Induction motor efficiency test methods: a comparison of standards

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ABSTRACT

In this work, fundamental aspects regarding the efficiency of induction motors are treated. Improved efficiency is the task of the hour. Environmental challenges, which include climate change, global warming and greenhouse gas emission have been fuelling the need to increase energy efficiency in electrical rotating machinery. Furthermore, there is a need to establish a level platform for motor manufacturers globally where they can produce electric machines according harmonized standards. Not only does this establish trust with the market, but it allows legislators to enact policies which promote energy conservation and facilitate governments to provide incentives to organizations which make energy efficiency their priority. The efficiency data provided by manufacturers is measured or calculated according to different national and international standards. These standards use different means to incorporate the stray load losses and use different test methods; thus, the efficiency values obtained from different testing standards can vary. This leads to problems in competition and a potentially confusing situation for manufacturers and customers. Hence, there is a need to compare the standards and highlight the possible variations leading to these differences, their causes and recommend where possible, solutions on how they can be eliminated. A comparison of induction motor efficiency test methods according to the IEC 60034-2-1 and IEEE 112 standards is presented in this work. Standard direct-on-line squirrel cage induction motors rated at 3 Kw, 5.5 Kw, and 7.5 kW are tested according to the IEC and IEEE preferred standards. Data collected from tests carried out on the motors is used to calculate the efficiency for the various IEC and IEEE tests. The data obtained shows a similar variation in values of efficiency, stray load losses and excitation losses for the same machine, but calculated using different standards. These differences result from how stray losses are treated and calculated in the standards. As a result, there is a need to harmonize the international standards.

***Key Words*-energy efficiency, induction motors, induction motor test standards, induction motor test methods, stray load losses, copper losses, excitation losses, friction and windage losses, IEC 60034-2-1, IEEE 112**

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LIST OF ABBREVIATIONS AND SYMBOLS

IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
AS/NZS	Australian Standard/New Zealand Standard
JEC	Japanese National Standard on Rotating machines
BS	Chinese National standard on rotating machines
CNS	Canadian National Standard
EMCP	European Motor Challenge Program
SEEEEM	Standards for Energy Efficiency of Electric Motor
CEMEP	European Committee of Manufacturers of Electrical Machines and Power Electronics
MEP	Motor efficiency program

∂	lamination thickness, unit width [m]
b_c	width of the conductor in the slot [m]
B_{max}	maximum flux density [T]
E_2	voltage drop across rotor circuit [V]
f	supplied frequency [Hz]
f_1	supply frequency [Hz]
f_2	slip frequency
f_r	rotor frequency [Hz]
h_c	height of conductor in the slot [m]
I	direct current equivalent to AC flowing through conductor
I_1	phase current rms [A]
I_2	rms current flowing in the rotor circuit [A]
I_c	rms current through the magnetic iron core [A]
J, J*	complex conjugate of current density
K_e	proportionality constant
l	length of conductor in the slot [m]
L_1	per-phase stator leakage inductance [H]
L_2	per-phase stator leakage inductance [H]
N_r	actual rotor speed [rpm]
N_s	synchronous speed of revolving field [rpm]
p	number of poles

P_{AC} and P_{DC}	AC and DC resistive losses respectively [W]
P_{ag}	total air-gap power [W]
P_d	total power developed by induction machine [W]
P_{fe}	iron losses [W]
P_{in} (P_1)	input power into a balanced three phase motor [W]
P_m	magnetic core losses [W]
P_{out} (P_2)	output power [W]
P_{rc}	rotor core loss [W]
P_{sc}	total stator copper losses in a balanced three-phase motor [W]
P_{SLL}	stray load losses also known as additional losses in this work [W]
R_1	per-phase stator winding resistance [Ω]
R_1	phase resistance [Ohms]
R_2	per-phase stator winding resistance [Ω]
R_{AC}	alternating current resistance [Ω]
R_c	per-phase stator core loss resistance [Ω]
R_c	magnetic core resistance [Ω]
R_{DC}	direct current resistance [Ω]
rms	root mean square
R_{ref}	conductor resistance at reference temperature [Ω]
s	slip
SLL	stray load losses (additional losses) [W]
T	conductor temperature [°C]
T	rotor torque [Nm]
T_{ref}	reference temperature that α is specified at for the conductor [°C]
U_1	rms input voltage [V]
V_1	per-phase terminal voltage [V]
X_1	stator reactance [Ω]
X_2	rotor reactance [Ω]
X_m	per-phase magnetizing reactance [Ω]
α	temperature coefficient of resistance for the conductor material
ξ	reduced conductor height
σ_c	specific conductivity of the conductor
ω_m	rotor speed [rad/s]

LIST OF PUBLICATIONS

Listed below are the two publications, which were released as part of this research at the stated conferences. The articles have been attached to the annexure section of the dissertation.

a "Induction motor efficiency test methods: A Comparison of Standards I" in 24th Southern African Universities Power Engineering Conference (SAUPEC 2016). Publication can be accessed at http://www0.sun.ac.za/saupec2017/Papers/PaperView.php?%20PublicationID%20=%201583. The content of the paper is a summary of Chapter 3 in this dissertation.

b "Induction motor efficiency test methods: A comparison of standards II" in Industrial and Commercial Use of Energy (ICUE 2017) conference proceedings. The publication can be accessed on the ICUE google drive database, links provided. https://ieeexplore.ieee.org/document/8067991/ or https://drive.google.com/file/d/1FjbcQZE1_0qsSDdzNuPA5CjJb0I_n3B/view?usp=drivesdk. The content of the article covered the experimental and data analysis of the research which is in Chapters 4 and 5 of the dissertation

1 CHAPTER 1 - INTRODUCTION

1.1 Introduction

Induction machines are important in the current world. Present day civilization will struggle in the absence of these asynchronous motors. The use of these motors is very extensive in industrial and domestic applications. Electric motors consume approximately 60% of all the electrical energy fed into the grid, with induction polyphase asynchronous squirrel cage motors being a large portion of that percentage. With this energy consumption background, the determination of induction motor efficiency has become critical. Energy efficiency has become a matter of interest worldwide in the last three decades. Resources are being channelled towards developing and improving the use of electrical energy. Electrical energy prices have been rising and most governments are not able to meet the continued increasing demands of their consumers.

The accurate determination of induction motor efficiency is beneficial to three main groups of people, namely the manufacturers, customers and legislators [2]. Customers are concerned with the total energy loss of a machine or the efficiency of a machine, as this will determine the running cost of the machine. Therefore, accuracy of the declared machine efficiency is paramount and efficiency values, which obscure the real losses, are misleading [3]. Knowing the exact value of motor losses is not only important for saving energy, but it is also important to keep the motor heating within specified limits to ensure maximum machine life [4].

Furthermore, legislators need to be enlightened so that they can enact policies that promote efficient energy conversation, and if need be, even institute incentives, which encourage the manufacturing and acquisition of more efficient electrical machines. Finally, a standard procedure for determining the energy efficiency of electric motors creates an even global platform for electric motor manufacturers to fairly compete. Thus, a harmonized approach to determine electrical efficiency within the electrical standards is important to industry and its partners.

In this research, various induction motor efficiency test methods as recommended by different international standards organizations are compared. The test methods included are methods used by organizations like the IEEE, IEC, AS, JEC and BS. Emphasis will be placed on the determination of stray load losses, as it is the one grey area in which different efficiency values for the same electric motor are found.

1.2 Background

A brief survey of motors entering the South African market, will highlight the importance of having accurate efficiency values. Brazilian, European and Chinese manufacturers mainly supply South Africa's electric motor market. It is important to know which standards are being used to measure/calculate the efficiency of motors that are supplied to the local market. Figure 1 shows the major manufacturers of electric motors in the world, and the standards that they use.

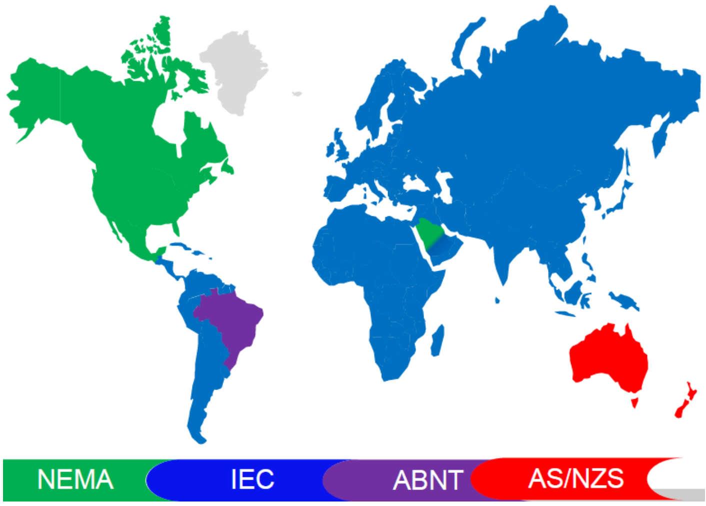


Figure1: International standards used in different parts of the world.

The major standards, as illustrated above, are IEC and NEMA. It is critical to note that NEMA standards are the same as ANSI and both fall under the IEEE standards. Thus, it can be confidently stated that two major standards are used globally. The Canadian CNS has been derived from the IEEE standard, and it includes the NEMA and ANSI standards whereas the IEC standard is found in the Australian AS/NZS, Chinese BS, and Japanese JEC. In South Africa, the SABS adopted the IEC standard just as it is. With so many suppliers of electric motors, industry usually opts for the cheapest option. Thus, it is important to have a harmonized standard for fair industry competition.

Legislators need to have accurate information about the energy consumption and efficiency of induction motors so that they can enact favourable laws to industry without compromising the goal towards a greener economy. They can set incentives for companies implementing changes to encourage organizations towards better energy efficiency, but this can only be achieved if the standards are harmonized.

Another important fact to consider is the average lifespan of an electric motor, which is at least ten years. This implies that most of the electric motors in industry have been in operation for quite some time. Implementing changes by means of replacing old motors with new premium efficiency motors require a lot of capital, therefore many companies simply take their motors for rewinding when they breakdown. Finding and recommending the optimum test method to determine efficiency ensure that industry partners who repair motors can provide accurate efficiency information to their clients. In turn, this will aid companies in decision-making, and it will provide relevant statistics to legislators when they enact policies that will encourage the conservation of electrical energy.

1.3 Problem Statement

The international and national standards stated above use different approaches to determine the efficiency of induction motors, with a major difference in how stray load losses are incorporated in the calculation procedure. As a result, it has been observed that the same motor, when tested by using different standards will produce varying efficiency values. These variations emanate from the different philosophies used to approach some of the separate losses during the calculation of efficiency. Therefore, this study intends to point out these discrepancies.

1.4 Research Objectives

The objectives of this research are to:

- Perform a detailed literature review of the test methods in standards and induction motor efficiency related topics;
- Compare the test methods in standards based on the available literature of the two standards;
- Carry out experiments to determine the efficiency of the selected induction motors using the test methods recommended by different standards;
- Analyse and compare the results from the experiments to identify the discrepancies, which are a result of the different philosophies used in the determination of stray load losses, and
- Make recommendations on how to harmonize the test procedures in standards.

1.5 Scope and Limitations

Induction motor efficiency test standards use several different methods in both the IEEE and the IEC standards. Most standards, which operate in different regions of the world, are based on either the IEC or IEEE standards. Therefore, the scope of this research was restricted to the direct and indirect (loss segregation) methods of both of the IEEE and IEC standards. Of the indirect methods chosen, only the loss segregation methods, which make use of a dynamometer braking machine and torque measuring device, were selected.

Limitations of this research included resorting to a few tests within the standards as the rest of the tests would require expensive equipment, which was beyond the budget limits of our available funds. Some of the equipment would include induction motors with embedded RTDs to measure temperature, same size induction motors to carry out reverse rotation tests, etc. Furthermore, the test bed could only accommodate motors below 7.5 kW due to the size of the dynamometer brake. Fortunately, there were several motors that fit the specifications of the test methods that were chosen for this research.

1.6 Outline of research Report

The research contents are briefly detailed as follows:

Chapter 2 – Literature Review: In this chapter, the history of induction motors will be briefly discussed. Following that, induction motor theory will be given in which the different losses and loss types will be discussed. Stray load losses and their origins will also be discussed with reference to previous work carried out by other researchers. The importance and origins of induction test standards will be discussed.

Chapter 3 – Verification of the test methods: The test methods have a mathematical procedure, which comprises of a set of equations used at each stage of efficiency testing. These mathematical models will be verified by means of carrying out the stipulated tests. Results from the tests will then be compared with the characteristics and correlation coefficients stated in the standards to verify the test methods. The comparison of the test methods highlighting the differences in procedures, the nomenclature and conditions of the tests, will be presented in this chapter.

Chapter 4 – Test data analysis: This section will present a comparison of tests performed on the same machines using different standards, to validate the study. Similarities and differences will be discussed. The author will indicate in what way loss segregation methods influence the stray load losses and this ultimately affects the final value of the calculated efficiency. Parameters like temperature and resistance will also play an important role in the computed final value of efficiency.

Chapter 5 – Conclusion and recommendations: The conclusions from the verification and validation procedures in Chapter 4 and 5 will be discussed. Recommendations with regards to harmonizing the standards will be made. Studies, which can be done to improve the results of research, will be recommended.

2 CHAPTER 2 - DEVELOPMENT OF THE INDUCTION MACHINE

2.1 Introduction

The work presented in this research seeks to illuminate the differences among the induction motor efficiency test methods recommended by different international standards. Differences in the standards result in varying efficiency values for the same motor. An understanding of the basic principles of the induction motor will assist in understanding the relationship between the motor, load, induction motor losses and finally the variations between the standards. Hence, the current chapter seeks to summarize the development of the induction motor from its invention and construction, as well as its operating principles and characteristics.

2.2 Laws of Electromagnetism

In 1831, Michael Faraday established a law that is known as Faraday's law of electromagnetic induction today. This law explains the relationship between the electric circuit and the magnetic circuit, which forms the basis of the principle of operation for induction motors. James Clerk Maxwell's equations, which he formulated in 1860, describe the laws of electricity. The impact of Maxwell's equations cannot be underemphasized, but they cannot be covered within the scope of this paper. However, the equations laid the foundation on which numerous electromechanical systems were invented by people like Nikola Tesla and Galileo Ferraris.

Between 1883 and 1887, Tesla discovered the concept of a rotating magnetic field, which he then used to develop prototypes of a two-phase induction motor (see Figure 2). Around the same period, in 1888, Ferraris developed a two-phase AC motor but with a rotor made of copper. Subsequently, Mikhail Osipovich Dolivo-Dobrovolsky, a Russian inventor, invented the wound-rotor induction motor in 1889. He later developed the cage rotor whose topology resemble today's squirrel cage induction motor.

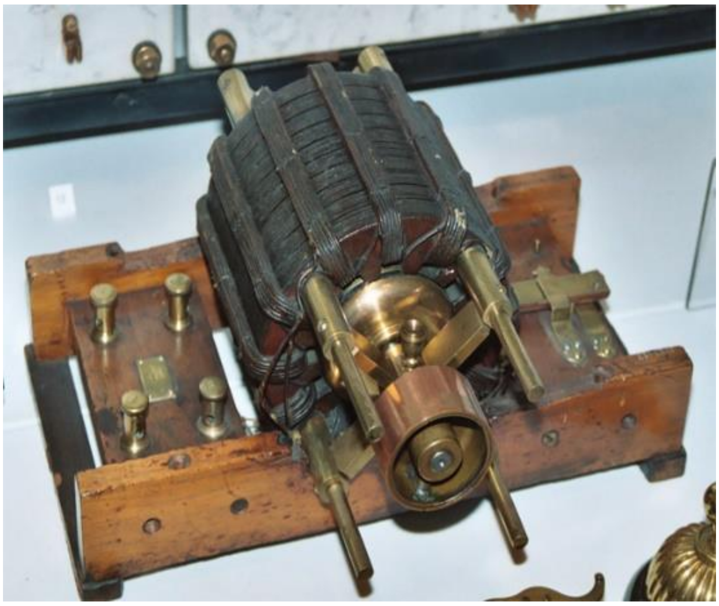


Figure 2: One of the original AC Tesla induction motors on display in the British Science Museum in London [1]

Over the years, the operating principles of the induction motor have remained the same. The changes from the original machines that we observe today are results of improved materials (alloys), manufacturing processes like stamped laminations and improved design tools. As a result, we now have different ranges of frame sizes, ratings, and different types of motors. Furthermore, due to increasing improvements in manufacturing technologies and legislative policies, some types of motors are being replaced by succeeding premium versions of motor with higher energy efficiencies.

2.3 Induction Motors and Energy Efficiency

In an electro-mechanical system, the conversion of electrical energy to mechanical energy takes place in the induction motor. Some of the energy input is dissipated as heat and lost from the system. Ways in which energy consumption of a system can be moderated are to increase the efficiency of the machine or reduce power consumption on the load side. However, it is critical to note that the average efficiency of induction motors, which are currently being manufactured, is high. Nonetheless, any small percentage improvement in the efficiency of a machine that forms part of the rest of the induction machines will go a long way in saving energy. Most energy savings can be realized on the load side of the motor, for example, in an application in which flow is being controlled, speed can be used instead of throttling, and thus improve the system efficiency.

Design, material improvement, better manufacturing methods or the use of more materials, when used alone or combined can also improve the energy efficiency of motors. The implementation of these improvements has obviously resulted in an increased cost of the induction machines. Fortunately, increased energy prices for plants with continuous duty cycle motors, which operate for long hours are in favour of these premium motors. The payback period of investments made on high-energy efficient motors can be a few months, especially for continuous duty-cycle induction machines.

While it may not be feasible in terms of costs to replace all operating induction motors with high efficiency machines, it is recommended when setting up new plants or replacing old machines, that premium motors are used. There is no consolidated global data on the acquisition of premium motors, but a few sources confirm that premium motors have a limited market share. The rate at which the premium motors are being bought reflects a slow but gradual increase. This is because the acquisition of high efficiency motor's effect on existing stock in the industry is limited although legislative standards may promote the acquisition thereof. [5] has shown that approximately 1.8 million premium efficiency motors are sold in the USA annually. On the contrary, approximately 2.0 to 2.5 million motors are repaired and returned to service annually. Motors rated below 15 kW are generally replaced with new units because the cost of repair is equal or greater than the cost of a new unit. Machines exceeding 40 kW are usually repaired upon failure as the cost of repair is generally below 60% of new motors. The large motors are usually repaired and brought back to service indefinitely. Government legislation, financial incentives, and utility-sponsored education may be instrumental in curbing such challenges.

The many programs supporting the energy efficiency of induction motors, standards and classes of induction motors are justified by the fact that any percentage of improvement on efficiency affects the economy positively and even has a positive effect on the environment.

The topology and basic operating principle of the induction machine will be discussed next. This will highlight the losses, which are intricately connected to efficiency. A steady-state equivalent circuit will also be discussed and how losses are derived from it.

2.4 **Induction Motor Theory**

The induction motor operating principle is similar to the transformer operating principle, with the major difference being that the former is dynamic, and the latter is static. The induction motor can be treated as a rotating transformer. In a polyphase induction machine, an alternating current is fed directly to the stator terminals. Rotor winding current is supplied through induction or transformer action. As a result, a rotating magnetic field is produced in the air gap, which rotates at synchronous speed according to the number of stator poles and stator frequency [6]. Induction motors can be classified according to their type of rotor windings, namely wound rotor and squirrel-cage rotor types as shown in Figures 3 and 4.

Figure 3: Squirrel cage rotor [6]

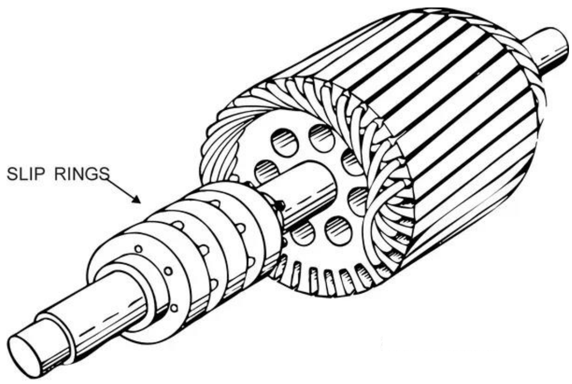


Figure 4: Wound rotor cage [7]

Due to their limited number of specialized applications, induction machines with wound rotors are not commonly used. For the purpose of this document, the research focuses on squirrel-cage rotor induction machines.

Advantages of the induction motor are:

i. Simple, rugged and almost unbreakable
ii. It costs are low and it is reliable
iii. Efficiency generally is high.
iv. Frictional losses are reduced due to the absence of brushes
v. The power factor is reasonable
vi. There are a minimum of maintenance costs
vii. Start-up is basic for most industrial applications

Disadvantages of the induction motor are:

i. Efforts to vary speed compromise the efficiency of the machine
ii. The inverse relationship between speed and load
iii. When compared to the DC shunt motor, the starting torque is less for the same rating [8].

2.4.1 Construction

The induction motor consists of two principal parts, namely the stator and the rotor.

2.4.2 Stator

The stator consists of copper winding and a core consisting of laminations (stampings) slotted to accommodate three-phase windings. The stator is fed from a three-phase supply. Magnetic stator cores are constructed from soft magnetic materials, which consist of thin stacked laminated sheets. The number of poles determines the speed of the machine, that is, the greater the number of poles the lesser the speed. The relationship between the number of poles and the number of stator slots is given below:

$$P = 2n \qquad (2.1)$$

where n is the number of stator slots per pole per phase.

Figure 5: Single laminated stator slot

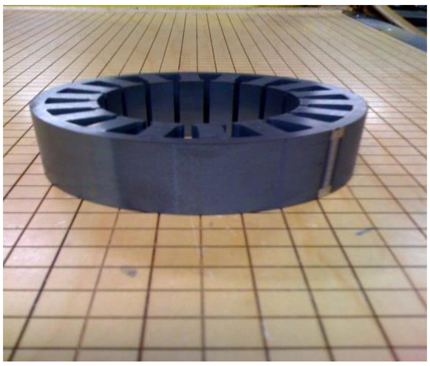


Figure 6: Staked laminated stator slots forming the stator core

2.4.3 Rotor

2.4.3.1 A squirrel cage

Induction motors meant for applications whose load requirements demand little starting torque usually have squirrel cage rotors consisting of a unified laminated core structure with a solid shaft forged through its centre. Parallel skewed slots carry the rotor conductors. Rotor bars can either be made of aluminium, copper or alloys. Once inserted into position, the bars are brazed or electrically welded or bolted to end rings thus short-circuiting them. The permanent short circuit inhibits varying the rotor resistance for starting purposes. A squirrel cage, as shown in Figure 3, will be the final structure of the rotor.

