The use of efficient induction motors is seen as having the biggest potential for saving energy. This is important to South Africa where saving energy is a major concern. Results obtained from tests done on a 3 kW high efficiency motor are compared. The three standards used were the CSA-390, a Canadian standard, IEEE 112, an American standard and the new European standard, the IEC 61971. Results show that the IEEE and CSA-390 produce higher efficiencies than the IEC standards. The reasons for this are discussed. The effects of equipment accuracy and supply harmonics are discussed in brief. A suggestion for a South African Standard with aspects drawn from the standards is put down, as the present SANS IEC 60034-2 (1972) is outdated.

The depletion of raw materials and the negative environmental impact of greenhouse gases have led to a search for energy saving policies, initiatives and research around the world. In South Africa, the situation has been compounded by a growing load demand and low power capacity. Eskom, as South Africa’s main supplier of electricity, produces power on an 8% reserve capacity [1] compared to the required 15% reserve capacity. This small capacity and growing demand has led to power cuts which in turn have led to lost profit [1]. The need for demand side management schemes, such as load efficiency, has therefore become a priority to solve the problem.

In South Africa the industrial and mining sectors are the major user of energy and account for more than two-thirds of the national electricity usage [2]. With motorised loads dominating the industrial sector and accounting for 64% of the country’s load [3], an improvement in energy efficiency of these loads can lead to the potential for cost and energy savings and a reduction of greenhouse gas emission of the order of 740-million tons of CO₂ equivalent per year [4].

Squirrel cage induction motors are the most commonly used motorised loads in industry [2]. They are also the largest single end-users of electricity in the world. These motors are rated from a few hundred watts to several megawatts. The induction motors are characterised by information provided by the manufacturer such as rated speed, power, voltage, current and efficiency [2]. The efficiency on the nameplate (given by the manufacturers) is measured and calculated according to a number of efficiency standards [5]. With many of the motors in South Africa coming from other countries, the efficiency on the motors needs to be consistent. This is not the case due to the different standards used. In this paper, different motor efficiency standards will be discussed.

The paper will discuss the following standards: IEEE 112, IEC 61972, CSA-390, SANS IEC 60034-2 (1972), IS4337 and JEC 2137. A proposal for a South African standard is also presented at the end of the paper.

The paper will begin with theory in efficiency and motor losses. The motor efficient standards will then be discussed. The CSA-390, IEEE 112 and IEC 61972 and other standard test procedures and efficiency determinations will be compared. Results from the testing will then be presented and discussed. Conclusions will then be drawn up.

Determination of efficiency and losses of induction motors

The efficiency of an induction machine represents the effectiveness of the machine in converting electrical power at its input to mechanical energy at the shaft (or output). This can be represented by the equation for efficiency, as:

\[ \eta = \frac{P_{\text{mechanical}}}{P_{\text{electrical}}} + \sum \delta \]  

(1)

The efficiency is therefore the ratio of the input electrical power and the output mechanical power. The difference between the input (electrical) and output (mechanical) power is the sum of the motor losses. This is illustrated in the power flow diagram in Fig. 1 [6]. Motors have been seen to lose a total of 60% of primary input power at certain stages of the energy conversation [2]. The different losses are discussed separately below.

Core losses (stator and rotor core losses)

Core losses (Fig. 1) are caused by eddy currents and hysteresis effects in the laminations and are influenced by the motor flux and frequency [7]. Hysteresis occurs due to magnetic saturation in
the iron from the changing polarity (positive to negative fifty times each second). Eddy current results from circulating and unproductive currents induced by the magnetic field in the stator [8]. These losses are relatively constant and can be obtained by performing no-load test on the motor.

Copper losses (stator and rotor copper losses)
Copper or FR losses, shown in Fig. 1, are losses in the rotor and stator windings [5]. The stator and rotor windings have an internal resistance that is proportional to the current drawn, the diameter and length of wire and rotor bars. The losses are dissipated in the form of heat and vary with the applied load.

Mechanical losses (friction and windage losses)
Mechanical losses or friction and windage losses are losses in the moving parts such as the air gap between the rotor and the stator, friction in the bearings at each end of the rotor, and any cooling fan attached to the rotor [8].

