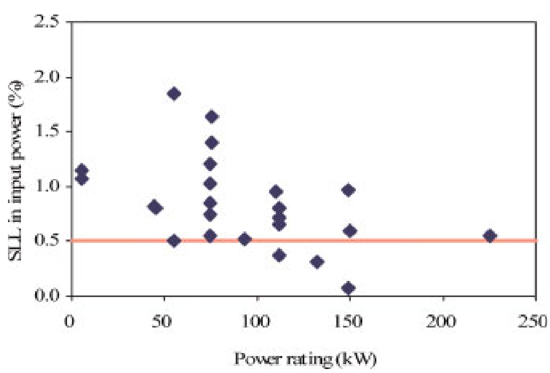

Figure 1. The ratio of SSL to input power by experimental determination.

instrumentation accuracy as IEEE 112 for measuring the major electrical and mechanical parameters.

The new standard also specifies an accurate determination of core losses under all load conditions. In the old standard, the core loss is assumed to be independent of loading, whilst it varies with the loading, in the new standard, based on the stator resistance voltage drop. That is, the core loss slightly reduces as the load increases.

In determining the SLL, the new IEC standard provides three methods: input-output method, Eh-star method (for motors rated between 1 and 150 kW) and empirical allocation. In the input-output method, it employs exactly the same technique as its IEEE counterpart by segregating the residual loss and smoothing it *via* the linear regression analysis. In the Eh-star method, the uncoupled motor is connected in star and fed by an unbalanced voltage supply. Since two phases are connected in parallel through an additional resistance, it removes the necessity of dynamometer and loading, and thus reduces the complexity and associated costs. Another feature of this method is that the test is conducted on a cold motor and carried out as quickly as possible to avoid excessive unbalanced heating of the three phases. The Eh-star method has been proven to be an accurate and economic alternative to direct measurement [14,15]. The third method allocates varying ratios to SLLs, as a function of machine rating, as shown in Figure 2. Whilst this is a definite improvement compared to the fixed allowance made in the previous edition of the IEC standard, it must be reiterated that SLLs are machine specific [16], and any arbitrary allocation for this should be avoided when direct measurements can be made.

With respect to the stator I^2R loss, the new standard requires the winding resistance to be corrected to an ambient temperature of 25°C together with an actual temperature rise (under rated condition), similar to the requirement in IEEE 112-B. But, the stator winding resistance is directly measured before the highest load and after the lowest load points by stopping the machine, measuring the terminal resistance and extrapolating back to zero time. This approach assumes the same resistance at all loads between the rated and highest load points. The resistances between the lowest and rated loads are calculated by an arithmetic mean of the above two measurements through a straight line interpolation. In general this approach may be accurate for the two measured load points, but not for those in between. Moreover, the speed at which these measurements should be made is open to interpretation and the tester's personal experience.

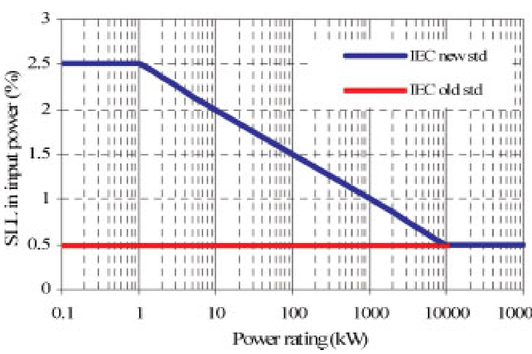

Figure 2. Assigned allowance for SLLs by the two IEC editions.

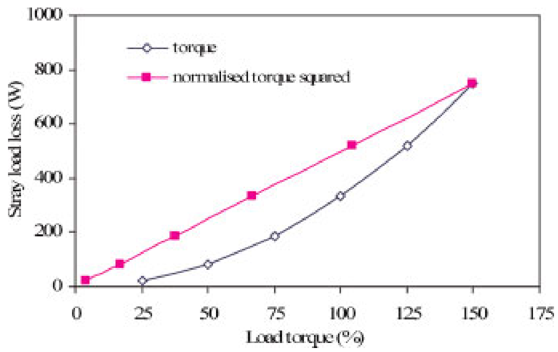

Figure 3. Curve fitting for SLLs by the new IEC standard (with hypothetical values).