Skewing the rotor slots reduces magnetic hum and allows the motor to run quietly. Furthermore, it reduces the locking tendency (cogging) of the rotor to that of the stator, which can occur as a result of direct magnetic coupling when the rotor's and stator's teeth are aligned.

2.4.3.2 A wound rotor

A wound rotor comprises three-phase windings mirror imaging the stator windings. The three-phase windings are then connected in star. The other three ends are attached to slip rings mounted on the rotor shaft. Carbon brushes riding the slip rings connect the windings to external resistances or short the rotor windings. Torque-speed characteristics of the wound rotor induction motor can be modified by changing the rotor current by inserting an extra resistance into the rotor circuit. It is this feature that makes them preferable in applications in which torque control or high starting torque is important, for example, in mine hoists. However, brushes and slip rings wear off with time, which in turn results in high maintenance costs [9]. Thus, they are less used.

2.4.4 Slip and Rotor Rotation

A magnetic field revolving around the rotor at synchronous speed and at a constant magnitude is produced when the stator windings are connected to an AC power source. The synchronous speed of the revolving field is given by $N_{s,}$

$$N_s = \frac{120f}{P}(rpm) \tag{2.2}$$

or

$$\omega_s = \frac{4\pi f}{P}\left(\frac{rad}{s}\right) \tag{2.3}$$

where N_s = synchronous speed

ω_s = synchronous angular velocity

f = frequency

P = number of poles

s = slip

An electromotive force is induced in the rotor winding by the revolving magnetic field. Because rotor windings are shorted, each coil experiences an induced current from its induced emf.

This leads to a torque (starting torque) which rotates the current-carrying coil, which is engrossed in the magnetic field. The rotor will rotate if starting torque is larger than load torque. A rotor and revolving field will then revolve in the same direction according to Faraday's law of induction. The rotor's rotational speed approaches synchronous speed, but there will always be a difference between its speed and synchronous speed. Slip is that difference between the synchronous speed of the machine and the rotor speed and is given by:

$$N_r = N_s - N_m \tag{2.4}$$

or

$$\omega_r = \omega_s - \omega_m \tag{2.5}$$

where N_r (or ω_r) = slip speed
N_m (or ω_m) = rotor speed

Slip s is given by:

$$s = \frac{N_r}{N_s} = \frac{\omega_r}{\omega_s} \tag{2.6}$$

or

$$s = \frac{N_s - N_r}{N_s} = \frac{\omega_s - \omega_r}{\omega_s} \tag{2.7}$$

It can also be shown that rotor frequency, $\boldsymbol{f_r}$, is given by:

$$f_r = sf \tag{2.8}$$

and it depends on the supply frequency of the motor [10].

2.5 Equivalent Circuit theory

The electromechanical characteristics of a polyphase induction machine can be studied using an equivalent circuit. Loading of the machine on its power source, which may be a constant voltage-frequency source like an utility power system or variable-voltage variable-frequency source in the case of electronic drives, can be analyzed using the equivalent circuit [6]. However, the equivalent circuit does not take into consideration harmonic fields in the induction machine, which are a major cause of stray load losses as well as harmonic torques. References [12] and [13] have used the finite element methods to estimate harmonic losses in their equivalent circuit model, and their work proves that the basic equivalent circuit model is not the best method to simulate the behaviour, performance and losses of an induction machine. Notwithstanding that, this research will make use of the basic equivalent circuit model to explain the conventional losses of an asynchronous induction motor.

To derive the equivalent circuit, a squirrel cage rotor is represented by an equivalent three-phase rotor winding as shown in Figure 7 below. Rotating magnetic fields, rotating at the same speed, are produced in the air gap when currents flow in both the stator and rotor. Voltages are induced in the stator and rotor windings at frequencies f_1 and f_2 respectively by the resultant air gap field rotating at synchronous speed.

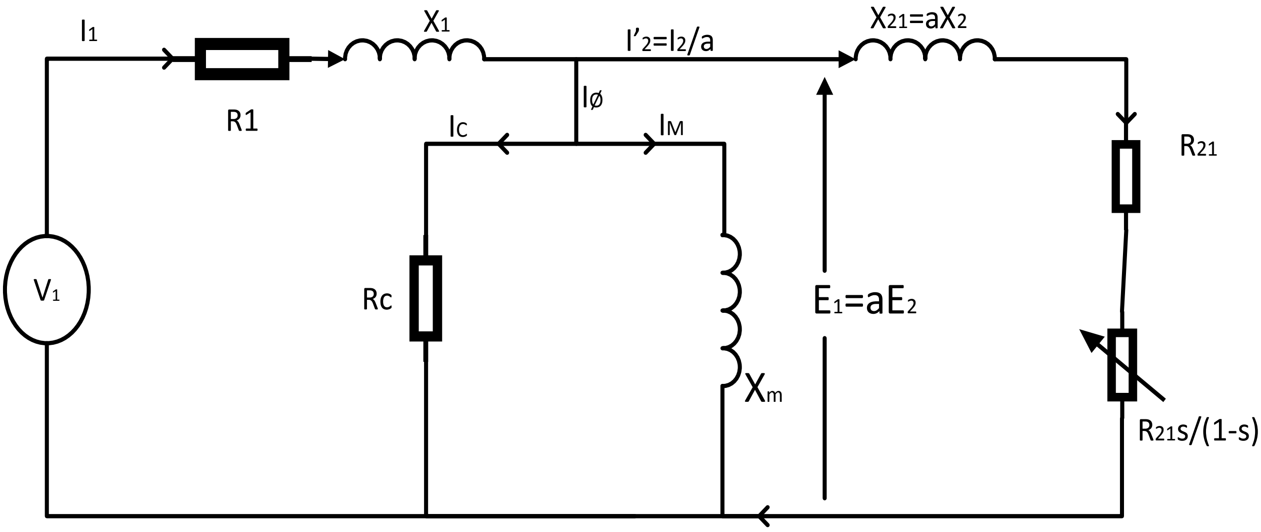


Figure 7: Equivalent three-phase rotor winding circuit [42]

Where:

V_1 = per-phase terminal voltage
R_1 = per-phase stator winding resistance
R_2 = per-phase stator winding resistance
R_c = per-phase stator core loss resistance
L_1 = per-phase stator leakage inductance
L_2 = per-phase stator leakage inductance
X_m= per-phase magnetizing reactance and $X_m = 2\pi f_1 L_m$
X_1 = stator reactance and $X_1=2\pi f_1 L_1$
X_2 = rotor reactance
s = slip

The performance of the induction machine at any specific slip can be calculated from its equivalent circuit. This is because slip changes with load resistance and slip regulates itself according to the mechanical load on the rotor shaft. Thus, power that is developed by the induction machine is equal to the power transmitted to the load resistance.

Therefore, input power into a balanced three-phase motor is:

$$P_{in} = 3U_1 I_1 cos\theta \quad (2.9)$$

where θ is the angle between applied terminal voltage V_1 and I_1

Total stator copper losses are given by:

$$P_{sc} = 3I_1^2 R_1 \quad (2.10)$$

Total magnetic (core) loss is given by:

$$P_m = 3I_c^2 R_c \quad (2.11)$$

The air-gap power becomes:

$$P_{ag} = P_{in} - P_{sc} - P_m = \frac{3I_2^2 R_2}{s} \quad (2.13)$$

Rotor loss is given by:

$$P_{rc} = 3I_2^2 R_2 = sP_{ag} \quad (2.14)$$

The total power developed by the machine will be given by:

$$P_d = P_{ag} - P_{rc} = SP_{ag} \quad (2.15)$$

where

$$S = 1 - s = \frac{N_r}{N_s} = \frac{\omega_r}{\omega_s} \quad (2.16)$$

2.6 **Electromechanical Torque**

A brief discussion of torque relationships will be provided, as they assist in efficiency calculations that are based on measured rotor output. To begin with, the power factor of the rotor determines the rotor torque as shown below:

$$\mathrm{T} = \mathrm{k}_1 E_2 I_2 cos\emptyset \quad (2.17)$$

The total torque developed by the machine is given by:

$$\mathrm{T}_t = k \frac{sE_1^2 R_2}{R_2^2 + (sX_2)^2} \quad (2.18)$$

where the constant is $k = \frac{3K^2}{2\pi N_s}$ (2.19)

If a slip is such that rotor reactance/phase is equivalent to rotor resistance/phase when the motor is running, then the machine is operating at maximum torque. Thus, the torque equation becomes:

$$T_{max} = \frac{3}{2\pi N_s} \cdot \frac{E_2^2}{2X_2} \quad (2.20)$$

Deductions from the above torque equations are that:

- The maximum torque of an IM is not dependent on rotor resistance.
- However, rotor resistance can be varied until it is equal to rotor reactance thus getting maximum torque. Consequently, slip-ring motors achieve maximum torque at desired speed or slip.
- Standstill reactance should be kept as small as possible as it varies inversely with $T_{max.}$
- The square of applied voltage is directly proportional to the maximum torque.
- Maximum torque, R_2=$X_{2,}$ is achieved when the motor starts at *s=1*.

Alternatively, the torque speed/slip characteristics can be used to clarify the torque equations listed above as shown in the following section.

2.7 **Torque-speed/slip characteristics**

Slip values are in the range between 0 and 1 and rotor resistance R_2 is the parameter under consideration.

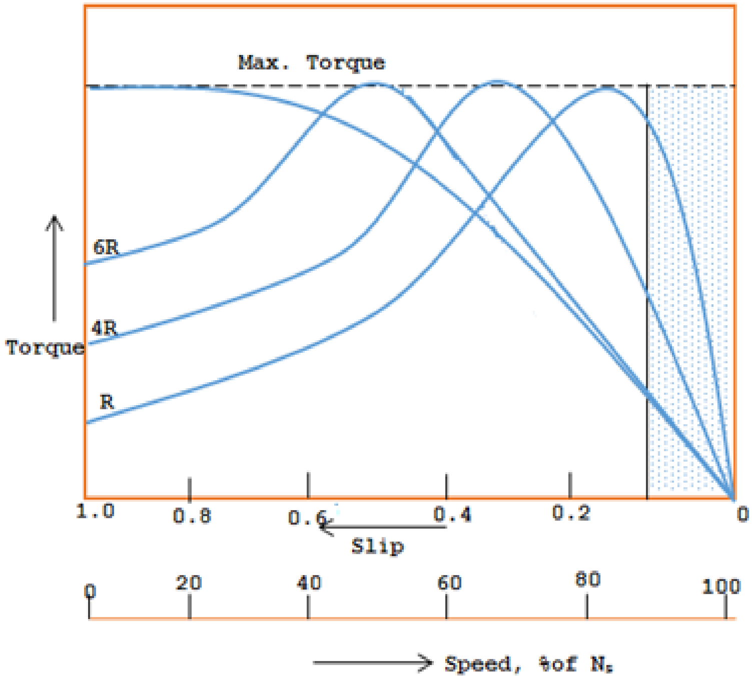


Figure 8: Slip torque characteristic of an induction motor [13].

$$T \;= k\frac{s\emptyset E_2\,R_2}{R_2^2+(sX_2)^2} \tag{2.21}$$

When slip is s = 0, torque is T = 0. sX_2 is negligible compared to R_2 at speeds close to synchronism, therefore T directly varies with s when R_2 is kept constant. This is indicated in equation 2.21:

$$T \propto \frac{s}{R_2} \tag{2.22}$$

A further increase in slip will make R_2 negligible with respect to sX_2, providing the following relationship:

$$T \propto \frac{s}{(sX_2)^2} \propto \frac{1}{s} \tag{2.23}$$

Two important inferences from the torque equations listed above are that the torque is proportional to the square of the applied voltage at any speed. Secondly, torque and speed vary when the supply frequency is changed.

2.8 Induction Machine Losses

The biggest portion of the losses that influence the efficient conversion of electrical to mechanical energy occurs in the windings and magnetic cores of the machine. During the design stage of an induction machine, the losses are calculated using analytical methods.

Once manufactured, tests are carried out to determine the losses. This validation process should produce results with a variant that is small. Standards use different methods to determine the losses. Loss segregation and input-output methods are the two major categories under which all the test methods fall. These methods will be discussed in detail in the following chapter. This section will summarize the losses found in the induction motors, and state some of the analytical methods of calculating the losses.

2.8.1 Types of losses

Losses are commonly classified based on their location, that is, winding losses (stator and rotor), core losses (stator and rotor), and the friction and windage losses. A common method used to represent losses in electric motors is the through the utilization of the Sankey Powerflow Diagram. Regrettably, as shown in Figure 9, the powerflow diagram does not account for stray-load losses in electric motors. It only shows conventional losses, which are stator and rotor copper losses, iron losses, and friction and windage.

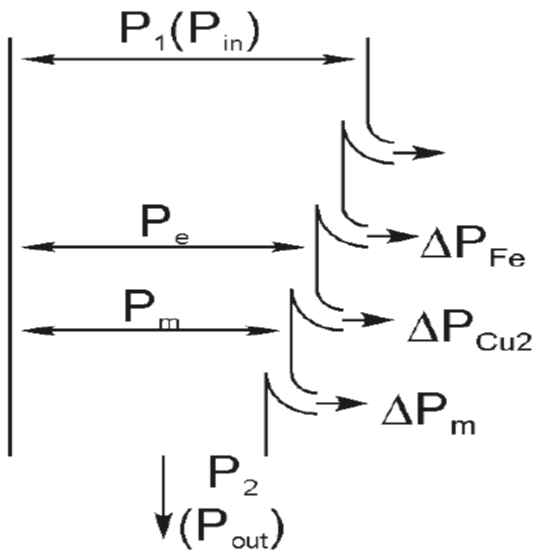


Figure 9: Sankey Powerflow diagram showing conventional losses in an induction motor [14]

The difference between the summation of the above-stated losses, output- and input power is stray losses. Stray losses are difficult to compute and account for. Previous literature and work done on the investigation of stray losses indicate that electromagnetic losses in the winding and core are responsible for stray losses. Electromagnetic losses consist of fundamental losses and harmonic losses (space harmonic losses, and time-harmonic losses) all found in the stator and rotor of the machine. The induction machine's magnetic flux consists of both harmonic components and the fundamental flux, whose shape closely resembles a sine wave. Usable rotating torque, together with the required tangential forces between the stator and rotor is provided by the fundamental sine wave magnetic flux. Harmonic components yield parasitic torques. The accelerating speed-torque behaviour of the machine is greatly distorted by the presence of these parasitic torques. Components of these space harmonics will be listed and briefly described later in this chapter.

The scope of this research will not include time harmonics as they are found in static converter fed systems.

2.8.2 Resistance/Ohmic Losses

Resistance losses are also referred to as copper losses, even though other winding conductor materials, for example aluminium and other alloys, are subject to these losses. As stated above, ohmic losses are located in the stator and rotor winding of the induction machine. These losses are a result of current flowing in conductors and are defined by the following relationship:

$$P = I^2R \tag{2.24}$$

where P = resistance loss
I = current flowing through the conductor
R = resistance of the conductor

The magnitude of resistance losses is directly proportional to the square of the current, hence they are load dependent. Ohmic losses depend on the effective resistance of the winding under rated frequency and operating flux conditions. An alternating current flowing through a conductor is unevenly distributed across the cross section of the conductor, resulting in a larger current density in the region close to the surface or skin of the conductor than the region further from the conductor surface. As frequency of the alternating current flowing through the conductor increases, the skin effect becomes more pronounced. In turn, it results in an increase in the effective resistance of the winding conductor. Hence, the conductor cross-section available for current flow is reduced. Since skin effect affects the effective resistance of the conductors, in higher loss values under alternating current are experienced in the conductors in contrast to the measured DC resistance of the motor at standstill. The difference between these loss values is accounted for in the determination of stray losses, which shall be discussed in the subsequent sections [6].

The electrical resistance of conductors also increases with temperature, as there will be more collisions within the conductor. The following formula describes the relationship between change in temperature and corresponding resistance output.

$$R = R_{ref}[1 + \alpha(T - T_{ref}) \tag{2.25}$$

where R = conductor resistance at temperature T

R_{ref} = conductor resistance at reference temperature

α = temperature coefficient of resistance for the conductor material

T = conductor temperature in degrees Celcius

T_{ref} = reference temperature that α is specified at for the conductor

Hence it is important to use the correct resistance values for the operating temperatures when carrying out efficiency tests to get accurate results.

Resistance losses in the stator windings can be minimized by using more copper and increasing the size of slots resulting in fewer turns. This, in turn, will decrease stator winding resistance. A major setback of this approach is the resulting increase in cost and difficulty in construction. Coil overhang can be decreased, reducing winding resistance, but it poses the same difficulty of construction and increases inrush current [16].

Rotor losses are reduced by using larger cage bars and lesser turns in the stator, as well as increasing the size of the end ring. Furthermore, decreasing the slip by means of increasing the flux density in the air gap, results in lower resistance losses. Unfortunately, these measures may result in increased inrush current and reduced starting torque [15], [16].

2.8.3 Iron losses

Iron losses are dependent on supply voltage and frequency. Eddy currents flowing in the conductor and core magnetization resulting from fluctuating flux densities greatly influence these losses. In induction machines, the losses are principally limited to the stator iron.

The following equations highlight how iron losses are dependent on the supply voltage and voltage. In both equations, when the constants are changed accordingly, frequency and flux density can be replaced by speed and voltage respectively.

i) Eddy-current loss

$$P_e = K_e(B_{max} f \partial)^2 \qquad (2.26)$$

where ∂ = *lamination thickness*

B_{max} = *maximum flux density*

f = *supplied frequency*

K_e = *proportionality constant*

ii) Hysteresis Loss

$$P_h = K_h f B_{max}^2 \tag{2.27}$$

where K_h = proportionality constant

The iron core losses are considered to be constant. However, the MMF of load currents considerably alters the space distribution of flux density in the machine, hence increasing core losses. This increment in losses is classified as part of stray load losses. The use of a lengthier core and better lamination alloys can reduce iron losses [17].

2.8.4 Friction and Windage Losses

These are mechanical losses caused by the friction of the bearings in the induction machine and the friction between the moving parts and air inside the motor's casing. Windage losses vary by the cube of the speed of rotation of the induction machine. The friction component of mechanical losses varies directly with the speed of the machine. Since most machines run at a constant speed, these losses are considered as constant. A no-load test, with the machine run at incremental voltage points, will give the value of the mechanical losses.

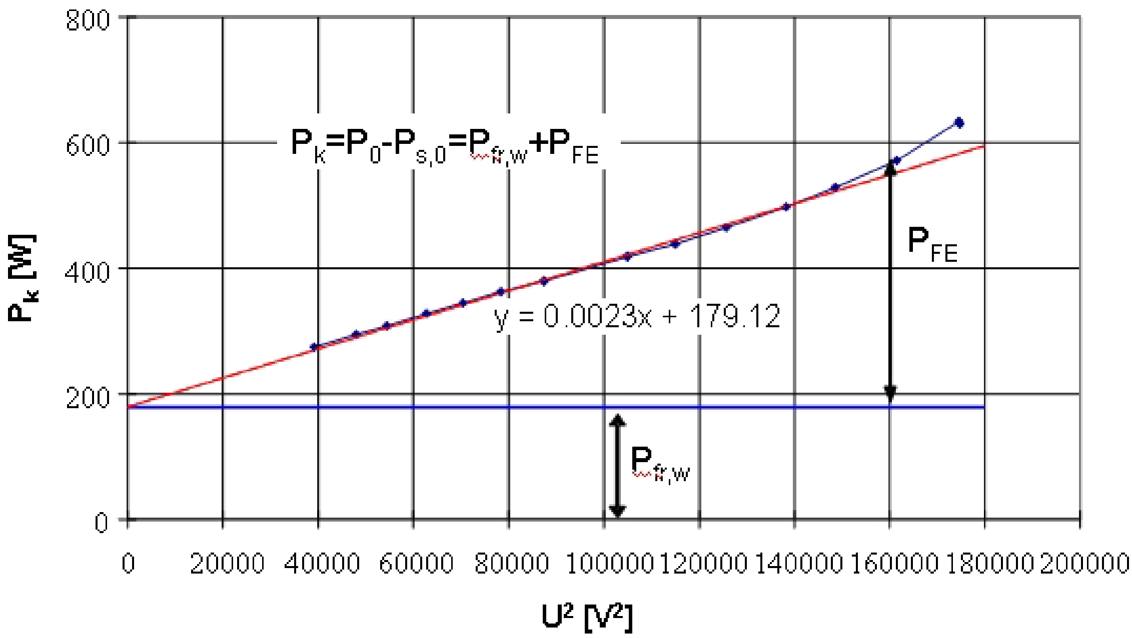


Figure 10: Constant losses vs the square of input voltage curve to determine friction and windage losses and iron losses

Depending on the rating of the electric motor, improvements in the heat transfer system facilitates a reduction of the windage losses. Friction losses can also be reduced by using lower friction bearings and better lubrication on moving parts of the motor.

2.8.5 *Stray Load Losses*

Stray losses in an induction machine consist of the difference between the total input power and the calculated sum of the following losses; I^2R loss (stator and rotor), core losses, windage and friction losses. Changes in the flux distribution and eddy currents in the machine conductors cause the load current to generate stray losses in the induction machine.

2.8.5.1 Origin of Stray Losses

Four restrictions in the design and manufacturing of induction motors have been identified to be the origin of stray load losses. Firstly, the steel used in the manufacturing of laminations has limitations, which cause it to saturate when the motor operates at or above a certain threshold. Secondly, manufacturing imperfections can also lead to the generation of stray load losses. Cross-bar currents resulting from the defective insulation of rotor cage bars can be categorized as manufacturing imperfections. Furthermore, the practical geometrical structure required for the ease of manufacturing and solidly fitting winding conductors results in leakage flux and space harmonics. These will be discussed in detail in the following section.