Stray-load losses (SLLs)
Stray losses have been the subject of number of studies and analyses [10]. This is because they are hard to model and to quantify [9]. Stray-load losses can be described as the losses that remain after stator and rotor losses, core losses and mechanical losses have been accounted for [9]. The largest contribution to stray losses is harmonic energies generated when the motor operates under load [10]. These energies are dissipated due to harmonic currents in the windings, harmonic flux components in the iron parts and as leakage in the laminated core. Motor vibration can also be seen as another source of SLLs.

Motor efficiency standards
In this section, the important aspects of the different motor efficiency standards are highlighted. The IEC 61972 is a European standard that has now taken over the old IEC 60034 standard. Australia and China are other countries that are known to also use IEC 61972 [11]. The standard is made up of two methods of testing motor efficiency:

Method 1: uses a torque measurement device to measure the output power and from this derive the SLLs. This method is called a ‘direct method’ and is specified for motors up to 150 kW.

Method 2: determines the SLL by assigning a value that is dependent on the rated power of the machine e.g. for a 1 kW motor, the SLL is 2.5% of full load and a 10 MW motor 0.5% [6]. This type of approach is called an ‘indirect method’.

The IEEE 112 is an American standard that provides a number of methods for testing motor efficiency. These can be classified according to the size of the tested motors or the method approached. Brazil employs the IEEE 112 standard [11]:

Method A: is limited to machines with ratings less than 1 kW.

Method B and B1: is used to test machines (horizontally or vertically mounted) rated in the range of 1 - 300 kW. The efficiency is calculated by taking into account the losses in the motor. The SLLs are indirectly (equation 4) attained. Method B can be used for motors higher than 300 kW when a large number of motors need to be tested concurrently. An assumed temperature is given in method B1.

Methods E, E1, F or F1: are used to test vertically mounted machines in the range of 1-300 kW.

The difference between the first three (methods A, B and C) and the rest of the methods is the latter uses an equivalent circuit to calculate the efficiency.

The CSA-390 is a Canadian standard that provides three methods:

Method 1: is similar to the IEEE 112 Method B with the all losses measured and the SLLs obtained indirectly.

Method 2: omits the torque reading and directly measures SLLs by summing the fundamental frequency and the high frequency components of the stray-load loss.

Method 3: is similar to Method F and uses the equivalent circuit and direct measurements of core loss, windage-friction loss, and SLLs.

Table 1, taken from the standard, shows the use of the methods on different size motors.

The SANS IEC 60034-2 (1972) is a South African standard that is taken from the IEC 60034-2 [12]. The standard is an exact copy of the European standard without any change to the technical aspects [12]. The standard describes methods of testing the efficiency of rotating machines i.e. induction, synchronous and DC motors. Two methods are available in the standard:

Method 1: approximates the efficiency by first calculating the total summation of the machine losses. The SLLs are estimated to be 0.5% of the electrical power [7], [9], [10].

Method 2: the input and output power at the motor shaft are directly measured and used to get efficiency [12].

Other standards that were not available are the Indian standard (IS4337) and the Japanese standard JEC 2137. These are discussed below.

The Indian Standard, like the IEC 60034-2 standard, gives a value of 0.5% of electrical power as the SLLs. This value has been found to be an overestimate [5] or unsupported. This standard has therefore been found to produce higher efficiencies [9].

The JEC 2137 uses an indirect method (the standard either assigns a SLLs value or in this case does not take into account the SLLs to determine the efficiency. The stray losses are ignored and therefore the efficiency has been found to be much higher than both the IEE 112 and IEC 60034-2 [9]. The standard not only ignores SLLs but also the effects of temperature on the copper losses.

The procedures and results produced by testing the IEEE 112 method B, the C390 method 1 and the IEC 61972 method 1 and 2 are not available.
on a 3 kW high efficiency motor will follow. These three methods were chosen because they cover machines rated at less than 150 kW. These size motors are the common machine sizes found in industry [2].

**Lab setup**

The lab setup is shown in the Fig. 3 below.