In no-load and partial-load tests, the new standard categorically specifies the testing voltage/load points, which were not done so in the previous edition. This is another improvement but still has its flaws. Taking the load tests for example, the standard specifies at least six approximately equally spaced load *torque* points between 25 and 150%. However, when deriving SLLs the test results are plotted against load *torque squared*. This is shown in Figure 3 for clarity. It is evident that, by extrapolating a linear line to zero torque, the higher load points will carry a greater weighting factor over the lower ones and thus dictate the level of SLLs. A similar scenario occurs for no-load tests in specifying the voltage points to separate windage and friction, and core loss. In fact, these problems can be easily overcome by specifying testing points with approximately equal spacing of torque squared (for load tests) or voltage squared (for no-load tests), including these rated load torque/voltage points.

Based on the improvements made in the new IEC standard, it is thus expected to provide more accurate loss and efficiency results than the old IEC standard.

2.3. Institute of Electrical and Electronics Engineers (IEEE) 112-B (Reference)

It is widely accepted that IEEE 112 represents a milestone in machine testing standards and has stood the test of time. In this standard, a set of relatively high instrumentation accuracy is specified, as is given in Table I.

Also in this standard, the stator resistance is determined by direct measurement prior to any heat run. This serves as a reference resistance (together with the measured winding temperature) and is later used to calculate winding

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resistances under test conditions, with reference to winding temperatures which are measured. This approach may be better than the IEC new standard as long as the mean winding temperature can be detected with precision. But, this is generally intrusive and technically challenging under field conditions.

Another potential problem with the IEEE 112-B standard is that it does not compensate for stator resistance voltage drop in core loss calculations. This may result in an overestimation of core loss under load conditions and can subsequently affect the calculation of SLLs. Nevertheless, as a compromise, the standard makes provision for the SLL to be determined directly by dynamometer testing and to be corrected to a specified condition.

Overall, IEEE 112-B is capable of yielding reliable and repeatable loss and efficiency results. In this paper, therefore, it is used as a benchmark to justify the IEC new standard.

3. TESTING FACILITIES

Figure 4 shows a schematic of the experimental setup for standard machine testing. The test equipment includes a dc load machine coupled to the test machine by a torque transducer mounted in a Carden shaft. There are no additional bearings in between the torque transducer and the test machine. Dc machine armature current control ensures smooth torque even at light load. The test machine is supplied by an ac generator (alternator) which is driven by an inverter-fed synchronous motor. This guarantees a reliable ac supply with a precise supply frequency. The generator itself is controlled by the automated voltage regulator and is capable of providing for the machine under test an ac voltage from 0 to 130% of nominal value. As a result, supply imbalance and distortion are negligible with a balanced load in the test. Coupled to the same shaft as the generator and the synchronous motor is another dc machine which reclaims energy from the test machine. These as a whole form an improved Ward Leonard system.

In addition to this test rig, a separate 30 kW calorimeter is also employed for validation of power loss measurements. This calorimeter is capable of measuring power losses in induction machines of up to 30 kW with an overall measurement accuracy of better than 0.2%.

It should also be pointed out:

(i) The calorimetric tests are of long duration and costly.
(ii) There is a difference between calorimetric and standard methods in partial-load tests. Standard partial-load tests should be conducted under the same thermal conditions that apply to rated load. Using the calorimeter, however, partial-load tests take place at the steady state machine temperature associated with that partial-load condition. This may lead to some differences between the two methods for all partial-load results, especially if the test machine is experiencing a rapid temperature change while the measurements are being taken.

4. ESTIMATING MEASUREMENT UNCERTAINTY

In any measurement, the methodological, instrumental and human uncertainties are three key sources of uncertainty. In the case of machine testing, the methodological uncertainties are caused by inadequate theory of loss predictions, incomplete definition of the test and imperfect realisation of the test procedure. The instrumental uncertainties arise from the inaccuracy of instruments used for electrical and mechanical measurements. The human uncertainties are generally associated with the ways the personnel interpret the standards, conduct the test and process the test results.

In the literature, the maximum uncertainty estimation (MUE) has been reported for evaluating measurement uncertainty [17,18]. For instance, the uncertainty (ε) in