Conductors of large machines rated above 300 kW have diameters greater than or equal to 1.5 mm. Some machines have fabricated rectangular conductors inserted in the stator and or rotor slots. Machines of this rating experience stray losses, which result in the skin effect. The skin effect will be elaborated on after the succeeding brief classification of stray losses according to different researchers.

It is worth noting that numerous studies have been done on stray losses, which date back to the early 21st century. This has led to the different classifications of the components of losses, although the authors meant the same thing, for example, Schwarz [18] classified the components as illustrated in the Table 1.

Table 1: Leakage flux (load) stray losses.

Class	*Component*	*Origin*	*Type and location*
1a and b	Surface loss	Permeance variations (harmonic flux)	Stator and rotor core losses
2a and b	Tooth pulsation losses	Permeance variation due to relative tooth positions.	Stator and rotor core losses
3b	Tooth pulsation, squirrel cage, circulating current losses	Permeance variation due to relative tooth positions	Rotor I^2R losses
4a and b	Rotor I^2R losses	Gap leakage (harmonic) flux	Stator and rotor core losses
5a and b	Tooth pulsation losses	Gap leakage (harmonic) flux	Stator and rotor core losses

6b	Tooth pulsation, squirrel cage, circulating current losses	Gap leakage (harmonic) flux	Rotor I^2R loss
7b	Stator-harmonic, squirrel cage, circulating current losses	Gap leakage (harmonic) flux	Rotor I^2R loss
8a	Stator slot eddy current losses	Slot leakage flux	Stator I^2R loss
8b	Rotor slot eddy current losses	Slot leakage flux	Abnormal rotor I^2R loss at high slip only
9a	Stator overhang eddy current losses	Overhang leakage flux	Stator core loss
9b	Rotor overhang eddy current losses	Overhang leakage flux	Abnormal rotor core loss at high slip only

Chalmers and Williamson [18] break down stray load losses into fundamental and high-frequency components.

Fundamental frequency losses are a product stator leakage fluxes penetrating the structural parts of the machine, for example, the end plates and end brackets. Eddy current losses caused by leakage flux are included under this class. When the machine is operating at no-load or on light load, the magnitude of fundamental stray losses is very small as the losses are current dependent. Therefore, the fundamental frequency component of stray load losses is significant when the machine is loaded.

High-frequency components include losses in the rotor, which are caused by MMF harmonics due to the load current. Furthermore, induced losses in the stator windings due to rotor MMF are also included under high-frequency components generated by space harmonics caused by the uneven surfaces of both the stator and rotor.

2.8.5.2 Skin effect

The winding resistance of induction motors is calculated from direct current measurements done when the motor is at rest. During tests, the machine is shut down briefly and the dc resistance is measured before the temperature changes. Alternatively, using temperature values at measurement points, the resistance can also be calculated using a temperature correction formula.

$$R = R_{ref}[1 + \alpha(T - T_{ref}) \quad (2.26)$$

Direct current measurements to deduce resistance pose a challenge when large machines are being considered. This is due to the fact that the machine operates under alternating current. Alternating current resistance is affected by a couple of factors namely skin effect, proximity effect, temperature and even specific winding design.

The behaviour of an induction motor from standstill to full speed is closely dependent on the shape of the rotor bar used in the construction of the machine. Under starting conditions, rotor bar current crowds to the top of the bar during starting, thus changing the effective bar resistance at starting, as compared to machine running at full speed. At standstill, the current density is high in the upper section of the rotor bar and depending on the design and configuration of the bar, a high resistance and reactance are attained. These, in turn, produce high torque at reduced inrush current [20]. The different configurations of rotor bar shapes that can be manipulated to give the desired starting torque characteristic are illustrated in Figure 11.

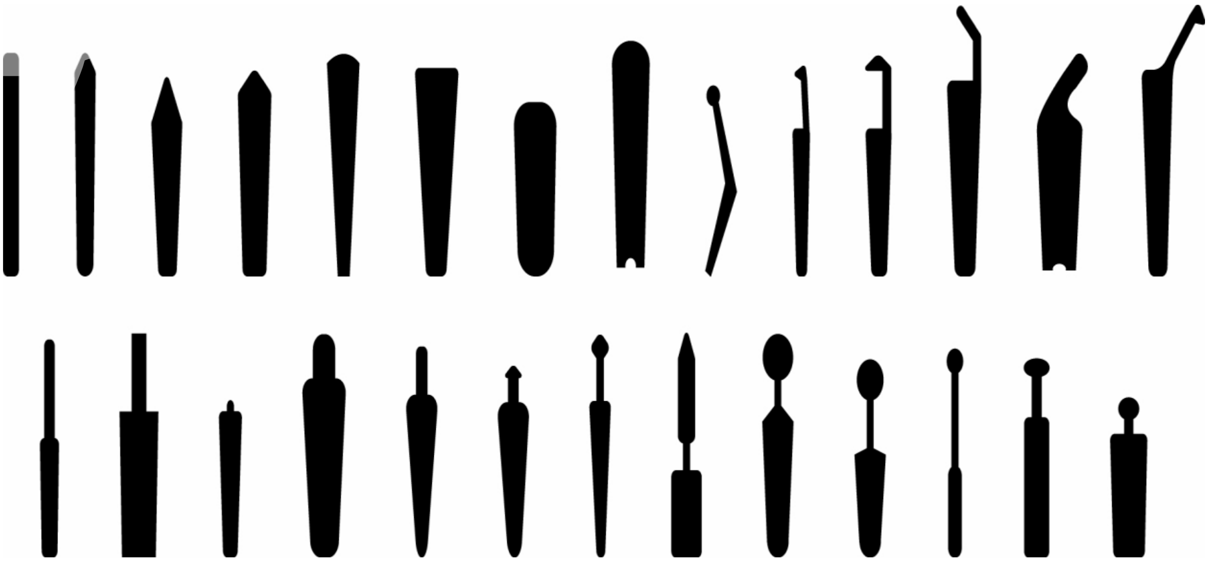


Figure 11: A variety of possible rotor bar shapes [9]

Manufacturers of induction machines keep their rotor design profiles classified to guard against competition. This is because slot profiles have economic implications as they determine the efficiency of the machines [21]. The performance characteristics of induction motors are determined by the profile of the rotor bars as well as the material used to make the conductors. The literature about slot configurations in this dissertation will be limited to information from the public domain. Typical profiles would be round, square, rectangular, wedge, teardrop, oblong, oval, keyhole, knife bars, sash bar, etc.

Configurations can be in single cage or double cage profiles. Double cage rotor bars may have different materials like brass bars on top and copper bars deeper in the slot.

2.8.5.3 The Effect of Skin Effect on Conductor

In order to describe the relationship between alternating current resistance and measured DC resistance, mathematical formulae have been developed. To begin with, there is a resistance factor formula. This is a ratio of alternating current to direct current resistances by which the

DC resistive losses are multiplied to deduce the equivalent AC losses [7]. For a single fabricated rectangular conductor in a slot, the following relationships have been formulated.

Resistance factor, k_R is:

$$k_R = \frac{R_{AC}}{R_{DC}} = \frac{P_{AC}}{P_{DC}} \qquad (2.27)$$

where R_{AC} = alternating current resistance

R_{DC} = direct current resistance

P_{AC} and P_{DC} = AC and DC resistive losses respectively

AC resistive losses, P_{AC}, are given by the following relationship:

$$P_{AC} = \frac{b_c l}{\sigma_c} \int_0^{h_c} JJ^*.dy \qquad (2.28)$$

and DC resistive losses are given by:

$$P_{DC} = R_{DC} I^2 = \frac{l}{\sigma_c b_c h_c} I^2 \qquad (2.29)$$

where b_c = width of the conductor in the slot

l = length of conductor in the slot

h_c = height of conductor in the slot

J, J^* = complex conjugate of current density

σ_c = specific conductivity of the conductor

I = direct current equivalent to AC flowing through conductor

In the case of a slot comprising of multiple conductors, the resistance factor is given by:

$$k_{Rk} = \varphi(\varepsilon) + k(k-1)\psi(\varepsilon) \qquad (2.30)$$

where φ(ξ) and Ψ(ξ) are given by:

$$\varphi(\varepsilon) = \varepsilon \frac{\sinh 2\varepsilon + \sin 2\varepsilon}{\cosh 2\varepsilon + \cos 2\varepsilon} \qquad (2.31)$$

and

$$\psi(\varepsilon) = 2\varepsilon \frac{\sinh \varepsilon - \sin \varepsilon}{\cosh \varepsilon + \cos \varepsilon} \qquad (2.32)$$

It can be seen from equation (2.30) that the top layer of conductors has the largest resistance factor when compared to the bottom layer. Hence, conductors at the bottom of the slot in a series-connected configuration contribute less to resistive losses when compared to the top layers. The mean value of k_R in the slot is therefore given by:

$$k_R = \varphi(\varepsilon) + \frac{z_t^2 - 1}{3}\psi(\varepsilon) \tag{2.33}$$

If round conductors are used in the design of the induction machine, Equation (2.33) approximates to Equation (2.34), since losses caused by eddy currents in round conductors are 0.59 times that of rectangular wire losses.

$$k_R \approx 1 + 0.59\frac{z_t^2 - 1}{9}(\varepsilon)^4 \tag{2.34}$$

In medium voltage machines, circulating currents generated in conductors can be reduced during the design by transposing the conductors. Transposing conductors surround each conductor with an equivalent slot leakage magnetic flux, thus minimizing eddy current losses. Dividing conductors into sub-conductors also reduces the resistance factor.

A comparison of the skin effect experienced by a conductor exposed firstly to DC and then AC is graphically presented in Figure 12. It can be observed that when a direct current is applied, there is a uniform distribution of current density in the conductor with no skin effect being experienced. When alternating current flows through the conductor, skin effect intensifies current density in the conductors close to the surface of the slot.

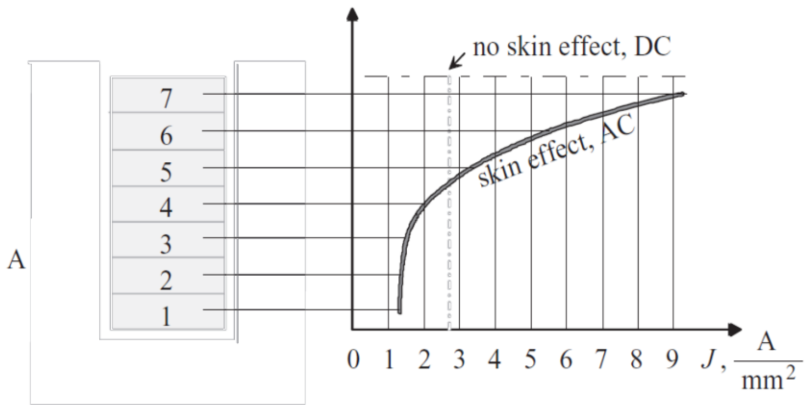


Figure 12: AC current density versus DC current density across slot cross section [9]

Induction machines with high ratings, which have fully transposed winding conductors, experience less skin effect due to the conductor transposition. Double cage rotors in which fabricated winding conductors are not fully transposed experience the skin effect more than rotors with transposed conductors. Due to the proximity effect of the conductors in double cage rotors, the current density distribution takes the shape shown in Figure 13.

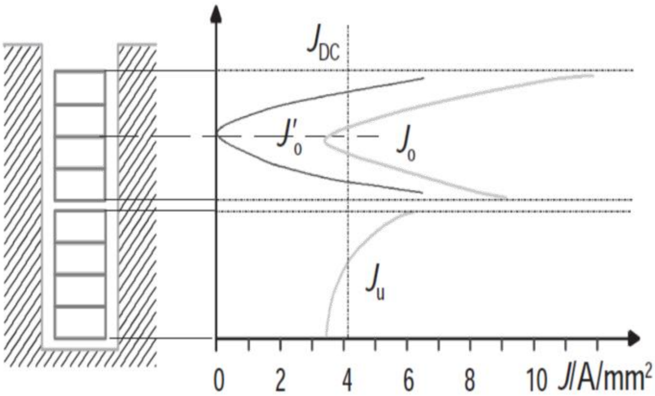


Figure 13: Current density distribution of two conductors in a slot [7]

Figure 11 portrays the different rotor bar shapes that have been designed based on an in-depth understanding of the effect of skin effect and the way in which it can be manipulated on machines that need a high starting torque.

2.8.5.4 Reducing the skin effect

The winding conductor's leakage inductance changes with leakage flux, which in turn determines the skin effect. So, the skin effect can be effectively limited by allowing for uniform flux in the conductors. Two methods that can be used to achieve this are:

i) multiple transposed conductors in a slot or
ii) a Roebel bar or Litz winding in exceptional applications.

2.8.5.5 Stray Losses and Induction Motor Performance

Stray load losses heat up various parts of the electric motor. As a result, motor efficiency is compromised and the machine rating changes. Acceleration and braking are equally affected by the heating effect of the stray load losses. Furthermore, the torque changes across the slip range of the motor.

2.8.5.6 Summary of Reducing Losses.

In [16], the major ways in which losses can be reduced are listed as.

Table 2: Summary of Loss reduction methods

Region	*Method*

Conductors	Proper ventilation Special conductors e.g. Roebel bar Conductors made from different materials Transposing the conductors
End-region	Rounding edges and avoiding 90 degree turns
Space harmonics between rotor and stator teeth	Increasing the air gap Using slot wedges to generate a next to even surface. Magnetic wedges can reduce these losses as well as torque pulsations, therefore increasing efficiency and decreasing machine noise[21].
Air gap	Proper skewing Balancing slot combinations between the stator and rotor.

Moreover, proper insulation during the manufacturing of the rotor bars can also assist in reducing stray losses. Stray losses resulting from time harmonics can be dealt with by improving the quality of supply voltage to the induction machine. It is interesting to note that even if all the above measures are taken, that for an induction motor with the same specifications, e.g. rating and frame size, will have stray losses that vary between manufacturers, or even within the same batch by one manufacturer.

2.9 **Conclusion**

In Chapter 2, the history of induction motors, as well as induction motor theory, have been discussed briefly. The losses in motors were identified and described in detail. Methods to mitigate these losses were also recommended. Of particular importance to this study was the discussion on stray load losses and their origins. It was shown that ample ground concerning the origins of stray load losses has been covered by previous researchers. Therefore, the chapter laid a foundation for the comparison of stray load losses in the context induction efficiency test methods. In the following chapter, a comparison of the various major induction motor efficiency test methods in the major standards will be presented.

3 CHAPTER 3 - COMPARISON OF INDUCTION MOTOR EFFICIENCY STANDARDS

3.1 Introduction

Induction motors consume the greater part of electricity delivered by utility companies. Statistics gathered by the International Energy Agency (IEA) highlight that an estimated 43% to 46% of electricity produced globally is consumed by motor driven systems. This results in approximately 6 040 Mt of carbon dioxide emissions [23]. Electric driven systems in fact are the largest end-users of electricity, followed by lighting systems. Of the percentage given above, asynchronous motors rated between 0.75 kW to 375 kW consume most of the energy. The motors are sold to equipment manufacturers who integrate them into electromechanical products like compressors, fans, tooling machines, fans, etc. Alternatively, stand-alone units are sold directly to customers who then build up electromechanical systems according to their different specifications. Most of the motors are used in industrial applications as prime movers of different systems, although some are used in commercial setups and infrastructures like ventilation systems.

Induction machines rated above 375 kW are usually custom-designed and only built after an order has been placed. Of the electrical power consumed by motors, they use 23% although they make up only 0.03% of the motor population. Unfortunately, no country in the world has minimum energy performance standards for this class of motors [23].

Losses in an electromechanical system are found in the motor itself and the driven system is coupled to the motor. Losses vary, depending on the application and other technologies used as part of the system, like variable speed drives [24]. Low powered machines are less efficient when compared to their high-powered counterparts. However, greater losses in systems are experienced when the constant-speed motor is coupled to a load whose power demand varies. Such cases would require the use of VSDs to regulate the speed and torque of the machine so as to match the mechanical load [25]. Having said that, it is critical to note that speed and torque control coupled with energy regeneration can offer greater energy saving than just implementing high efficient motors [26]. Figure 15 illustrates how device to system savings can be implemented [27].

3.2 Need for Standards

The amount of energy consumed by electric motors requires that there are standards to facilitate and regulate energy savings. Unfortunately, there is no single instrument globally that facilitates this. However, different countries and regions have standards provide guidelines that are meant to influence decision making as far as the acquisition of motors is concerned.

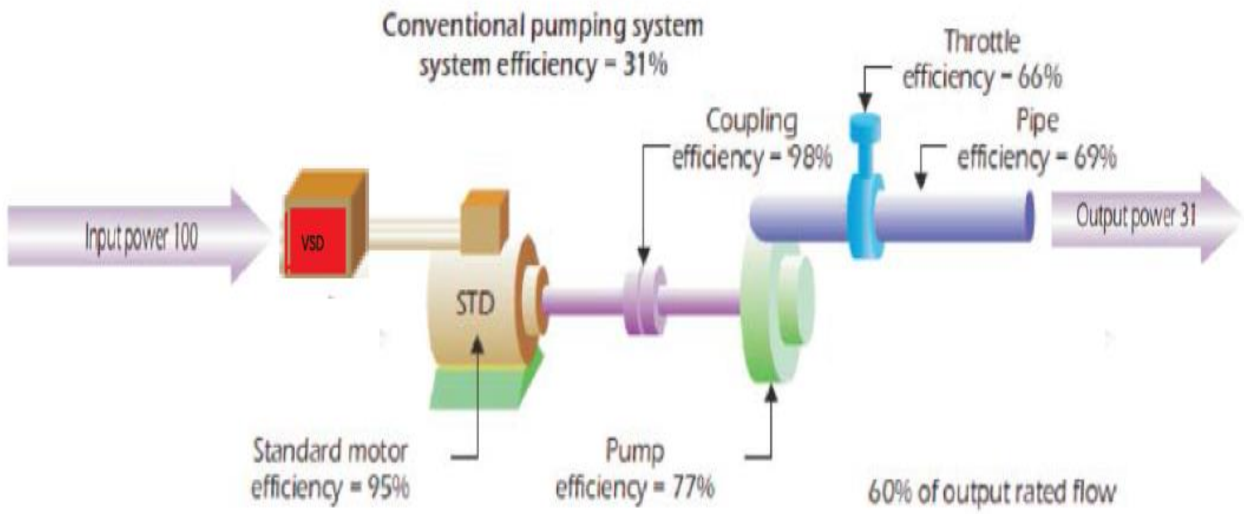


Figure 14 Energy saving across a complete drive system [23]

The availability of cost efficient energy saving motors on the market poses no certainty for their implementation. A variety of policies is necessary to cross the barriers that exist to acquire and install/use energy efficient motors [28].

Major stakeholders involved and affected by standards are represented in Figure 16. This shows how to effectively plan a comprehensive strategy for electric motor systems [29].

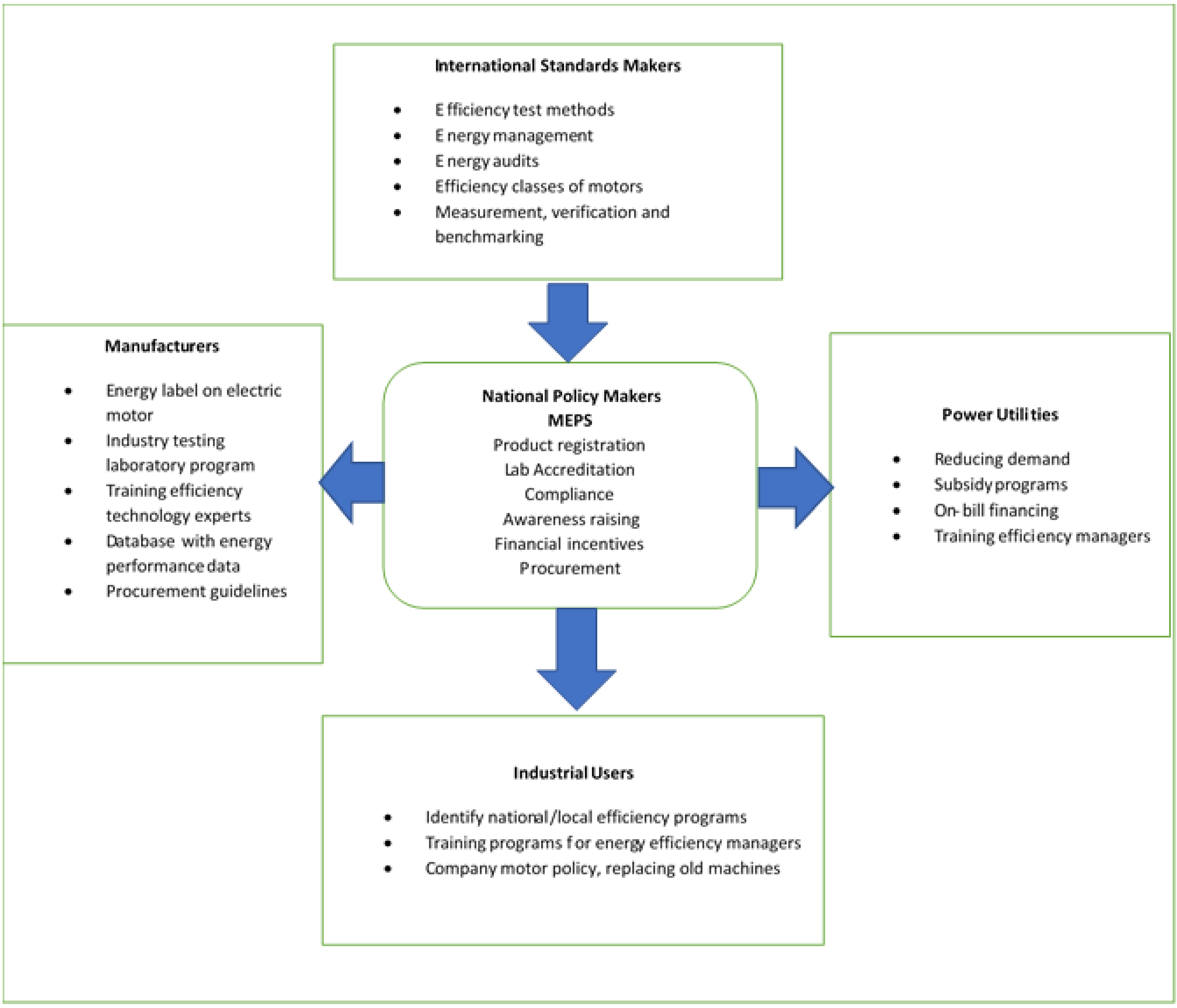


Figure 15: Major stakeholders in the development and use of standards

A couple of different continuing programs in Europe indicate a progressive proactive approach in matters concerning motor efficiency. The most prominent are the European Motor Challenge Program (MCP) [29], Standards for Energy Efficiency of Electric Motor System (SEEEM) [30] and European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) labels of asynchronous motors [31] and the IEC 60034-30 standard [32].