![Fig. 3: Lab setup.](image)

Two types of supplies were used. A 3-phase voltage supply from the mains (supplied by Eskom) and a supply generated from 250 kVA synchronous generator. The reason for this was to try and minimise the effects of voltage unbalance and voltage harmonics on the efficiency testing. The quality of supply is compared in Table 2. The voltage harmonic content and voltage unbalance were within standard specifications.

<table>
<thead>
<tr>
<th>Comparison of Supplies</th>
<th>Mains</th>
<th>Gen</th>
<th>Standards requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total harmonic distortion</td>
<td>3,946%</td>
<td>1,257%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Voltage unbalance</td>
<td>0,372%</td>
<td>0,071%</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>

Table 2: Comparison of supply.

A Yokogawa power meter was used to record the input frequency, power, voltage and current. A 3 kW high efficiency (eff 3) induction motor was used in comparing the three efficiency standards. Three thermocouples were inserted into the front-end stator windings (see Fig. 3). The front-end windings are the point of highest temperature due their distance from the cooling fan. The thermocouples were inserted in each phase. The different temperatures are shown below. The hottest phase was found to be the phase closest to the bottom of the tested motor.

<table>
<thead>
<tr>
<th>Temperature readings of thermocouples</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>107.07°C</td>
<td>101.69°C</td>
<td>103°C</td>
</tr>
</tbody>
</table>

Table 3: Thermocouple readings.

A 15 kW DC motor was used as a dynamometer and was used to load the tested motor. The DC and tested motor were coupled through a torque transducer. The speed of the motor is measured by an optic tachometer.

**Procedures and calculations**

The CSA-390-1, IEEE 112-B and IEC 61972-1 follow the following main testing procedures and calculations:

**Temperature test**

To accurately compute the losses of a motor, the temperature has to be taken into account. The tested machine is loaded at the rated load and is run until the temperature (of the stator windings) does not change for more than 1°C between measurements (every 30 min). This test allows for the temperature correction of stator winding resistance and therefore correction on the stator losses.

**Variable load test**

The machine is run at the rated conditions; the machine is loaded with six-load point ranging from 150% down to 25%. The winding temperature before the commencement of test has to be more than 10°C for the IEEE 112 and CSA390, and 5°C for the IEC 61972 method during testing. From this test, the stator and rotor losses are calculated (equation in Appendix A).

**No-load test**

The test is done with the motor uncoupled from the loading device (or dynamometer). The tested motor is then run with the supply at rated frequency and voltage (some motors might require a number of hours to stabilise the bearings). The IEEE and CSA-390 uses variable voltages ranging from 125% to the point where current begins to increase (due to loss of voltage and increase in slip) while the IEC uses a minimum of four voltages between 125% and 60% of rated voltage and three or more between 50% and 20% of rated voltage are used. The windage and friction, and core losses are obtained from this test (equations in Appendix A).

The SLLs, in the three standards, are calculated using Eqn. 1. This is an indirect method of acquiring SLLs.

\[
P_{\text{stray loss}} = (P_{\text{input}} - P_{\text{output}}) - P_{\text{windage friction}} - P_{\text{rotor}} - (P_{\text{rotor}}) \times s - P_{\text{core}}
\]

The calculated SLLs are used in a linear regression method and the relationship of the regression determines the quality of testing.

The variations between the standards are mainly found in the calculation of the efficiencies.

**Results**

The results obtained from numerous tests are presented and discussed in this section.

**Efficiencies**

The IEEE-112 and CSA-390 standards produced efficiency values that were almost identical. The average difference between the efficiency values was 0.176%. This can be seen in Fig. 4. This is due to the similar procedure and calculations in the two standards. The efficiency found by these two standards was higher than that of the IEC standard. This is due to the difference in procedure and calculation as mentioned in the previous section.

The IEC standard requires the no-load test to be done immediately after the load test. This ensures that the windings temperature remains as high as possible. This is different from the IEEE and CSA standards, which requires a bearing stabilisation. This procedure allows the winding temperature to fall. These different temperatures relate to a low resistance and high resistance values respectively. This will mean that the IEEE and CSA standard will have lower stator losses than that of the IEC standard. The effect of this is the calculation of different friction and windage (FW) losses. The IEC will have a higher FW loss compared to that of the other two standards.