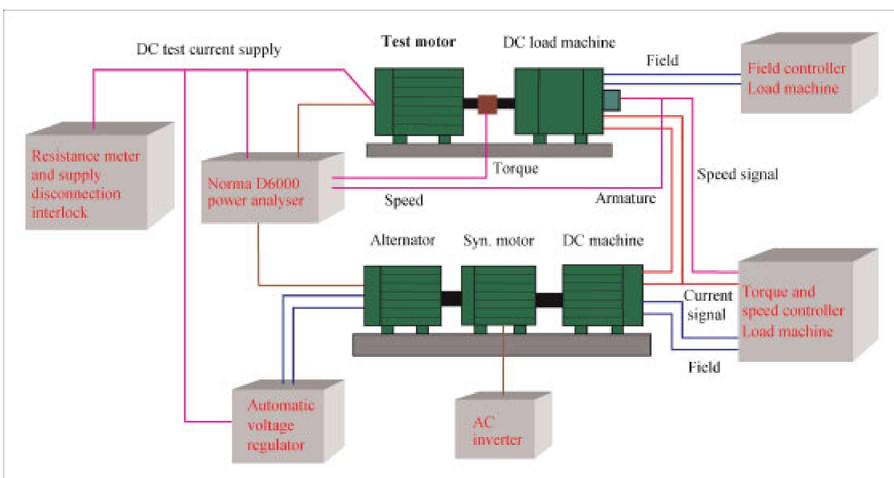

Figure 4. Schematic of the test rig [16].

machine efficiency (η) can be estimated by the following equation:

$$\eta(1+\varepsilon) = \frac{P_{\text{out}}(1 \pm \varepsilon_1)(1 \pm \varepsilon_2)...(1 \pm \varepsilon_m)}{P_{\text{in}}(1 \pm \varepsilon_a)(1 \pm \varepsilon_b)...(1 \pm \varepsilon_n)} \quad (1)$$

where $\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_m$ are the fractional uncertainties in the measured parameters associated with the calculations of output power P_{out} and $\varepsilon_a, \varepsilon_b, \ldots, \varepsilon_n$ are those associated with input power P_{in}.

From Equation 1, the maximum and minimum efficiency values are determined and then used to estimate the spread of measured efficiency. In essence, this method combines all of the possible and maximum instrument-related uncertainties present in a measurement. Clearly it represents an over-exaggerated worse case of measurement uncertainty which is highly unlikely to happen in the real world.

In order to improve this method, a perturbation-based RUE [19] is adopted in this paper. It recognises the differing influence of each measured parameter, and incorporates all the major uncertainty contributors in a quadrature addition, with reference to the instrumental accuracy specified in the standard.

Influence coefficients for each of the measured variables are determined by changing the value of that variable by a small amount Δx, and recording the corresponding change Δy in the output variable. After making a series of such perturbations, the influence coefficient for a variable can be calculated. By taking account of the accuracy of the measuring instrument for the variable, the impact of an uncertainty in the measurement can be quantified and also be compared with other uncertainty contributors.

The overall uncertainty by the RUE is given by

$$\varepsilon_y = \sqrt{\sum_{i=1}^{n} (I_{x_i}\varepsilon_{x_i})^2 + \frac{1}{y^2}\sum_{j=1}^{m} (W_{z_i} z_j)^2} \quad (2)$$

where ε_y is the fractional uncertainty in y, I_{x_i} is the influence coefficient of an uncertainty x_i on y and W_{z_i} is the influence coefficient of a noise z_j on y.

5. RESULTS AND DISCUSSION

The details of five test machines are given in Table II. All five machines were tested on the test rig following the standard input-output methods defined in IEC 60034-2, 60034-2-1 and IEEE 112-B. Additionally, a 30 kW machine (machine 2) was also independently tested inside the calorimeter.

Table II. List of test machines.

Machine	1	2	3	4	5
Rating (kW)	7.5	30	75	110	150
Voltage (V)	400	400	400	400	400
Current (A)	14.5	54	142	198	255
Frequency (Hz)	50	50	50	50	50
Speed (rpm)	1455	1465	1478	1487	1488

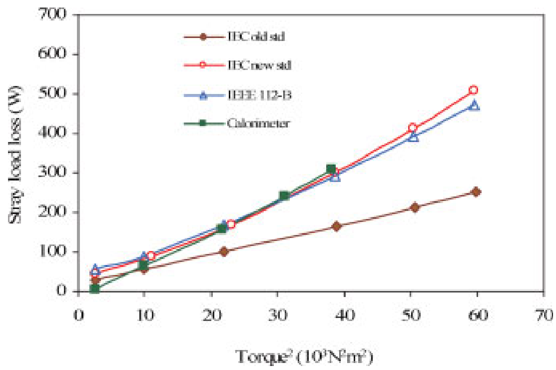

Figure 5. SLL results by calorimetric and standard methods.

5.1. Calorimetric tests

Because the SLL is sensitive to measurement uncertainty associated with the subtraction of the identifiable losses from the total loss, it is used here for comparison between standard input-output and calorimetric methods. Test results are plotted in Figure 5 for machine 2. Five load points at approximately 25, 50, 75, 90 and 100% were obtained by the calorimeter while six load points at approximately 25, 50, 75, 100, 125 and 150% were tested by the standard methods. It is obvious in Figure 5 that standard test results are validated by the calorimetric method, with the exception of the old IEC method which is inaccurate. For this particular machine, 0.5% of input power allocated by the old IEC standard is lower than the actual SLL.