The USA has compiled minimum efficiency performance standards (MEPS), which stipulate minimum efficiency requirements for common motors. MEPS is a part of the Energy Policy Act of 1992 of the USA, which in recent years saw NEMA premium rated motors becoming minimum MEPS rated. The Australian market accommodates electric motors whose minimum efficiency levels are equal to those in the USA, and thus only EEF1 equivalent motors can be imported. It is interesting to note that when the efficiency values of the same motors are measured and compared according to different test methods in various standards, efficiency values calculated based on standards from these regions in the world have different values, which poses a complex situation. The MEPS are regularly updated by referring to efficiency determination methods from different standards leading to varying test results. Furthermore, the rated power range of the motors is different depending on the region, that is, 0.73 kW to 150 kW and 185 kW for the USA and Australia respectively while the European CEMEP ranges between 1.1 kW and 90 kW.

Different regions have agencies worldwide that regulate and promote the use of standards in order to have efficient motors in their regions. In Table 3 the leading agencies/programs and the regions under their jurisdiction are listed.

Table 3: Leading agencies in the promotion and regulation of motor standards [33]

Coverage	*Name of Leading agency or program*	*Website*
Global	4E EMSA	www.motorsystems.org
Australia	Energyrating E_3	www.energyrating.gov.au
Austria	Klimaaktiv	www.klimaktiv.at
Brazil	Procel	www.eletrobras.com
Canada	NRCan OEE	www.oee.nrcan.gc.ca
China	China Motor Challenge	www.motorsystem.org.cn
Europe	Motor Challenge Programme	www.motor-challenge.eu
India	Bureau of Energy Efficiency BEE	www.bee-india.nic.in
New Zealand	EECA electric motors programme	www.eeca.govt.nz
South Africa	Eskom IDM	www.eskomidm.co.za/industrial
South Korea	KEMCO	www.topmotors.ch
Switzerland	S.A.F.E. Topmotors	www.topmotors.ch
USA	Motor Decisions Matter	www.motorsmatter.org

The differences stated above affect the market penetration and market share of the electric motors. Even though market share is dependent on other factors like energy costs in a specific region and increased consciousness on energy efficiency, implementation of MEPS has increased the acquisition of higher efficiency motors in the industry. Hence, if MEPS are completely harmonized and regularly updated it will create a fair global platform for companies to buy and sell their motor products competitively. Much work towards this goal has already been completed, e.g. the IEC has a standard that describes a labelling scheme for asynchronous polyphase induction motors [32]. Table 4 below shows how the labelling scheme corresponds to already existing labels.

Table 44: IEC labelling scheme in comparison with already existing labels by different motor orginizations

IEC Standard 60034-30	*CEMEP*
IE1	EFF2
IE2	EFF1
IE3	NEMA Premium level
IE4	Super Premium level

The approach used to generate the above classifications is based on the assumption that induction motor efficiency test methods are agreed upon through the different standards. However, major discrepancies exist between the standards on their proposed methods of determining efficiencies. As a result, issued certificates of machines and credibility of stated efficiencies are not reliable.

With this background in mind, the major standard boards on the global market, namely the IEC and IEEE have been taking initiatives to update their standards and harmonize them. The major difference between the methods was the determination of stray load losses. Furthermore, the standards do not consider non-ideal practical operating conditions. These include unbalanced voltage supply or the poor power quality that is absent when testing the machine in the laboratory. The next section of this chapter will discuss these differences in detail.

3.3 History of the IEC and IEEE

At the end of the 19th century' many inventions in the electrical field took place, with the inventions coming from different countries and regions on the globe. The inventions developed for the commercial market included filament bulbs, reliable power cables and generators. Therefore, there was a need to standardize such equipment, since Lord Kelvin had already standardized the electrical measuring units. Lord Kelvin maintained that 'when you can measure what you are speaking about, and express it in numbers, you know something about it' [34]. The standards would determine the ratings and performance criteria. Furthermore, it would create a standard for manufacturers to repeat their production and simplify their designs, thus reducing the cost of the product for customers. Furthermore, local manufacturers would be able to compete with foreign manufacturers.

In 1897, the American Institute of Electrical Engineers (IEEE) set up a committee that would work on standardization, which eventually came into existence in 1918 as the American Standards Engineering Institute [35]. At more or less the same time, the British Standards Institution was established under Sir John Wolfe Barry in 1902. Engineers from these different leading institutions decided to embrace common testing, safety measures, terminology and specifications that could be agreed on internationally. The outcome of this mutual agreement led to the formation of the IEC in 1906, whose primary objective was to study the consolidation of electrical machines and associated equipment. The emphasis of this body would be on the unification and consolidation of the standards.

Over the years, the IEC has developed nomenclature, symbols, rating of electrical machinery, rules, regulations for transmission lines, etc. The IEC has also collaborated with United Nations ISO on different directives.

The IEEE-SA is a standards association within the IEEE that develops standards, like the IEC. The IEEE standards are more prominent in the United States of America and South America. In fact, for every standard developed by the IEC, there is an equivalent IEEE standard. Differences between the standards may emanate from levels of standardization, which include compatibility, reference, exchangeability, and similarity. An illustration to show how these levels apply to Southern Africa is a result of the similarity, the grid that operates at the same voltage (alternating current) and the frequency. Unfortunately, our compatibilities as countries are different when connecting to these levels at domestic consumer level. This is because some countries use wall plugs with round sockets while others use square plugs.

The example clearly shows that the process of developing and establishing a standard is complex. This is a result of standards meaning to benefit the market and at the same time facilitating fair competition, will always have mixed intentions.

3.4 The Induction Motor Efficiency Standards

This thesis will deal with measurements. Losses of electric motors will be calculated from different measurements made from certain standards. Standards referred to in this work will include standards from table 5.

Table 5: Major standards referred to in the research

Standard	*Year*	*Description*
IEEE 119	1974	'Recommended practice for general principles of temperature measurements as applied to electrical apparatus.'
IEEE 118	1978	'Standard test code for resistance measurement'
IEEE 120	1955	'Master test code for electrical measurements in electrical measurements in power circuits.'
IEC 60034-28	2012	'Test methods for determining quantities of equivalent circuit diagrams for three-phase cage induction motors'
IEC 60044-8	2002-7	'Electronic current transformers'
IEC 60034-1	Draft 2014	'Rotating electrical machines. Part 1: Rating and performance'
IEC 60034-2	Draft 2014	'Rotating electrical machines. Part 2-1: Standard methods for determining losses and efficiency from tests (excluding Machines for traction vehicles).'

Some of the standards referred to in Table 5 stipulate the conditions, which instrumentation and auxiliary equipment must meet to produce the desired results. As observed, such standards have not gone under much revision since their release, for example the IEEE 119 of 1974.

A comparison of standards in this study will focus primarily on those standards that determine the performance of induction machines as well as the machine losses. Evaluation of power losses in machines cannot be separated from standardized procedures. While manufacturers seek to improve the design of induction machines due to environmental, energy costs and legislative concerns, there is always the need to practically test the efficiency of motors. The results thus obtained can be compared to those derived by design tools like finite element tools. Test results should be reproducible, reliable and accurate. In order to achieve that, a measurement standard with an accepted procedure should be used.

3.5 **Determining Efficiency of Induction Motors**

The determination of the efficiency of induction motors can be classified under two categories namely, direct methods or indirect methods. All the methods in the standards fall under either of the above-mentioned categories. The following section of the research seeks to verify the two major models applied by the IEC and IEEE standards to calculate the efficiency of induction motors.

Efficiency is generally given by the following ratio:

$$\eta = \frac{P_{out(mechanical)}}{P_{in(Electrical)}} = 1 - \frac{P_{loss}}{P_{in}} \quad (3.1)$$

Direct measurements uses terminal voltage and current to calculate input power, and shaft torque and speed to obtain output power. Alternatively, an indirect method also known as segregation/summation of losses can be applied. In this method, the separate losses namely resistance/ohmic losses, iron losses, friction and windage losses and stray load losses, are calculated separately. This method is usually preferred, because torque measurement expenses are eradicated. The SLL can be evaluated as follows:

$$P_{SLL} = (P_{in} - P_{out}) - P_{Conv} \quad (3.2)$$

where

$$P_{Conv} = P_{St} + P_{Ro} + P_{Fe} + P_{W,Fe} \quad (3.3)$$

To determine copper losses, the motor is put under a load test where stator current is recorded at each load point and losses calculated using the DC resistance. P_{Fe}, P_{FW} are determined from a no load test.

A study of different induction motor efficiency test standards shows that the major difference between standards is the way in which they determine additional losses. There are basically two indirect methods to determine SLL. The first one is the input-output method where the separate losses are determined, including measuring speed and torque accurately. A fixed or variable allowance value was used to estimate the SLL in the previous versions of the standards. It could be 0.5% of the rated input power of the motor when it is running at rated load. Furthermore, torque measurements were not carried out in this method. Values of SLL obtained by this method portrayed a large variance between the IEEE and IEC values of SLL.

The IEC 60034-2 also recommends the Eh-star method in which the motor, connected in star, runs at no-load on a single-phase source. An auxiliary resistance R_{Eh} is connected to in parallel with phases of the motor to create an unbalance in the supply [36].

The IEEE and IEC recommend other methods to evaluate losses, but this paper will consider those stated above. The paper will discuss the variances that lead to different SLL values of the same machine measured by different standards.

3.6 **Test bench Setup**

3.6.1 General Test Procedure

Major induction machine test standards recommend a similar process for temperature tests, winding resistance tests, load, and no-load tests. The load test can be conducted with or without torque measurement. Figure 16 illustrates the test bench setup that was used as part of this research to carry out the tests.

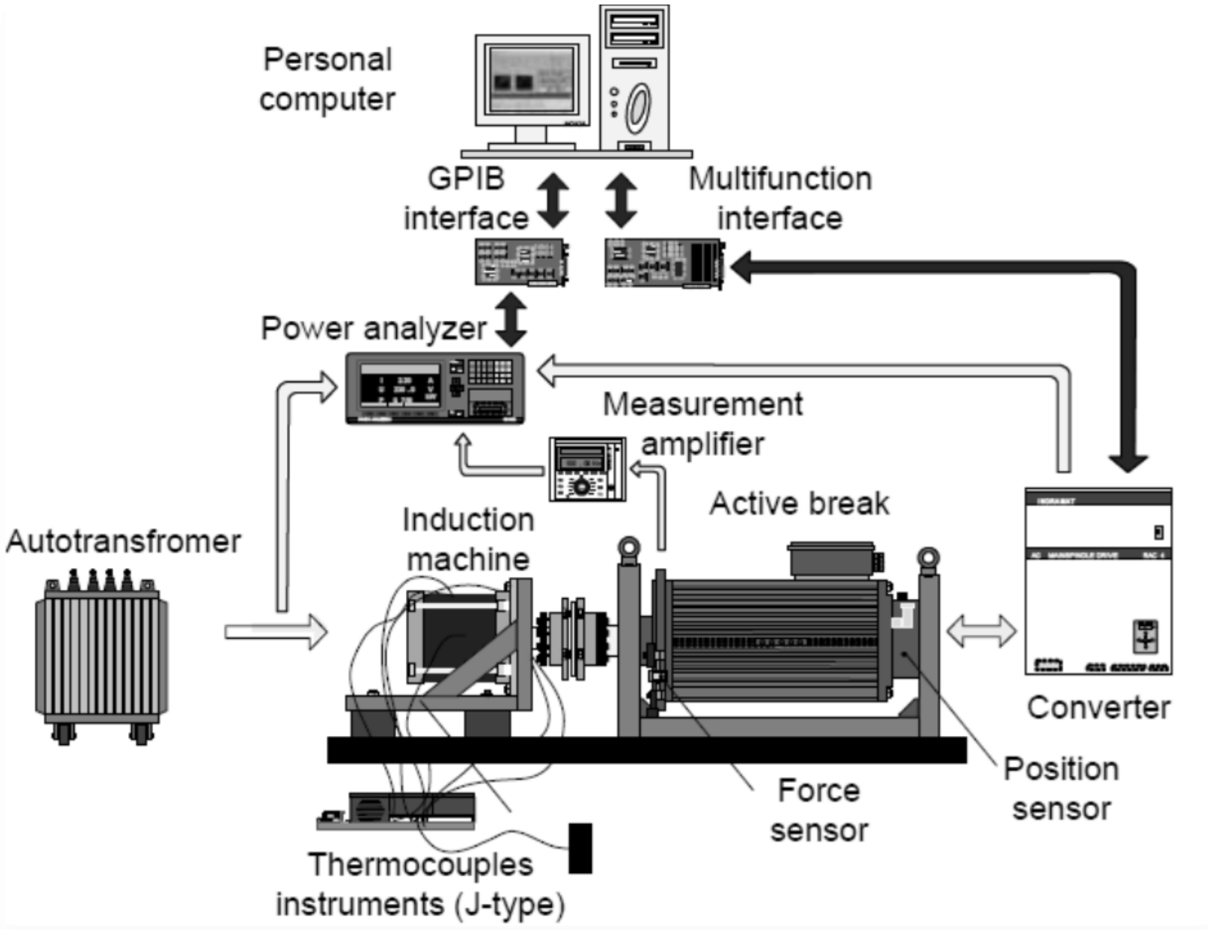


Figure 16: Schematic representation for the Test bench used in the experiments [37]

It is recommended that when carrying out the tests, readings must be taken quickly and the transition from one load point to the next load point done as quickly as possible to maintain thermal equilibrium conditions. In the case of a time delay, the previous temperature conditions should be established at first before the test continues. The following sequence is recommended when carrying out the tests according to IEC 60034-2-1 standard.

The bench setup should be stiff and subject to minimum vibrations when operational. Proper alignment between motor and loading machine should be secured, and an easy quick way of adjusting the load be applied. For the test bench used in this study, the motor was loaded using a DC motor acting as a generator. The load was a bank of DC resistors set at 10 ohms.

The load was then varied by controlling the output voltage of the variac feeding the bridge rectifier, which supplied the field for the DC motor. The speed and torque of the motor were measured by an in-line torque transducer, and the signal recorded by the power analyzer and imported to the PC.

Two variacs were connected in parallel to supply sufficient current to the test setup; their outputs were sent through a centre tap inductor. The centre tap inductor forces current in the two variacs to be equal thus ensuring that the two variacs share the current equally.

Shielded cables, routed separately from the power cables, for the instrumentation were used to terminate noise and distortion of signals. The power analyzer used to measure and record the data not only checked the integrity of supply voltage, but also recorded harmonics in the current and voltage, as well as unbalances in these variables.

Prior to running the machine, the DC winding resistance and the ambient temperature were measured. The reference temperature used in the calculations was 20℃. Having done the above, the next step was to establish thermal equilibrium.

a Thermal Equilibrium

The induction motor under test should be operated at rated load until it reaches thermal equilibrium. The IEC 60034-2-1 standard defines thermal equilibrium as the state in which the temperature rise of the motor is not changing by more than 2 K per hour (Figure 17). It can be obtained from a time-temperature rise plot in which the straight lines connecting two successive intervals have the maximum gradient stated above. It is imperative that, for a no-load test, the thermal equilibrium must be reached first, as the results from this test are very dependent on temperature.

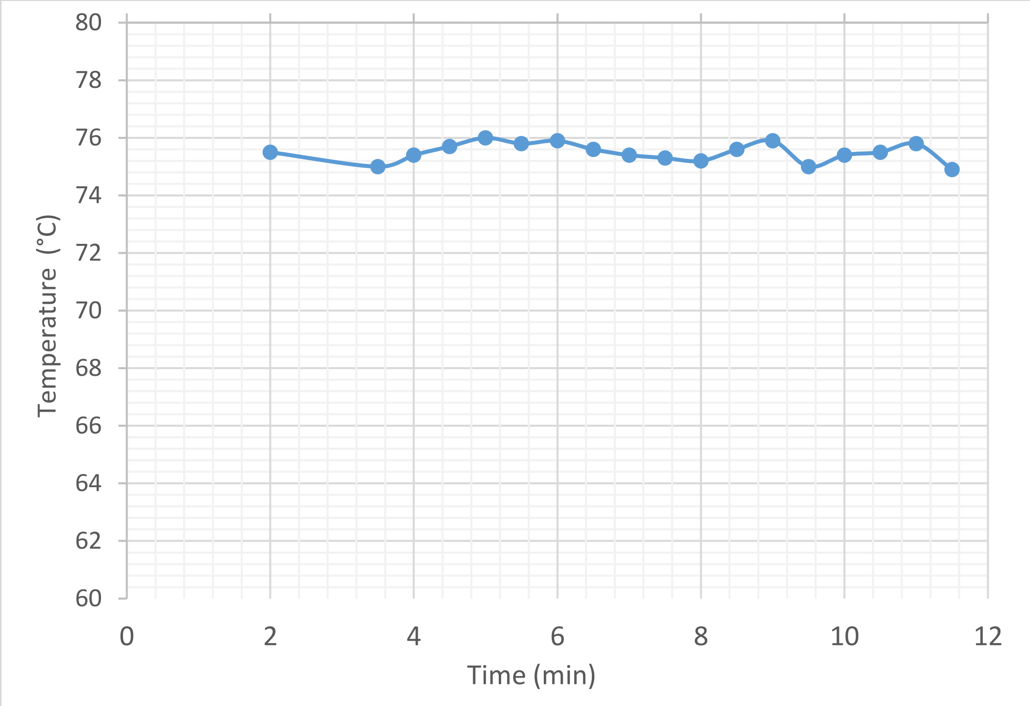


Figure 17: Thermal equilibrium profile for a 3 kW induction motor under test

The following relationship illustrates the above:

$$\theta_2 - \theta_a = \frac{R_2 - R_1}{R_1} * (k + \theta_1) + \theta_1 - \theta_a \qquad (3.4)$$

With θ_1 = cold temperature

θ_2 = end of temperature test

θ_a = coolant/ambient temperature at end of thermal test

R_1= resistance at θ_1

R_2= resistance at θ_2

k = coefficient of resistance where Cu is 235 and Al is 225

Thermal equilibrium allows friction and windage losses to stabilize, and readings of input power will not vary by 3% between readings taken at regular intervals.

The DC winding resistance temperature is also measured at ambient temperature. Both the IEC and IEEE standards recommend recording the DC winding temperature immediately after the thermal equilibrium test for a period of at most five minutes, while recording the resistance readings at regular intervals. Resistance readings are then plotted against time, in which the time constant should not exceed thirty seconds. The curve is then extrapolated to obtain the precise resistance value of the machine at shutdown as shown in the following curve.

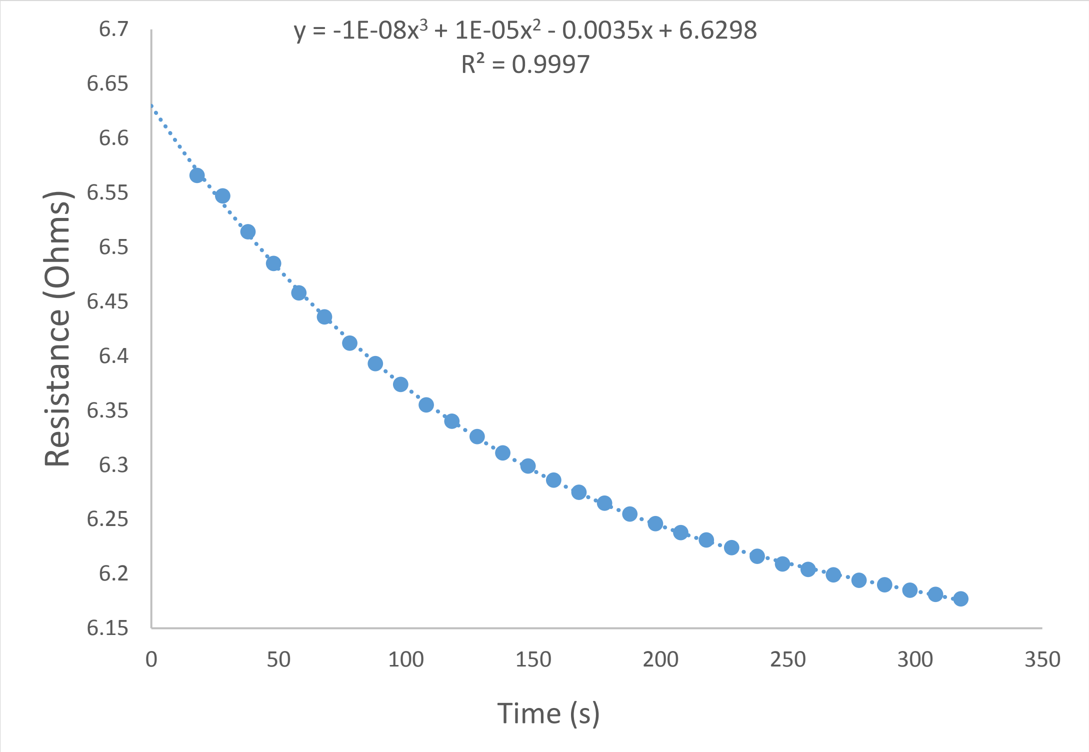


Figure 18: 5.5 kW Winding resistance decay immediately after machine shutdown

b Test at rated load

With rated terminal voltage and supply frequency, the machine is subject to its rated load and operated until a thermal equilibrium is achieved. The following values are recorded at the end of the test: P_N, I_N, U_N, s, f, R_N, θ_C, and θ_N.

c Load Test

Immediately after Test b, the machine is subjected to six load point tests, starting from the highest load point. Two of the load points should preferably be between 100% to 150% of the maximum rated load and the remaining four between 25% and 100% of rated load. Torque readings are also recorded at every load point. The following readings are recorded at each load point: P, I, U, T, s, f, R, θ_C, and θ_N. R should be measured immediately after the test has been completed. It is important to allow the machine to stabilize at each load point so that transient readings are not recorded.

d No-Load Test to determine the constant losses

The machine is operated at a constant frequency and rated voltage. Terminal voltage is then varied starting from the 125% rated voltage to minimum voltage where any further reduction will result in increases in current. The following parameters are measured at the different voltage levels, P, I, U, T, s, f, R, θ_C

θ_N. Resistance is measured immediately after this test. When decreasing readings are recorded, the machine must be allowed to stabilize at each voltage point so as to avoid transient readings caused by the inertia of the machine.

e Core losses and friction and windage losses are calculated from the no-load test. The difference between input electric power P_0 and stator copper losses is the summation of constant losses represented by P_k. P_k is the total of the iron, friction and windage losses. So P_k is plotted against voltage squared and the curve extrapolated to zero voltage in which the intercept is the value of friction and windage losses. Subtracting friction and windage losses from P_k results in the core losses. The following curve illustrates this procedure clearly.