The inclusion of equation 2 in the IEC standard is another reason for the lower efficiency values. The reduced voltages calculated from the equation produce smaller core losses values.
Fig. 3: Comparison of calculated efficiencies.

\[ U_i = \left( U - \frac{3}{2} I R \cos \varphi \right) + \left( \frac{3}{2} I R \sin \varphi \right) \]  

(3)

where
- \( I \) is the incoming current during no-load test
- \( U \) is the supply voltage
- \( R \) is the stator winding resistance
- \( U_i \) is the approximated voltage

The equation is an approximation of the losses in the primary of the motor.

Stray load losses

The SLL values were used in linear regression (of the SLL versus the torque squared) as check for the quality of the test. The IEEE 112 and CSA-390 together and the IEC 61972 required a correlation factor of 0.90 and 0.95 respectively. The sensitivity of SLLs to the other losses (see equation 1) is the reason for this. If errors are prevalent in the testing equipment or/and in data collection the correlation factor will be low.

Effects of supply harmonics

The effect of harmonics on the efficiency values was found to be very small when the harmonic content is within the specified minimum of the standards. The effects of harmonics were thought to lead to an increase in SLL and this would lead to inaccurate analysis of the quality of the test. The difference in efficiency can be seen in Fig. 4.

Fig. 4: Effects of harmonic content in the supply.

The average difference in the two curves is 0.296% efficiency.

This is a deviation of 0.4%, which is very small.

\[ L_x = \frac{L_{100} \cdot 2^{(T_x - T_c)/HIC}}{2} \]  

(4)

where
- \( L_x \) is the % lifetime at temperature \( T_x \) (in °C)
- \( L_{100} \) is the % lifetime at rated temperature \( T_c \) (in °C)
- \( T_x \) is the hot-spot temperature for insulation class (in °C)
- \( T_c \) is the total allowable temperature for insulation class (in °C)
- \( HIC \) is the halving interval (in °C) (14, 111, 9, 3, 8, and 10 for class A, B, F, H and H’, respectively).

The effects of the high temperatures at such overloads can lead to a degradation of the insulation of the windings. This can be seen from equation 3 taken from [13]. The higher the stator winding temperature (\( T_x \)), the lower the lifetime.

Equipment accuracies

The required instrument accuracies (see Appendix A, Table A1) were very hard to replicate. This meant that the acquired values are limited to the available equipment during testing.

The effects of this are shown in the calculated efficiency graphs, Figs. 3 and 4. The peak efficiency occurs at 55% of loading. This is not the case when it comes to the characteristics of motor efficiencies. Manufacturers produce motors to peak at 75% loading. This is done because motors are normally run under this loading point.

Conclusion

The above results from the different tests done on a 3 kW high efficiency motor show that there is a number of differences in the three standards that were tested. The project is still ‘work in progress’ and errors have been seen. Procedure and calculation differences have also been found in the standards that were not available in time for the final paper. These differences between standards as discussed in this paper and in literature lead to the different values of nameplate efficiencies.

With South Africa’s standard (the SANS IEC 60034-2 (1972)) being outdated, the need for a formulation of a national standard is needed. The standard should not follow a specific standard but should take the positive aspects of the different available standards.

Appendix A

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>±1,0%</td>
<td>±0,2%</td>
</tr>
<tr>
<td>Current (A)</td>
<td>±0,5%</td>
<td>±0,2%</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>±0,5%</td>
<td>±0,2%</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>±0,5%</td>
<td>±0,1%</td>
</tr>
<tr>
<td>Speed (RPM)</td>
<td>±2</td>
<td>±1</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>---</td>
<td>±0,2%</td>
</tr>
<tr>
<td>Resistance (Ohms)</td>
<td>±0,5%</td>
<td>±0,2%</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>±2</td>
<td>±1</td>
</tr>
</tbody>
</table>

*The instrumentation accuracies are also for the IEC 612792 standard.
References


Acknowledgement

This paper was presented at the PowerAfrica 2007 conference in July 2007 and is rephrased with permission.

Contact H M Mzungu, UCT, Tel 021 650-2750, mznhes001@uct.ac.za