From these curves it can also be argued that the new IEC results are closer than others to the calorimetric results over the whole load range. This is due to its more accurate determination of core loss where the stator voltage drop is offset. At light loads the SLL results differ significantly for all methods. This is explained by the diverse procedural definitions and rapid thermal disturbance the machine is experiencing when the load is reduced from the highest to the lowest during the test.

5.2. Power losses

For these five machines, the measured losses present different types of discrepancy. Between the two IEC standards, the differences in core loss and, friction and windage losses (at rated load) are slight although the new standard specifies a more accurate method for determining the iron loss. Here therefore, attention is focused on stator joule loss, rotor joule loss and SSL.

As can be seen in Figure 6, the two IEC methods yield similar rotor joule losses and slightly different stator joule losses. For the five machines tested (all with insulation Class B), the actual winding temperatures at rated load were close to 95°C for machines 1, 2 and 4 but were 120.3 and 104.7°C for machines 3 and 5, respectively. As a

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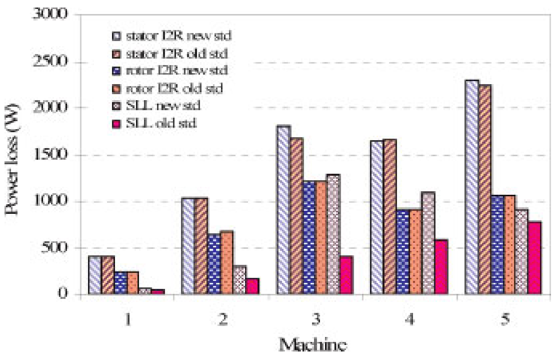

Figure 6. Comparisons of three loss components between the two IEC editions.

consequence, for the latter two machines the stator joule loss is slightly underestimated by the old IEC standard (Figure 6).

However, the biggest difference still lies in SLL results despite the fact that this loss component is generally a small portion of the total loss [20,21]. Among all five machines under test, the discrepancies are significant for machines 3 and 4.

Taking the extreme case (machine 3) for example, the rated SLL by the new IEC standard is 1281 W, which is three times more than that assumed by the old IEC standard (405 W). Further investigations reveal a subtle degree of machining on the rotor surface. This helps explain why this machine runs hotter than others. Machining the stator or rotor is a common practice in repair shops to increase the air gap or to mitigate rotor asymmetries but is rarely exercised on new machines. In theory, most of the SLL occurs in stator and rotor teeth at the air-gap surface [22] so that the machining can have a significant impact on this loss component [3]. Furthermore, the machining of machine 3 also gives rise to rotor joule loss, which is 21% of the total loss in this case and which is greater than that of a similarly rated machine. For this machine, an arbitrary assumption of 0.5% by the old IEC standard is proved to be an underestimate of the SLL in reality.

Not surprisingly for machine 3, the discrepancy in SLL, in conjunction with that in stator joule loss (127 W), will reduce the efficiency of the new IEC standard by 1.1% compared with the old standard. Clearly, the method by which the SLL is determined can significantly influence the calculated efficiency.

5.3. Machine efficiency

Machine efficiency results are illustrated in Table III. There are three observations that can be made from this table. Firstly, all the efficiency figures from the old IEC standard are greater than those of the new IEC standard and IEEE 112-B, by 0.2–1.2%. This confirms a long-standing view that the old IEC standard generally yields optimistic efficiency values [12,23,24]. Secondly, the ratios of SSL to input power for the five machines are all in excess of 0.5%. Again, this is the main cause for falsely higher efficiencies by the old IEC standard. Thirdly, the new IEC standard provides nearly the same efficiency figures as the IEEE counterpart with differences virtually within the measurement accuracy. Although the new IEC and IEEE 112 standards adopt different approaches to determine the stator winding resistance (and thus stator joule loss), the consequent variations in nominal efficiency are insignificant for this group of machines. This is due to the fact that the SLL is a collection of all measurement uncertainties and is finally corrected by a linear regression approach. In effect, the impact of every uncertainty on the efficiency is minimised.

Table III. Efficiency results for different standards (%).