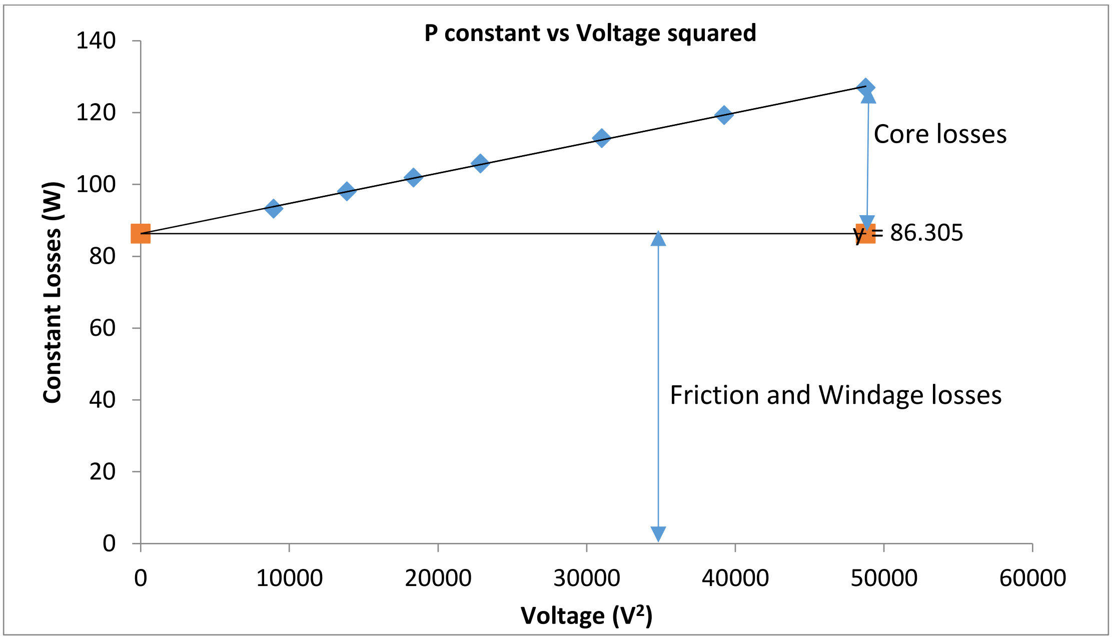


Figure 19: 3 kW No-load constant losses versus the square of input voltage to determine core losses and friction and windage losses

Having obtained the constant value of friction and windage losses, the standards proceed to recommend a method to calculate the core losses at a specific rated voltage. Iron losses obtained from subtracting friction and windage losses from the constant losses, are plotted against phase-phase voltage for voltage points above ninety percent, but at less than one hundred and twenty five percent of the rated voltage. The resulting curve, when smoothed produces a linear equation, which can give the exact value of core losses at a specific voltage. This approach considers the resistive losses, which sometimes produce a slight voltage drop during load tests.

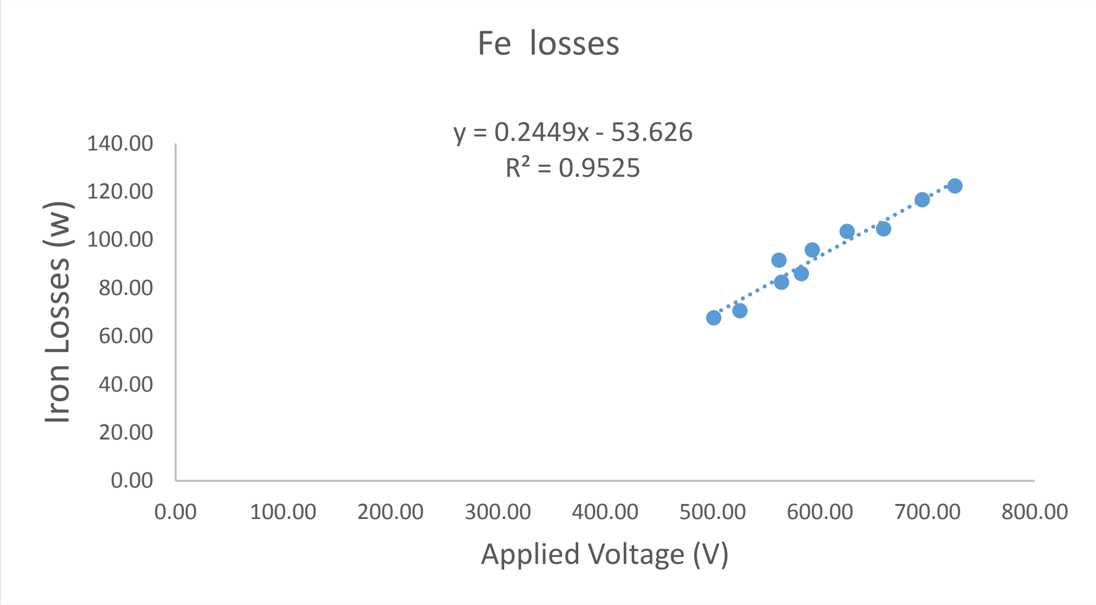


Figure 20: 3 kW Iron losses at a specific load voltage

Stator winding losses, for delta connected machines where R is the line-line resistance, are calculated from the following equation:

$$P_s = 1.5 \cdot I^2 \cdot R \tag{3.5}$$

Where the machine windings are star connected, phase resistance is given by the product of 0.5 and the line-to-line resistance. For each load point, the average winding resistance is used in the calculations. It can be measured at respective load points or winding temperature readings at each load point and it can be used to calculate resistance at that specific load. When stator resistance is corrected to reference coolant temperature, the corrected winding losses are calculated.

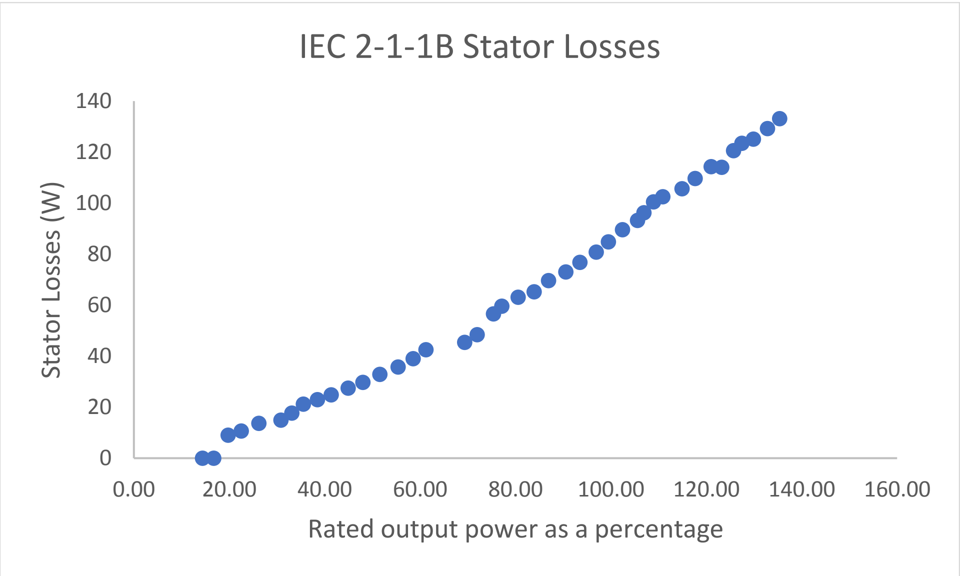


Figure 21: 3 kW Stator losses at various load points during the variable load test.

Rotor winding losses are given by the following equation:

$$P_r = (P_{el} - P_s - P_{Fe}) \cdot s \tag{3.6}$$

The value of slip at the specific load points, corrected to the reference temperature, and corrected stator losses are used to obtain corrected rotor losses. Figure 22 shows the rotor losses when calculated according to the above procedure.

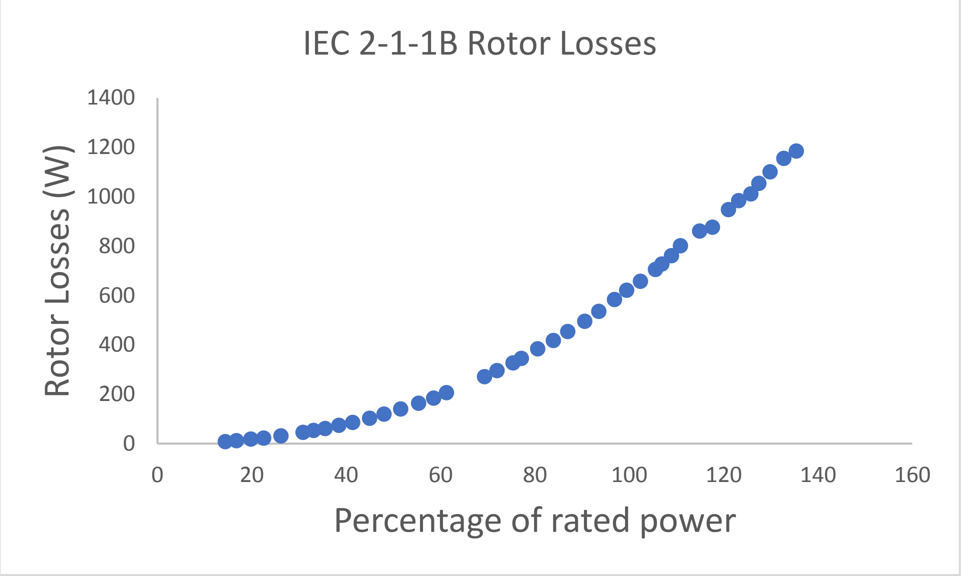


Figure 22: 3 kW Rotor losses at various load points during the variable load test.

Finally, stray load losses are calculated depending on the method used. As explained above, the four main methods for the determination of stray load losses are the Input-output method torque measurement, Eh-Y method, and the fixed and variable allowance methods. The input-output method will result in the following curve in which the SLL are plotted against the torque squared. The points should generate a straight line as shown in Figure 23. Failure to achieve that is an indication that there is an error with instrumentation or test procedure, hence the test must be repeated until the curve forms a straight line.

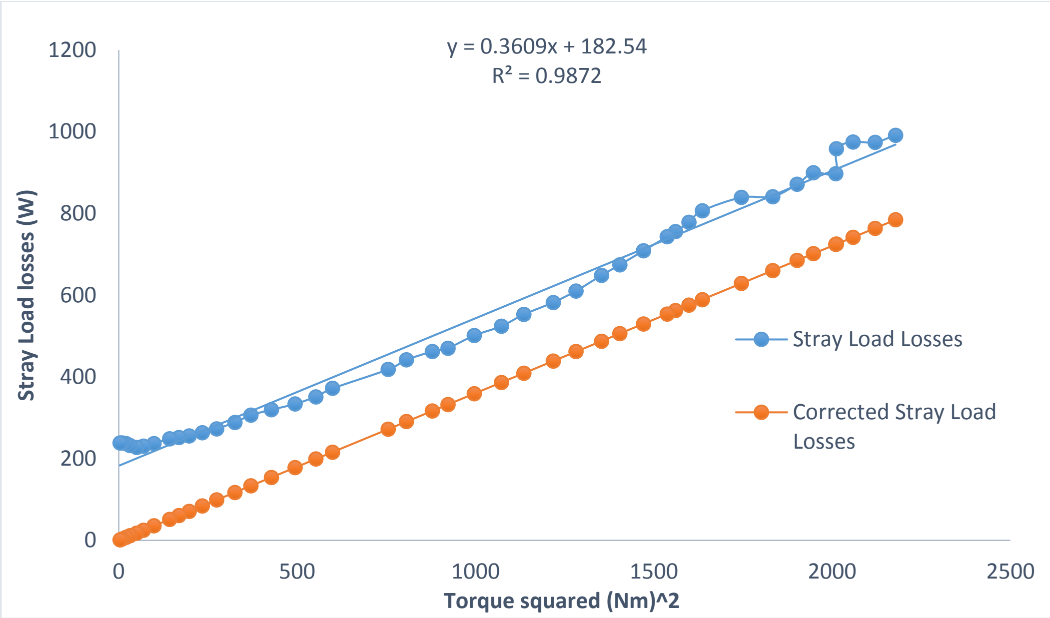


Figure 23: 3 kW SLL before and after linear regression analysis

A linear regression analysis is used to smooth the data and generate a straight line in the order of:

$$P_{SLL} = A \cdot T^2 + B \qquad (3.7)$$

Corrected SLL are obtained when load torque is zero therefore the curve is corrected by having it pass through the zero intercept. This is achieved by eliminating B in the Equation 3.7 and obtaining:

$$P_{SLL} = A \cdot T^2 \qquad (3.8)$$

Efficiency is then calculated using Equation 3.8.

3.7 **Uncertainty of measurement**

In this section, uncertainty of measurement is discussed briefly. Absolute certainty in the determination of quantities during measurements is impossible. Therefore, it is important specify the accuracy of an instrument before calculations can be made. The correctness of a recorded measurement is indicated by the specified accuracy.

Definition of terms

For the purpose of clarity, the following terms have been defined.

Uncertainty of measurement - "parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The parameter may be a standard deviation or a given multiple of it" [38].

Accuracy -" this is a qualitative concept which defines the closeness of the agreement between the result of a measurement and a true value of the measurand" [38].

Precision-" this refers to the random spread of measured of values around the average measured values."

Resolution-" the smallest magnitude to be distinguished from the measured value".

Measurement uncertainties result from either systematic errors or random errors or both. Systematic errors originate from measuring instruments, for example zero error, or from wrong use of instrument by experimenter and imperfect methods of observation. Random errors result from noise and interference caused by stray currents and voltages on the instrumentation.

Importance of calibrating test equipment

Before applying calculations and statistical methods to analyse recorded data, equipment used to obtain measurements must be calibrated and valid calibration certificates presented whenever readings are collected. This will ensure reliable results from the tests, as well as eliminate systematic errors on the instruments. It is difficult to detect systematic errors since all the data is off by the same value. Measurement results are affected by systematic errors. Data analysis through statistical means cannot identify systematic errors as well, hence the importance of calibrating equipment to be used during the tests.

The test equipment used in this research had accuracies meeting the requirements of the both the IEC and IEEE standards in Table 15. In order calculate efficiency through Direct or Indirect methods, parameters like current, torque and speed were measured with instruments in series [39]. The instrumentation accuracy of the test equipment used during the experiments is given as follows:

- Voltage was direct measurement (accuracy- 0.01% Rdg + 0.038% Rng +(0.004% x kHz)+ 5 mV)
- Current was measured with two instruments in series, namely an LEM IT 60-s CT hall-effect transducer (accuracy - 0.03%) and Power analyser (accuracy - 0.01% Rdg + 0.038% Rng +(0.004% x kHz)+ 300 uA
- A Magtrol TMB 311/431 inline torque/speed meter (accuracy - 0.15%) and Power Analyser measured speed and torque. Torque accuracy in the Power analyser was given as (accuracy – 0.05% Rdg + 0.05% Rng).

Measurement Uncertainty

The overall measurement uncertainty consists of two values namely:

a) Uncertainty over full scale reading
b) Uncertainty of reading

Uncertainty over full-scale reading results from tolerances and instrument errors, including tolerances, instrument gain, digitization of signals during conversion in AD convertors and absolute deviation of instrument readings. For example, the power analyser has an accuracy specification of (0.01% Reading + 0.038% Range + (0.004% x kHz)+ 5 mV). This accuracy incorporates the inner operations of the ADC and other circuitry in the meter, which have offsets, nonlinearities and tolerances that change from range to range, and function.

Table 6 gives the accuracy calculations of voltage readings of the 5 kW no-load test, recorded at different ranges of the power analyser.

Table 6: No-Load accuracy calculations

Voltage (V)	*Range (V)*	*Accuracy (V)*		*Accuracy (%)*
459.16	1000	0.430936	-0.43094	0.09385
295.68	300	0.148588	-0.14859	0.05025
29.616	30	0.019382	-0.01938	0.06544
4.3233	10	0.009252	-0.00925	0.21401

The complete accuracy for the readings gives an average of 0.1% which is sufficient for the measurement. Hence selecting the lowest measurement range gives the most accurate results. The power analyser selected auto-ranges, thus producing results within the acceptable range of accuracy. An auto-range in a modern digital meter is a mode in which the meter automatically selects to record measurements in upper ⅔ of the range in which the readings are taken.

With all factors combined, accuracy values for each reading are calculated as shown in Appendix C and shown in Figure 24. The resulting error voltage when plotted against the measured value shows a constant increase which is proportional to the change in scale. Readings were recorded in the upper ⅔ of the scale.

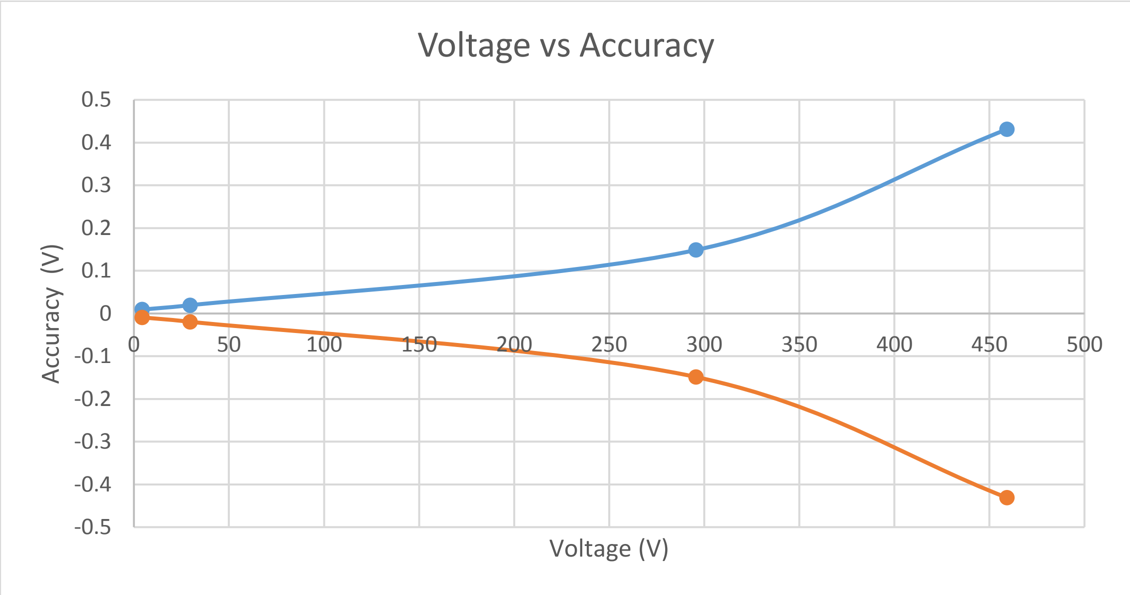
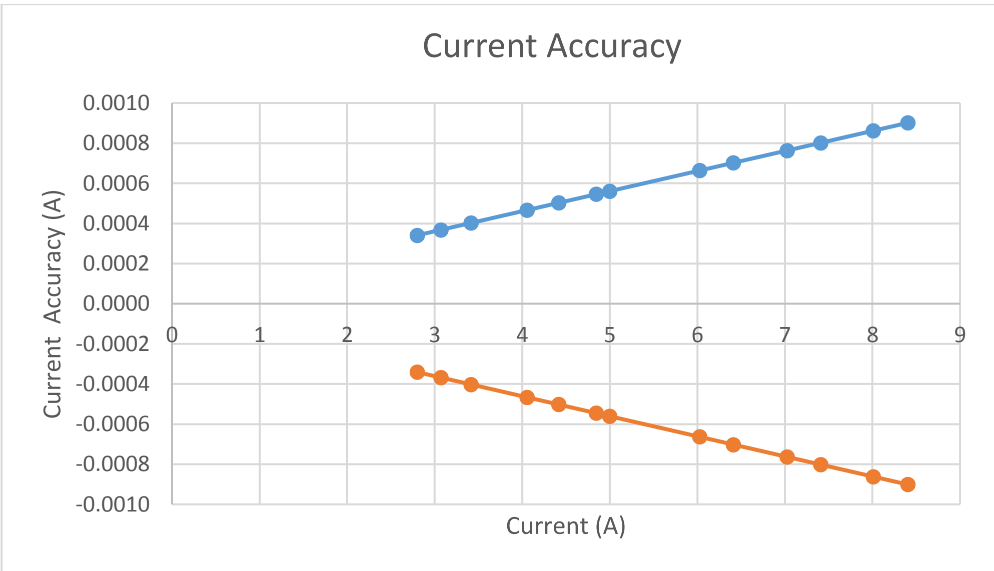
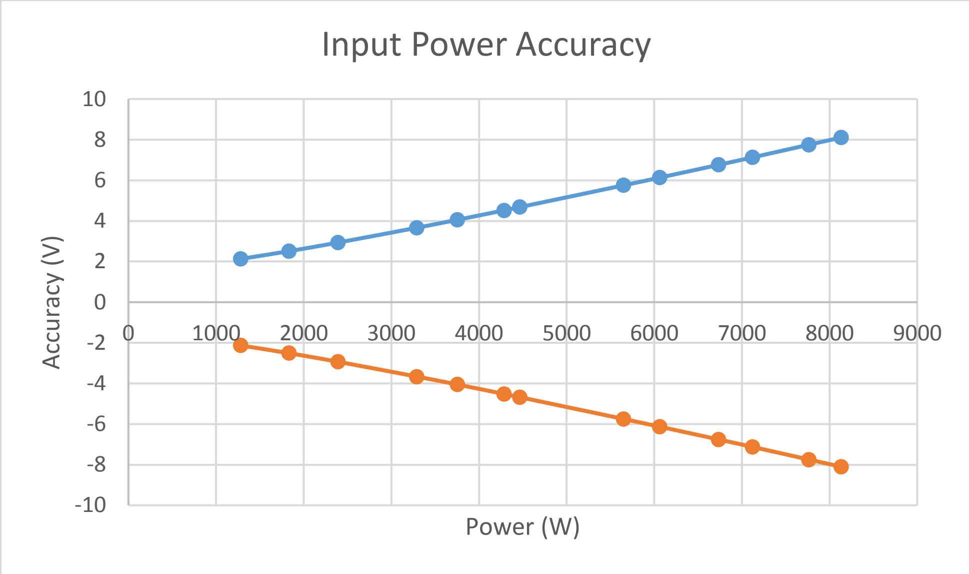


Figure 24: No-load voltage accuracy for 5 kW motor

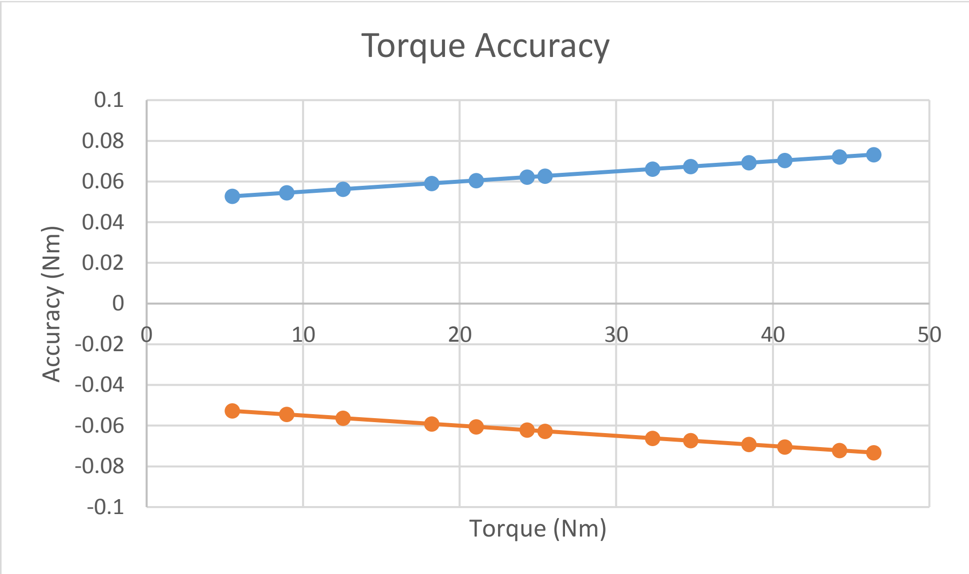
When readings were recorded within the same range, the error values were constant. The error Current values plotted on the graph include all the factors combined, i.e the % error + lsd etc.



a)



b)



c)

Figure 25: Accuracy characteristics for a) current, b) input power, and c) speed

In Figure 25, the accuracy characteristics have the same trend, where the accuracy values tend to increase proportionally to the increase in range. The power analyser auto-ranges, taking readings in the upper ⅔ of the selected scale for every reading. Accuracy values for speed were generally constant with a slow rise in gradient. This was mainly because the speed transducer had measured the speed in the same range for the motor.

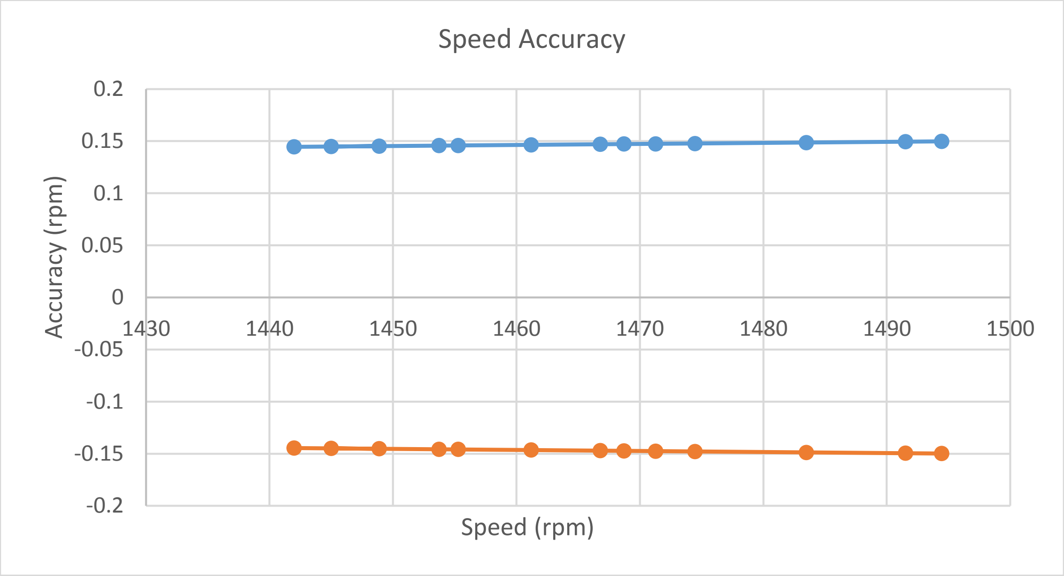
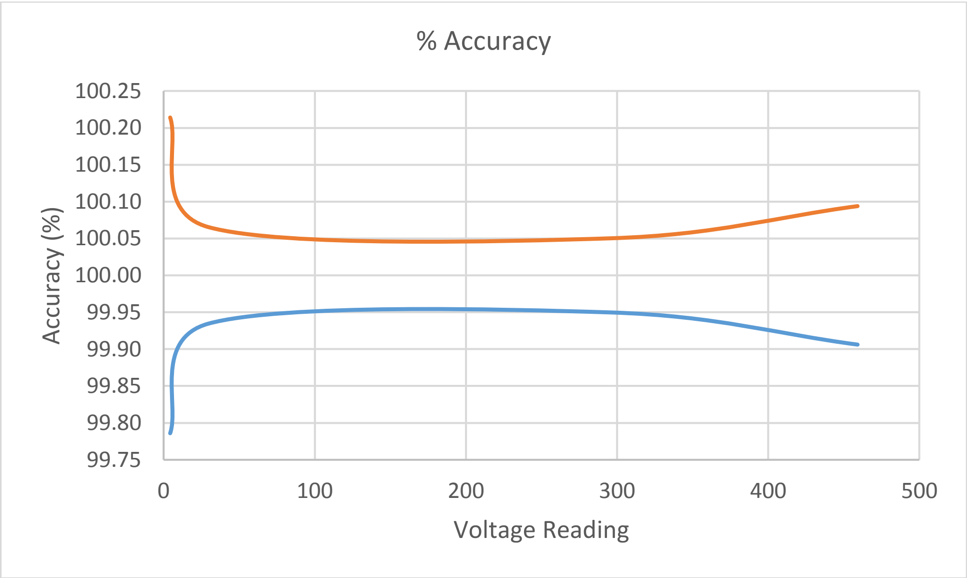
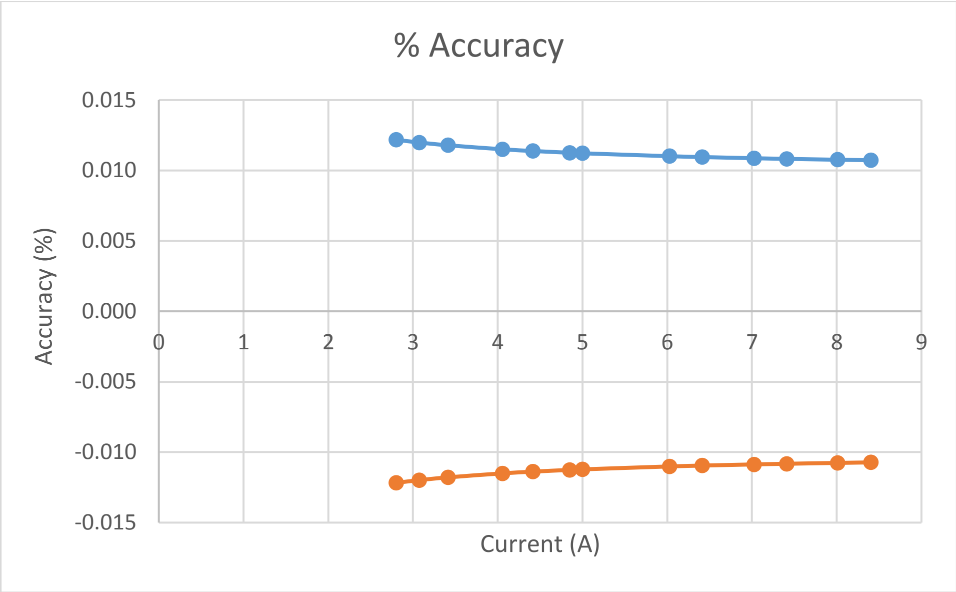


Figure 26: Accuracy characteristic for speed

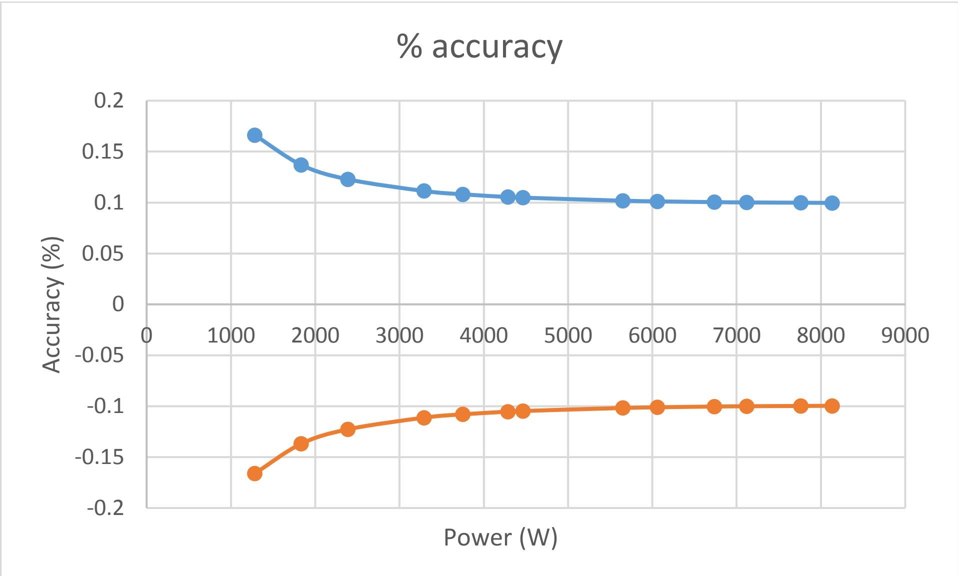
Furthermore, accuracy can be expressed as a percentage of reading value as shown in Figure 2. If the least reading is discarded, the error is near constant, which indicates that required accuracy (+/- 0.2%) of IEC60034 is met. The lowest reading is just outside the limit.



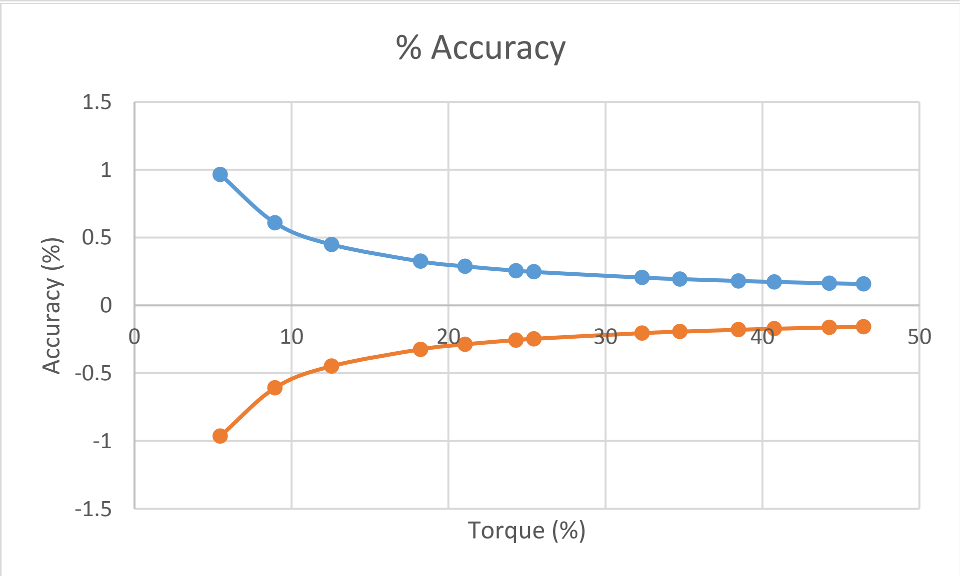
a)



b)



c)



d)

Figure 27: Percentage accuracy for a) Voltage, b) Current, c) Input power, and d) Torque.

Figure 27:a) has steep rises at low voltage readings. These are a result of the 5 mV in the accuracy specification of the power analyser instrument. As the reading value increases, 5 mV become negligible hence reliable values are obtained when readings are taken in the upper ⅔ of each range of the meter.

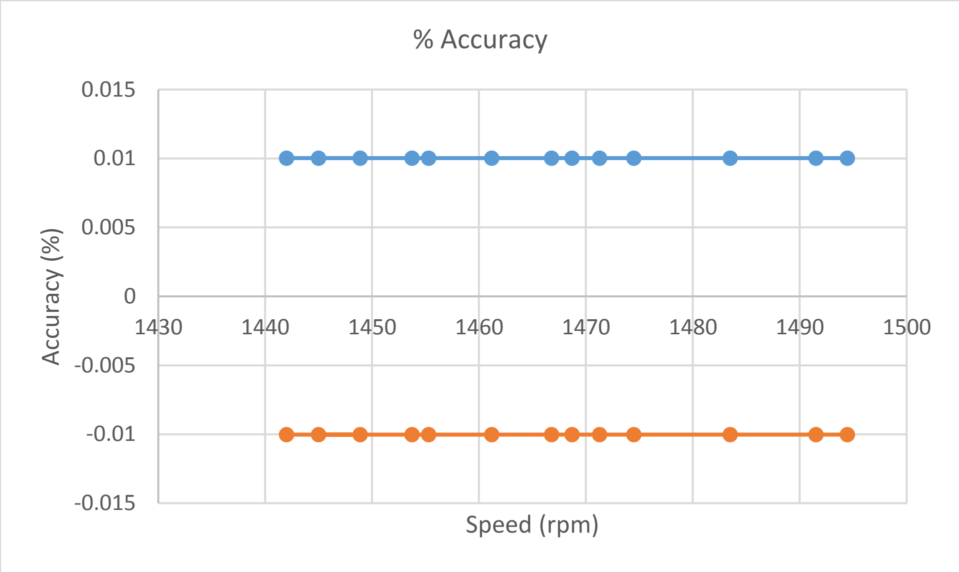


Figure 28: Percentage accuracy readings for speed

Figure 28 shows percentage accuracy to be constant, which is attributed to the single range in which the speed was recorded by the speed transducer. However, all the accuracies of the instruments were within the 0.2% recommended by the IEC 60034-2-1.

Cumulative Uncertainty for Instruments in Series

As indicated above, some of the measurements were recorded by two instruments connected in series, for example, current. The additional accessories or probes have different tolerances and gains (from the main power analyser), which must be taken into account when computing the final measurement uncertainty. To achieve this, summation in quadrature is used where the total reading uncertainty is given by:

$$\%Total = \sqrt{(\%Reading)^2 + (\%Uncertainty\ of\ Second\ instrument)^2} \qquad (3.8)$$

The curves in the following Figure 29 indicate that accuracy computed from summation in quadrature for instruments connected in series is higher than the accuracy for one instrument. The blue characteristic represents accuracy from one instrument whereas the red curve for summation of the accuracies both instruments connected in series. Hence, it is always important to incorporate all instruments used to record data so as obtain a true picture of the uncertainty of measurements.

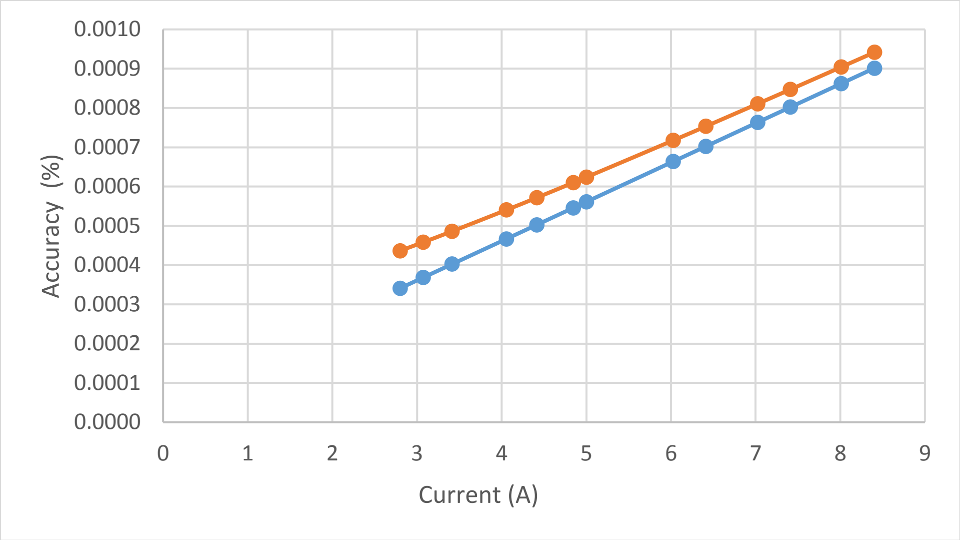
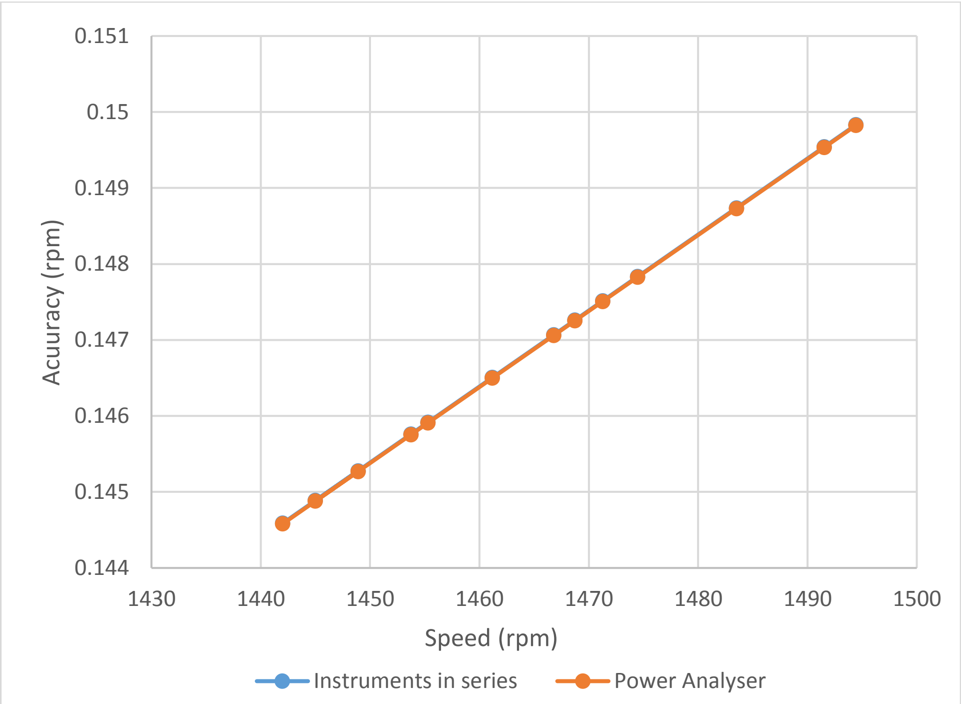
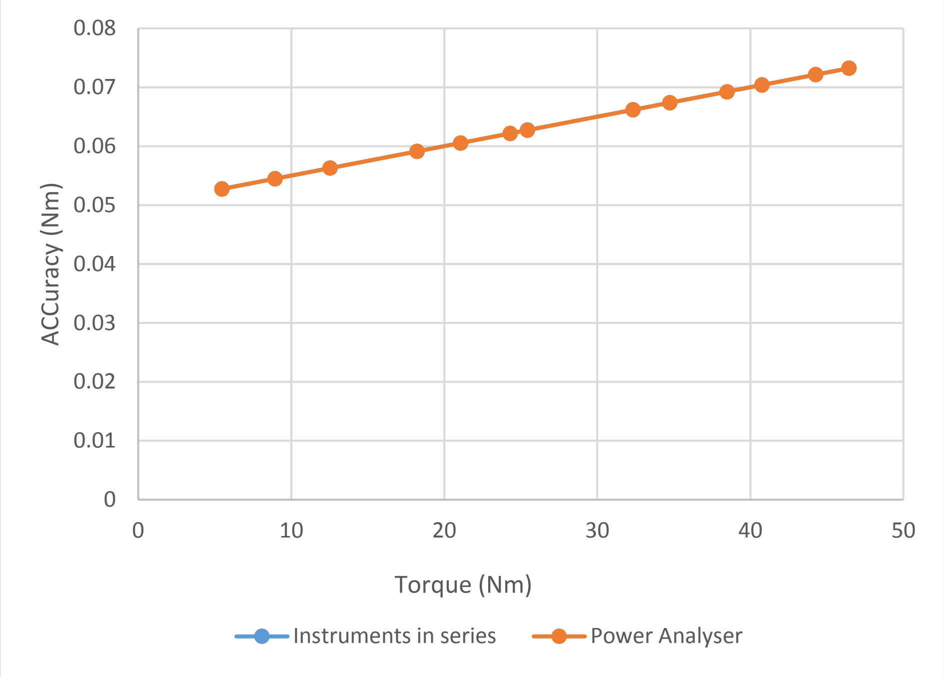


Figure 29: Cumulative accuracy and accuracy from the main instrument.