Machine	1	2	3	4	5
Old IEC std	89.0	92.7	94.2	95.3	95.6
New IEC std	88.6	92.5	93.1	94.7	95.3
IEEE 112-B	88.7	92.5	93.0	94.8	95.4
SSL/input power	0.79	0.51	1.58	0.94	0.58

5.4. Instrumental measurement uncertainty

The effect of measurement uncertainty on machine loss and efficiency calculations was established in Matlab, following the previously described MUE and RUE methods. Major measurement uncertainties associated with input power, supply voltage and frequency, load torque and speed, stator current, resistance and temperature were taken into consideration when assessing the sensibility of measurement uncertainty.

Again, since the SLL is susceptible to measurement uncertainty, it is used to detect the uncertainty's sensibility. Test results from the new IEC standard are shown in Table IV for comparison. It is necessary to indicate that in this study input power is obtained from the measurements of voltage and current by three-phase power analysers. Seen from this table, supply voltage, stator current, load torque, supply frequency, winding resistance, rotor speed and winding temperature are the most significant factors in descending order. This of course is easily understood since the SLL is derived from the input power (voltage, current) deducting the output power (torque, speed) and further deducting the identifiable losses. Similarly, supply frequency is critical for accurate determination of slip which has a direct bearing on the rotor joule loss. However, it is striking to find that the rotor speed is much less significant in the estimation of SLLs albeit it is in the output power calculations. First, speed can easily be measured to an accuracy of 1 rpm. In relative term, this would be translated into 0.07% (for a 50 Hz 4-pole motor) or 0.03% (for a 50 Hz 2-pole motor). Fractional perturbations in this already small uncertainty will clearly

Table IV. Uncertainty's influence and impact on the SLL by the new IEC standard.

Parameter		Influence coefficient	Realistic error (%)	Rank of impact
Power	Voltage	0.68	0.14	1st
	Current	0.65	0.13	2nd
Torque		0.62	0.12	3rd
Frequency		0.61	0.07	4th
Resistance		0.03	0.005	5th
Speed		0.006	0.001	6th
Temperature		0.005	0.0003	7th

show little impact on the SLL. Second, the total power crossing the air gap includes the output power and rotor joule loss. In principle, the rotor speed simply defines how the air-gap power is split between the two. Therefore speed inaccuracy has a minimised effect on the SLL. Nonetheless, it is worth emphasising that its impact on the efficiency is a totally different story.

After attaining each uncertainty's influence coefficient and its impact on the machine efficiency, a method's measurement accuracy can be estimated by adding major uncertainties' influence coefficients in a quadrature manner, with respect to the instrumental accuracy defined by the standard. These are also presented in Table I where calculation results are averaged out owing to their similarity among the five machines. It can be observed that the new IEC standard is capable of determining machine efficiency to an accuracy of 0.19% with the worst-case uncertainty of 0.34% whilst the old IEC standard can provide an accuracy of 0.72% with the worst-case uncertainty of 1.3%.

Clearly, these results demonstrate that, from an instrumentation view point, the new IEC standard is justified in measuring the relatively small loss component of an induction machine in an accurate and repeatable manner.

6. CONCLUSIONS

This paper has investigated the induction machine efficiency and its related uncertainty from machine testing, based on the application of two editions of IEC testing standards: the focus here, being on the newly published standard IEC 60034-2-1. The improvements in the new IEC standard are found to be: the specification of higher instrument accuracies, a more detailed definition of the test procedures to be followed and the use of more accurate models for estimating core loss and SLL. One possible problem with the new standard is the way in which it determines stator winding resistance. Nevertheless, personal experience and care taken during the tests may help minimise this uncertainty.

Experimental results from the case study involving five induction machines have confirmed the effectiveness of the new IEC standard. These results have been validated by the calorimetric method. It can be concluded that the new IEC standard has highly aligned itself with IEEE 112 and it can provide reliable loss and efficiency results provided its testing procedures are followed.

However, in the era of today's global marketplace, there is an increasing need for a single internationally accepted standard used in industry for evaluating induction machine performance. For this to happen there is a need for greater co-operation between the IEC and IEEE (ANSI) standard making bodies, and, whilst at present some degree of harmonisation has been established, such as agreeing dual logo standards and providing comparisons between their equivalent standards, real progress toward a unified international standard is slow and the way forward remains cloudy.

LIST OF ABBREVIATIONS

Symbols

ε	uncertainty
η	efficiency
Δx	perturbation in x
Δy	change in y
P_{in}	input power
P_{out}	output power
I	influence coefficient of an input
W	influence coefficient of a noise
Z	noise

Abbreviations

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MUE	maximum uncertainty estimation
RUE	realistic uncertainty estimation
SLL	stray load loss

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