Figure 30 below shows the same comparison of the accuracy values between one instrument and two instruments connected in series. Parameters with this arrangement were restricted to speed, torque and current, where the characteristic curves for current are in Figure 25a.



a)



b)

Figure 30: Cumulative accuracy and accuracy from the main instrument for a) Speed and b) Torque

The characteristics in Figure 30 have the blue and red curve representing the cumulative accuracy of the instruments in series and accuracy by the power analyser respectively. Figures 30 a) and b) indicate that curves for torque and speed parameters do not show the variation as the difference between the specified accuracy of the power analyser and total accuracy from the summation of quadrature of the instruments connected in series is very small. The curves seem to be superimposed, thus indicating that the power analyser and auxiliary equipment used to take measurements was within the IEC specified range as well.

Moreover, the above characteristics indicated that after manually calculating the uncertainty in measurement of the different parameters namely rms voltage, rms current, speed, and torque the difference between the measured and calculated value was very minute. It therefore establishes confidence in the instrumentation used for data acquisition as it has minimum error. Furthermore, the use of digital instruments, which have auto-range capabilities, secures that in most instances readings are taken with instrument operating close to the maximum value of the full-scale reading of the range.

However, the IEC standard needs to quantitatively define uncertainty and move from generic definitions namely “low, medium and high” as stated in section 5.2 of the IEC 600034-2-1 standard to uncertainty ≤ 0.2%. This value is achievable if modern instruments and data acquisition technologies are used for measurements.

3.8 **Comparison of Standards**

If the efficiency of a polyphase induction machine is evaluated using more than one of the methods any one of the standards, different values of efficiency are obtained. The following sections will shed light on the origins of these discrepancies. Efficiency values are dependent on the standard and test method used. A literature comparison of the standards shows that differences between the standards can be categorized as minor and major differences. Minor differences can be identified in the terms used in the document content, titles in the various sections and the recommended scope of the measurement tests. Major differences in the literature of the standards are in the recommended instrumentation, accuracy requirements, and test procedures. The following section will highlight these variances.

The IEC 60034-2 standard was originally published in 1972, but was updated in 1995, 1996, 2007 and 2014. The first version of the IEEE standard 112 was released in 1964, with revisions being done in 1996, 2004 and a draft version in 2014. The test methods in the standards generally have not changed and few alterations were made.

3.8.1 Minor variances

Minor variances are largely found in the nomenclature used in the standards. To begin with, the titles of the standards vary. For example, the title of the IEC 60034-2-1 “Rotating electrical machines: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)” whereas the title of the IEEE standard is “Standard Test Procedure for Polyphase Induction Motors and Generators”. The former is then divided into sections with test procedures for DC machines, induction motors and synchronous machines respectively while tests in the latter may be applied to generators or motors depending on the application. The IEEE 112 does not provide for the classification of the procedure into sections and subsections that separate motors and generators.

In terms of content and scope, the standards exhibit slight differences, though it is not in the same order. References to other standards, instrumentation requirements, and calculation formulae and procedures comprise the content of the standards. Furthermore, the standards are in harmony concerning the induction motor loss components, although they vary in terms of methods, and reference conditions to evaluate these losses. Table 6 has a brief comparison of some the major nomenclature differences:

Table 7: A comparison of the different nomenclature between the IEC 60034-2-1 and IEEE 112.

Parameter	*IEC 60034-2-1*	*IEEE 112*
Ohmic losses in windings	Stator/rotor winding losses	Stator/rotor I^2R losses
Active iron losses	Iron losses	Core losses

Losses resulting from load current in the active iron as well as eddy current losses in conductors.	Additional load losses	Stray load losses
Unaccountable losses after conventional loss components have been determined.	Residual losses	Uncorrected stray load losses

3.8.2 Major Variances

Major variances include differences in power supply specifications, instrumentation, temperature references, test procedures and calculation of results. These will be discussed in detail.

3.8.2.1 Power Supply Comparison

Voltage requirements for the source supplying the test bench during tests should be within the limits listed in Table 7.

Table 8: Recommended power supply values

Parameter	*IEC 60034-2-1*	*IEEE 112*
Frequency deviation (%)	0.1	0.1
Total Harmonic Distortion (%)	1.5	5
Voltage Unbalance (%)	0.5	0.5
Voltage Deviation from rated.	-	-

This IEC 60034-2-1 references THD in the preceding IEC 60043-1 in which it is referred to as the Harmonic Voltage Factor (HVF). The factor is given by the sum of voltage harmonics over rated voltage. The IEEE standard computes the HVF as the sum of voltage harmonics over the fundamental voltage. According to a number of testing laboratories and manufacturers, the IEC value of 1.5% is difficult to attain [40]. The IEEE standard specifies an allowance of 5% in total harmonic distortion. THD affects the efficiency of the motor, although the relationship between THD and efficiency is challenging to quantify. However, higher efficiency values can be achieved when THD is lower.

3.8.2.2 Instrumentation Comparison

Table 8 compares the requirements for instrumentation accuracy as stated in the respective standards.

Table 9: Instrumentation requirements in the IEC 60034 and IEEE 112

Parameter	*IEC 60034-2-1*	*IEEE 112*
Temperature (℃)	±1	±1
Instrument Transformer (%)	±0.2	±0.3
Resistance (%)	±0.2 Full Scale	±0.2 Full Scale
Current (%)	±0.2 Full Scale	±0.2 Full Scale ±0.5 Reading
Frequency (%)	±0.1 Full Scale	±0.1 Full Scale
Voltage (%)	±0.2 Full Scale	±0.2 Full Scale ±0.5 Reading
Speed (rpm)	±1	±1
Power (%)	±0.2 Full Scale	±0.2 full scale ±1 Reading
Torque (%)	±0.2 Full Scale	±0.2 Full Scale ±0.7 Reading

From Table 8 it is clear that instrumentation specifications are generally similar according to the different standards. The range of accuracy is between ±0.1% to ±0.2%, is common on the majority of instruments on the market. Additionally, the IEEE standard recommends measurement uncertainty, which is based on the reading of the instrument. If tests are carried out using digital instruments that have auto-range, this challenge can be solved.

3.8.2.3 Test Procedure

The two standards use the summation of losses, although they apply it differently. Table 9 highlights these differences in the tests. To begin with, the IEEE 112 standard recommends installing a temperature sensor on the machine whereas the IEC 60034-2-1 standard advocates reading the resistance before and after the test. The IEEE approach can be easily implemented as it takes minimal effort to dismantle the machine and insert a temperature sensor. The inability to state whether the machine has achieved temperature stabilization is the major disadvantage of being unable to read the temperature on the motor.

Table 10: Differences in the summation of losses applied by the IEEE 112 and IEC 60034-2

Procedure	*IEC 60034-2-1*	*IEEE 112*
Winding temperature by sensor	Optional	Yes
Load test	Yes	Yes
Measuring winding resistance	All three line-line resistances	Any one of the combinations

Temperature recording at the rated load	Yes	Yes
The winding temperature during the load test.	The resistance of stator before and after the load test.	Temperature detector values.
Winding temperature during the no-load test.	Resistance of stator before and after the load test.	Temperature detector values.
Stabilization losses in the bearings	No	Yes
Number of test points at no-load	Eight fixed points	A minimum of six variable values.

Moreover, the IEC 60034-2-1 advocates that winding resistance must be measured across all three line-to-line terminals. Unless the readings are automatically recorded, this approach can be impractical if readings are to be taken within the time interval recommended following the temperature test. This is because resistance values decay over time from the instant of shutdown, as shown in Figure 25, hence taking line-line resistance readings for all three phases sequentially compromises the quality of data. On the other hand, the IEEE 112 standard is more practical as it allows for a single resistance value to be recorded. According to the IEEE 112, the remaining two resistances across the other phases are not included in the calculations, unless if these two resistance values are recorded when the motor is at cold temperature.

Finally, the IEC 60034-2-1 does not recommend bearing temperature stabilization of the electric motor under test and dynamometer setup. Its no-load test immediately proceeds to the load test. The assumption is that the motor would have stabilized and it also cuts down on the test time, hence avoiding running the motor for a few hours to achieve stabilization.

3.8.2.4 Calculation of results

A comparison of the calculation of results between the two standards is given below.

Table 11: Computation of results procedure between the IEC 60034-2 and IEEE 112 standards

Computation	*IEC 60034-2-1*	*IEEE 112*
Machine rated load resistance	$t = t_{0} \leq$	$t \leq t_{table}$
Motor load resistance	R_{stator} (before, after or linear)	$T_{detector}$
Core losses calculations considering voltage drop in the stator	Yes	Yes
Correlation coefficient of the residual losses	0.95	0.90

Correction of friction and windage losses	Yes	No
Input power correction	Yes	No
Temperature coefficient correction	235	234.5

From Table 10 it is evident that the computing of winding resistance is different in the two standards. The IEEE 112 standard uses the resistance measured within an allowed time interval. The IEC60034-2-1 standard accepts the resistance computation from the value recorded when power to the machine is switched off. The CSA standard interpolates the time interval to get an exact value of the resistance. At the moment no investigation to give substantive evidence on the impact of the final efficiency values has been carried out, and standards committees are still debating on the best approach.

Furthermore, the IEEE 112 standard uses a temperature detector to compute resistance at different load points. This approach to computing results differs from the IEC 60034-2-1 standard, which uses winding resistance to determine losses during the no-load and load tests.

Both standards compute core losses from the actual voltage drop in the winding conductors during a load test. Losses calculated using voltage drop values yield higher motor efficiency values especially for motors of less than 5 kW.

The correlation coefficients are different. This coefficient indicates the quality of the test. The IEC 60034-2-1 standard recommends a correlation coefficient of 95% whereas the IEEE 112B states 90%. Both the IEC and IEEE recommend discarding the results if they are below the stated coefficient and redoing the tests. If the tests continue to produce results with a correlation coefficient below the recommended values, then the error can be in the test procedure, instrumentation or calculations. Finally, the coefficient of temperature is 235 °C and 234.5°C for the IEC and IEEE respectively. The difference is minute and having the same value in the two standards would be logical.

3.9 Conclusion

The chapter presented a comparison between the IEC 60034-2-1 and IEEE 112B induction motor efficiency test standards. It was observed that both standards have similar test procedures and steps with a few variances between them. The scope of this work covered a comparison of the direct methods and indirect methods, and followed the test procedure within the IEC and IEEE standards. The stray load loss characteristics obtained from the tests, shown in Figure 24, had a correlation coefficient of 0.9872, which is in the recommended range of greater than 0.90 and 0.95 for the IEEE and IEC standard respectively. Moreover, a section on the uncertainty of measurement elaborated the effect of accuracy of the instrumentation used on the final values of efficiency. It was shown that indirect methods are preferable as uncertainty decreases with higher efficiency. In contrast, direct methods increase in direct proportion to an increase in efficiency of the electrical machine. A comparison of the major and minor variances between the major standards was presented. Minor variances include nomenclature, slight differences and similarities in the content and scope of the test procedures. Both standards refer to separate standards for instrumentation and temperature conditions and measuring conditions respectively. The major variances and similarities are found on the power supply conditions, instrumentation, temperature references, test procedures and computation of results. The following chapter will present and analyze test results from the experiments.

4 CHAPTER 4 - RESULTS AND DISCUSSION

4.1 Introduction

Having completed a literature comparison of the IEC and IEEE standards in Chapter 3, and carried out test measurements, the results obtained had a correlation coefficient of 0.98, which is within the stipulated range. This confirmed the test-bench setup met the requirements of the standards for valid tests. The following section will seek to highlight the varying efficiency values from the IEC and IEEE standards and explain the possible causes of these discrepancies. The variations in the efficiency values of the tested motors result from the calculation philosophy applied by the different standards. As will be shown in the following section, the same test data obtained from one motor produces different values of efficiency.

Measurement results for 3 kW, 5.5 kW and 7.5 kW motors will be presented and the calculations for efficiency, conventional losses and stray load losses are compared. The data obtained from a 4 kW motor was discarded because its correction coefficient was below the recommended value. As stated above, the same test data will be used, but the calculations will be done according to the IEC and IEEE test methods. The presentation will show that, while using the same test results, the standards produce different results. The origins of these differences will be identified in the following section.

4.2 Resistance

As stated in the previous chapter, resistance readings for the tests were taken at ten second intervals for five minutes immediately after machine shutdown. All three motors tested in this research showed the same characteristic of resistance decay over time and finally stabilizing after approximately five minutes. Readings were plotted against time and the curve extrapolated back to determine the resistance at t = 0, which is the time at machine shutdown. The resistance value obtained at machine shutdown was then used for calculations. A considerable difference exists between the value of resistance at shutdown and five minutes after shutdown, which in turn influences the magnitude of the value of efficiency obtained in the final computations. Hence, it was critical to quickly obtain readings and extrapolate the curve to acquire resistance of the electric motor at shutdown.

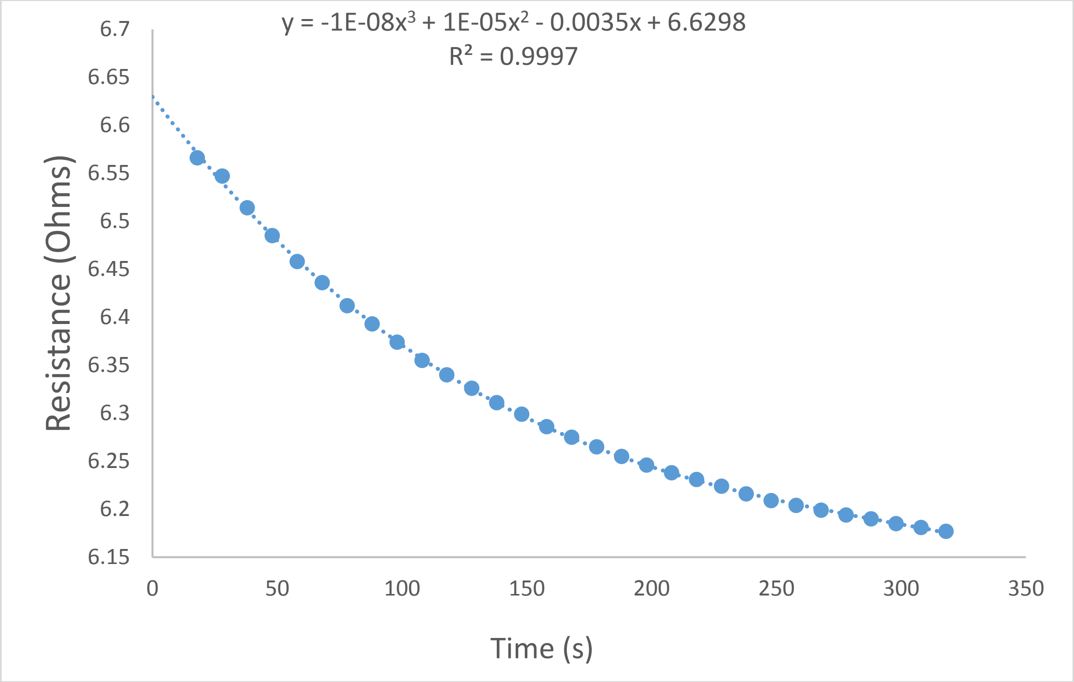
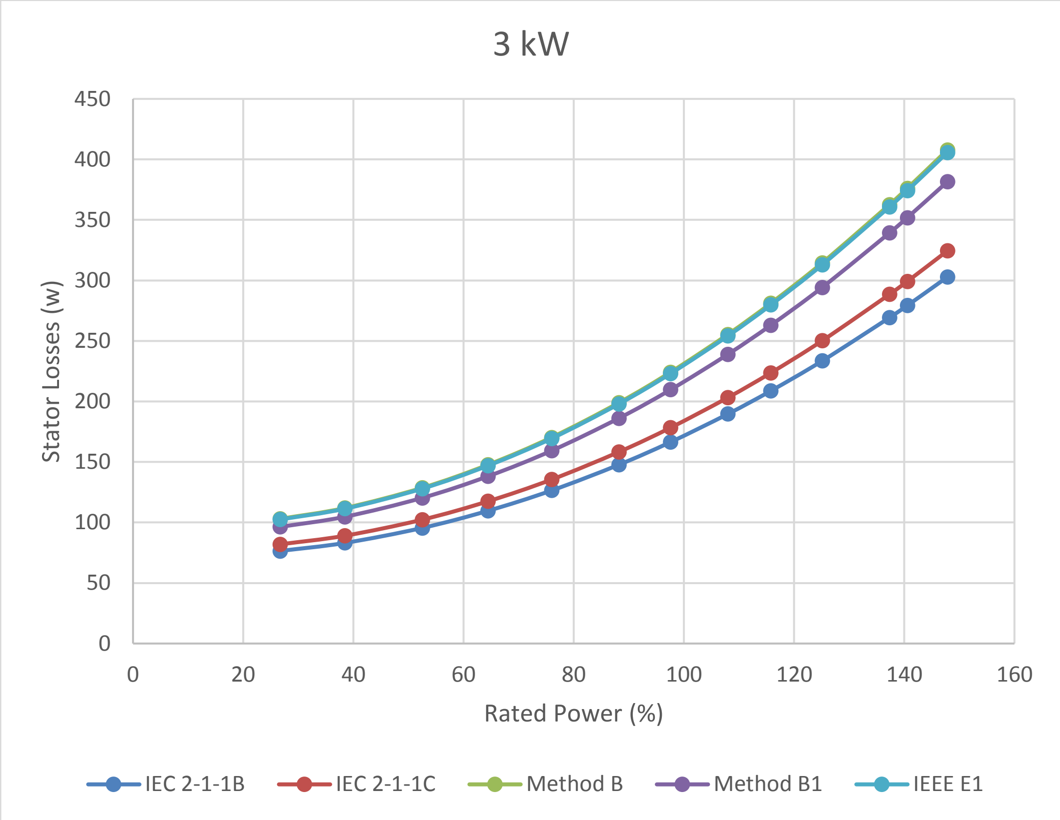


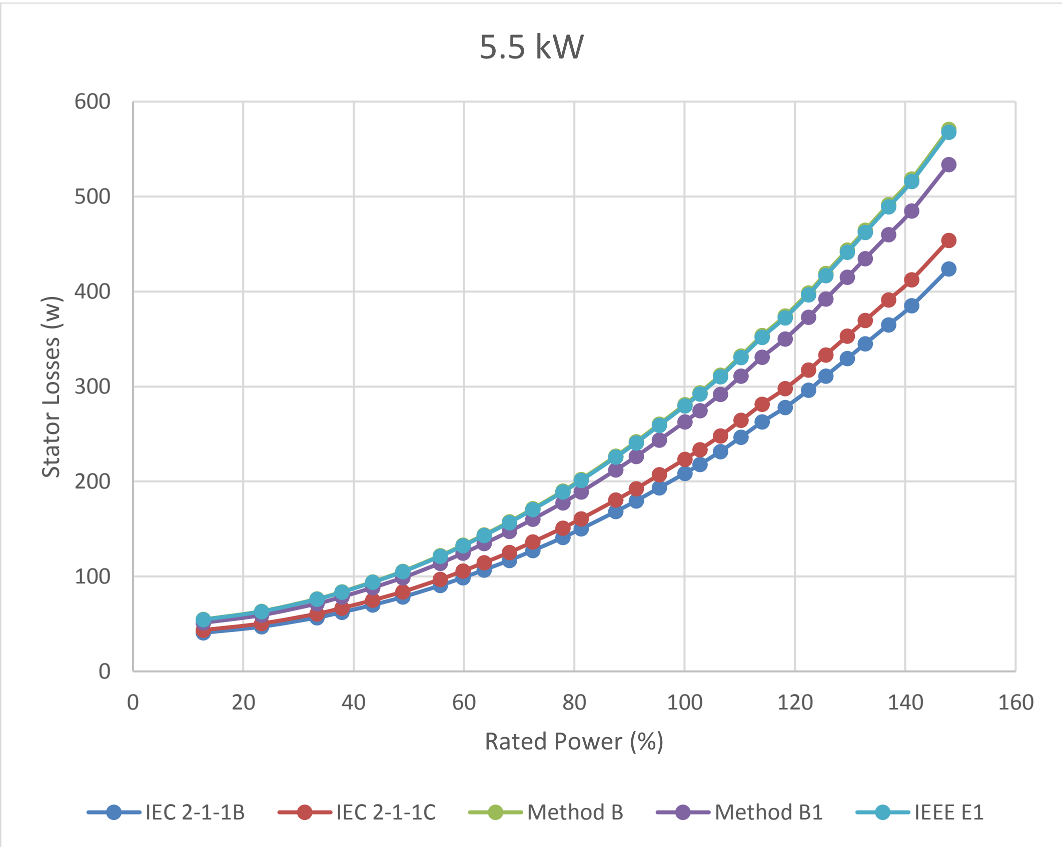
Figure 31: Winding resistance after machine shutdown

4.3 Stator Losses

Current readings to calculate stator losses were taken at regular load intervals between 20% and 140% of rated power. The induction machine ran continuously at each load point before recording the current to allow stabilisation and avoid recording transient values. The stator losses shown in figure 26 are calculated according to the IEC 60034-2-1B, IEC 60034-2-1C, IEEE 112-B, IEEE 112-B1 and IEEE 112-E1 test methods. Both the IEC 60034-2-1A and IEEE 112-A methods are direct methods, which do not segregate the losses, therefore they do not appear on the graphs. Segregation of losses begins by calculating the stator losses as presented above.


3 kW
Stator Losses (w)
450
400
350
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
Rated Power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

a)


5.5 kW
Stator Losses (w)
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
Rated Power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

b)

c)

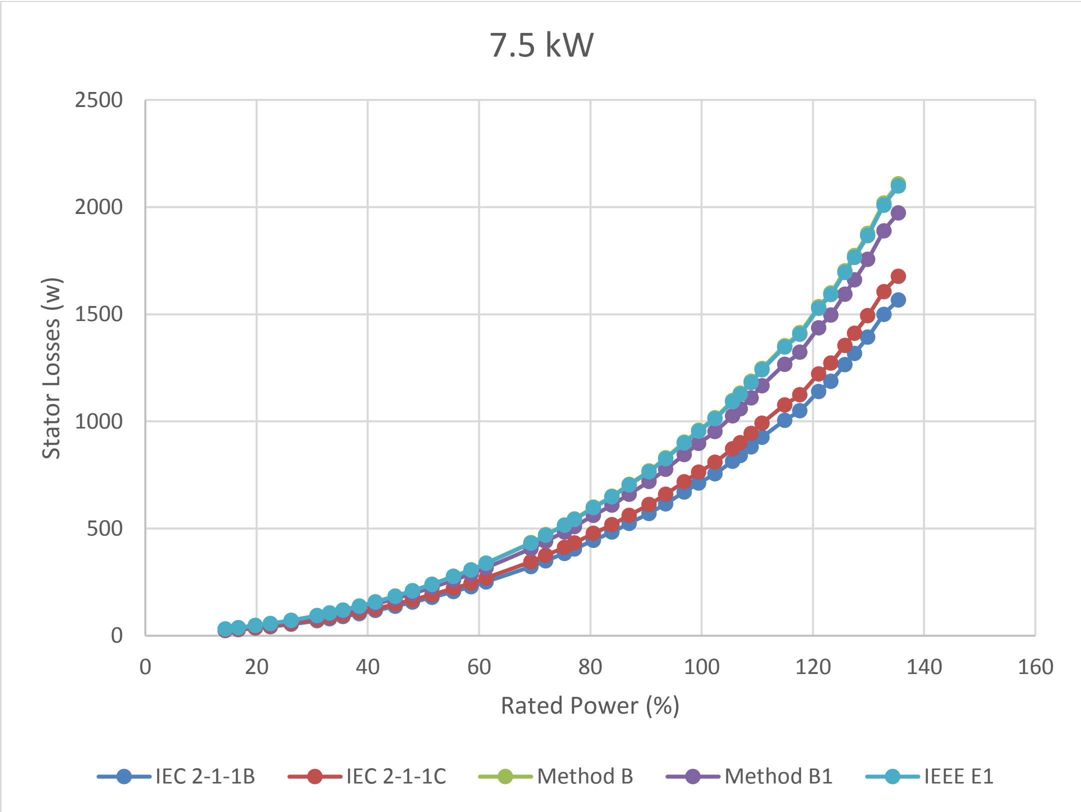
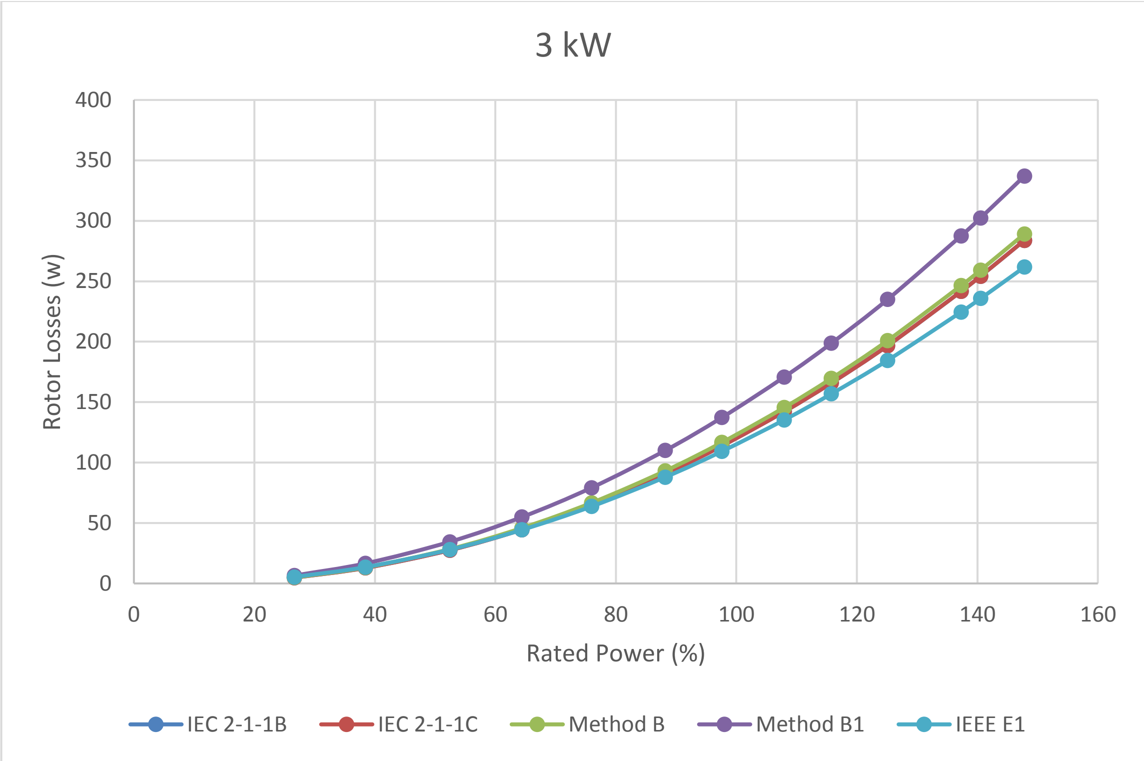


Figure 32: Stator losses at various load points for a) 3 kW, b) 5.5 kW, and c) 7.5 kW induction motor

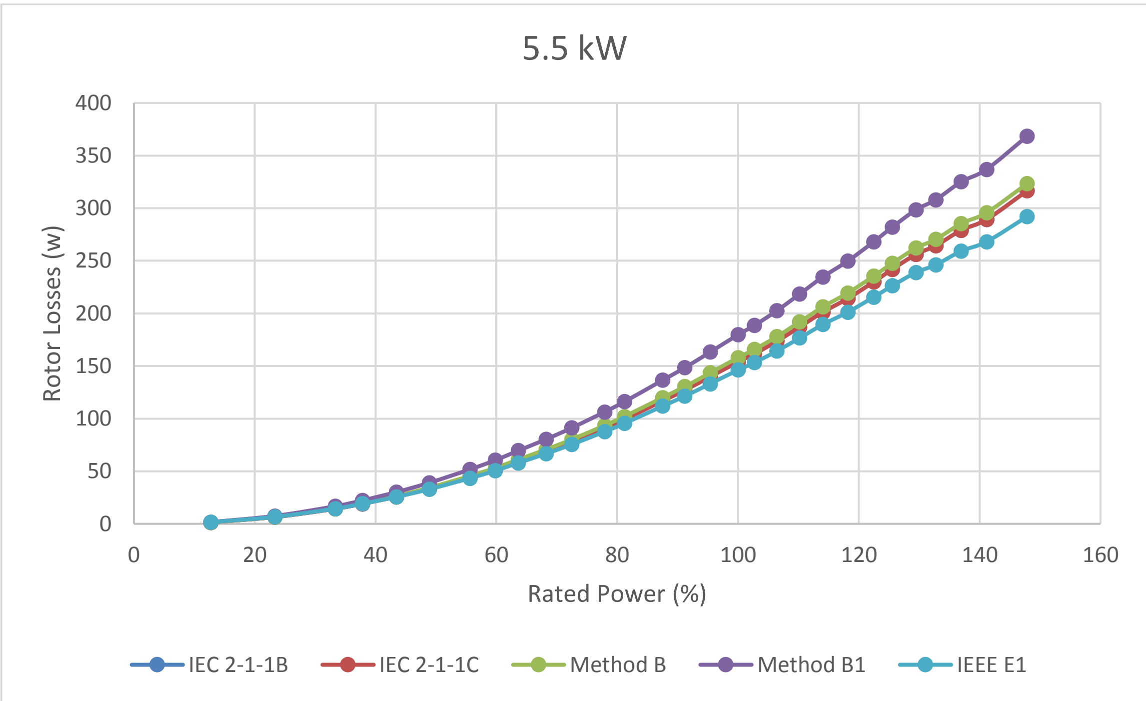
Stator loss characteristics from the five methods shown above indicate a general pattern of two groups, where the IEEE 112-E1, IEEE 112-B1 and IEEE-B test methods have higher values of stator losses when compared to the IEC 60034-2-1B and IEC 60034-2-1C test methods. Furthermore, the IEEE standards tend to overestimate stator losses in its calculations because it is not strict on winding temperature determination. This is because the values of the recommended temperatures, according to the Class of Insulation of the motor maybe higher than the actual hotspot temperature of the machine.

4.4 **Rotor Losses**

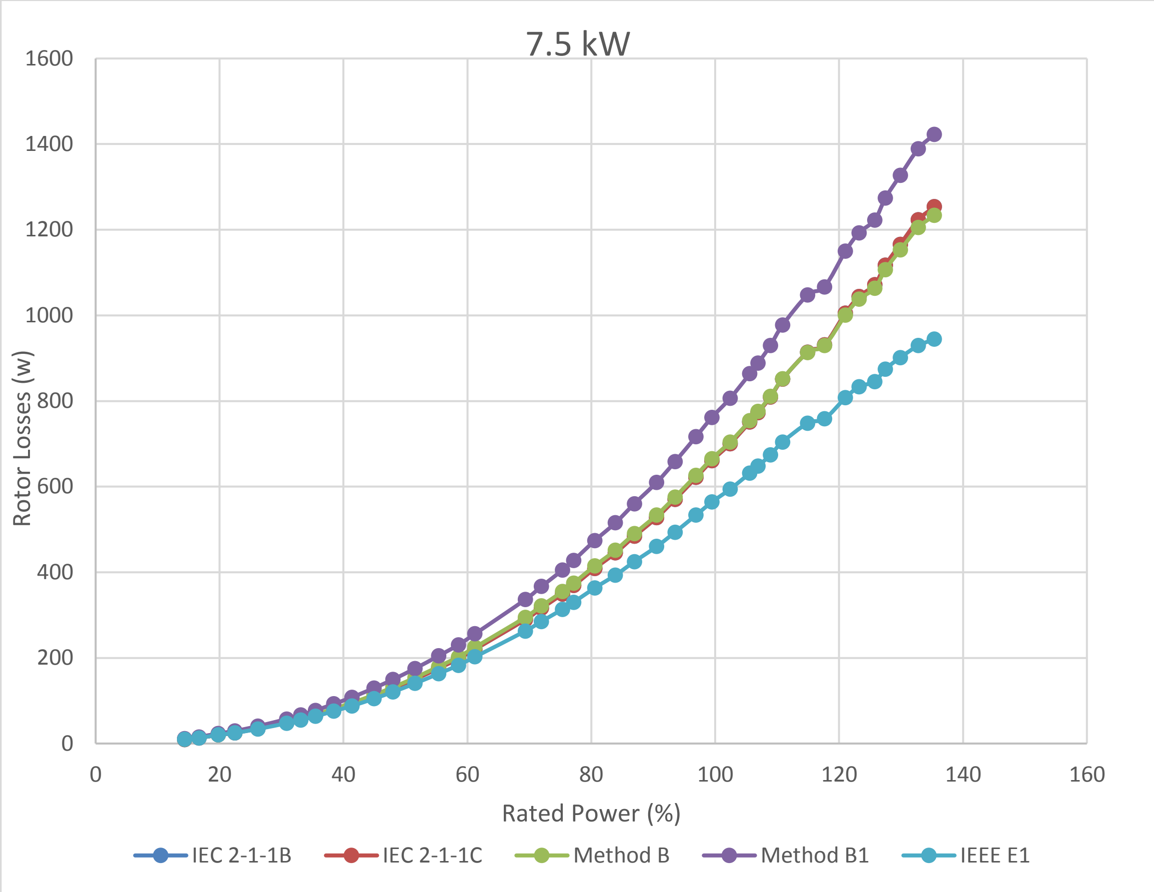
Rotor losses exhibit similar characteristics to stator losses. This is the result of stator losses being the main input in the rotor loss calculation formulae. Another important aspect, which gives rise to the different values of rotor losses, is the slip correction factor based on temperature correction of the slip of the machine. As stated earlier, the value of temperature used in the calculations, to a large extent, contributes to the discrepancies found in the final values of efficiency.


3 kW
400
350
300
250
200
150
100
50
0
Rotor Losses (w)
0
20
40
60
80
100
120
140
160
Rated Power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

a)


5.5 kW
400
350
300
250
200
150
100
50
0
Rotor Losses (w)
0
20
40
60
80
100
120
140
160
Rated Power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

b)

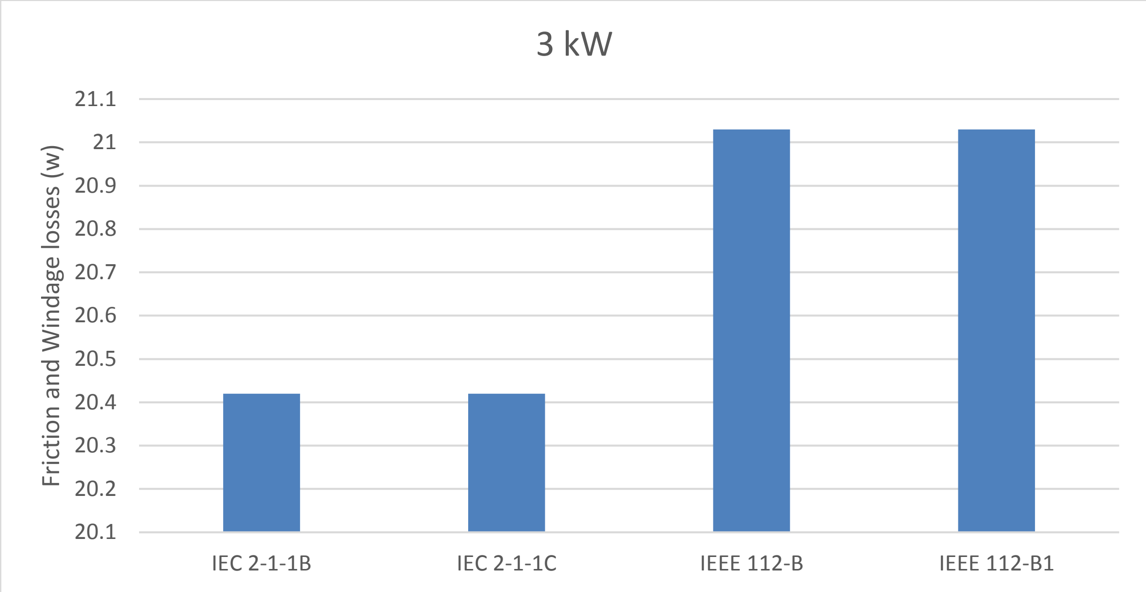


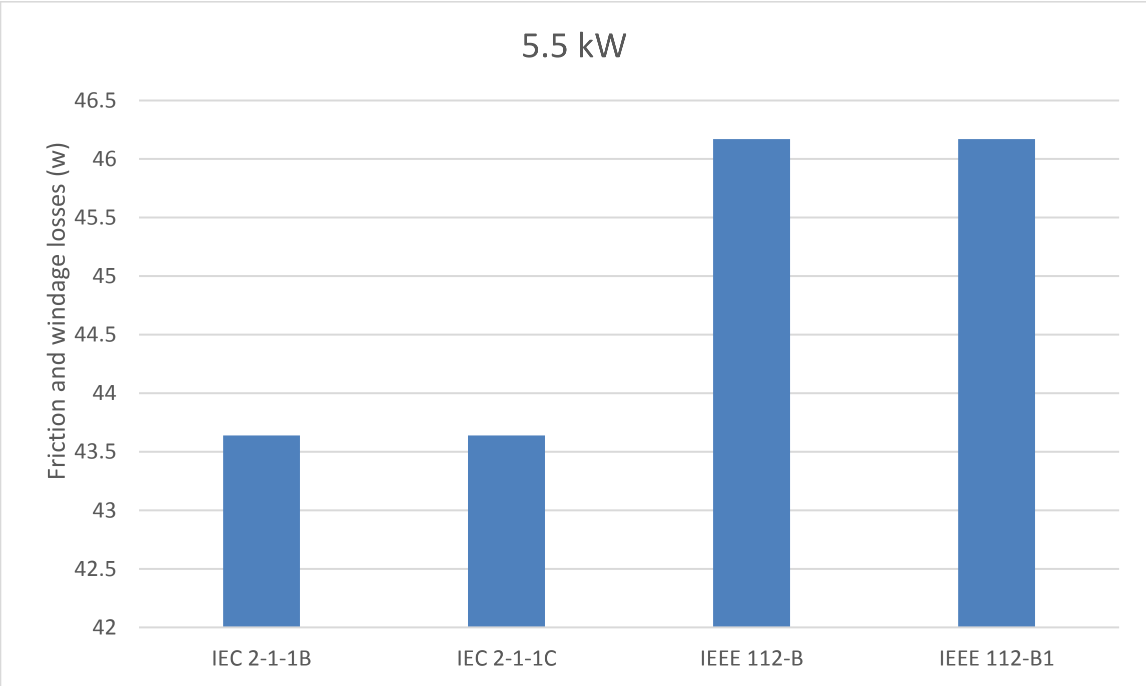
c)

Figure 33: Rotor losses under variable load points for a) 3 kW, b) 5.5 kW, and 7.5kW induction motor respectively.

4.5 Friction and Windage Losses

Both the IEC and IEEE standards use an almost similar approach to the calculation of friction and windage losses as illustrated in the following graphs. The friction and windage losses are considered to be constant by both methods. To obtain friction and windage losses, the IEC 60034-2 method separates the voltage percent characteristic from the iron losses curve whereas the IEEE obtains the friction and windage losses from the same curve with the voltage percent characteristic. As a result, the IEEE 112 friction and windage values generally tend to be higher than that of the IEC 60034 standards.


3 kW
Friction and Windage losses (w)
21.1
21
20.9
20.8
20.7
20.6
20.5
20.4
20.3
20.2
20.1
IEC 2-1-1B
IEC 2-1-1C
IEEE 112-B
IEEE 112-B1
a)


5.5 kW
Friction and windage losses (w)
46.5
46
45.5
45
44.5
44
43.5
43
42.5
42
IEC 2-1-1B
IEC 2-1-1C
IEEE 112-B
IEEE 112-B1
b)

c)

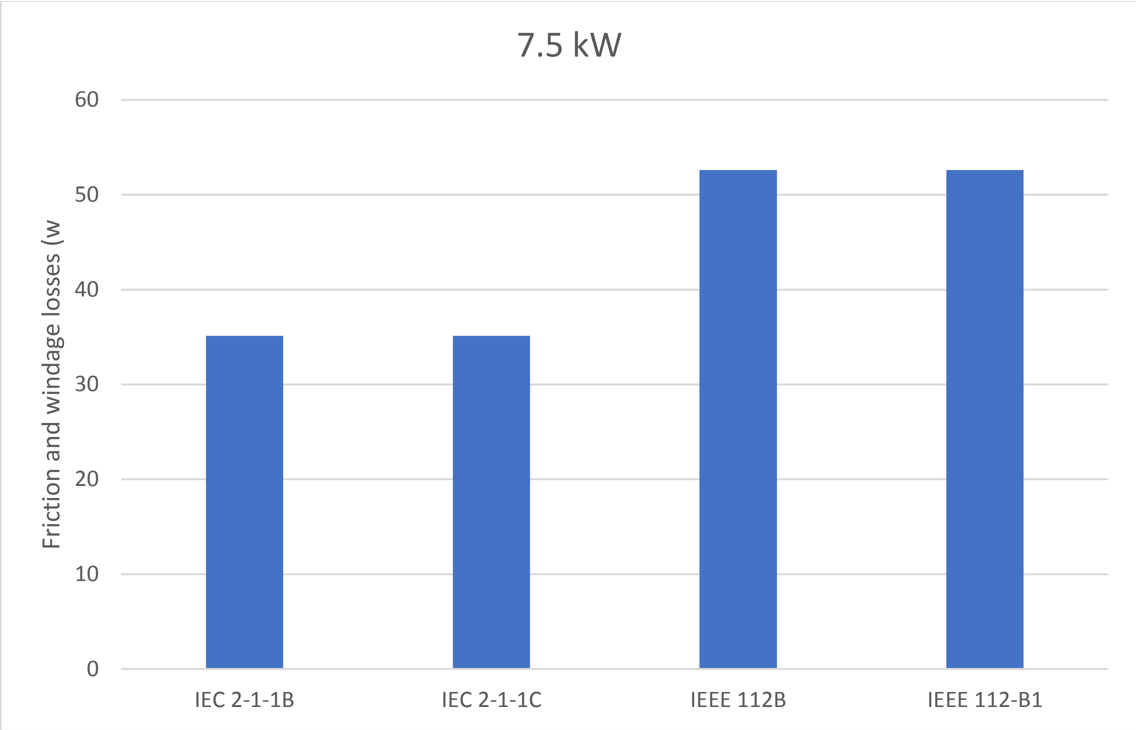


Figure 34: Friction and windage losses for a) 3 kW, b) 5.5 kW and 7.5 kW induction motor

Hence, there is a difference of between of 2% to 5% in the losses. From the different values obtained within the tests, the differences had more to do with the size of the motor rather than the calculation methods. It was also noted that smaller motors have relatively higher friction and windage losses as compared to larger motors. Thus, as the size of the motor increases, the percentage of friction and windage losses expressed against the total losses of the machine tends to decrease. This fact is validated by the comparison between the friction and windage losses of the 5.5 kW and 7.5 kW motors as a ratio of their total losses at 100% load respectively.

Table 12: Percentage differences between the friction and windage losses of a 5.5 kW and 7.5 kW motor.

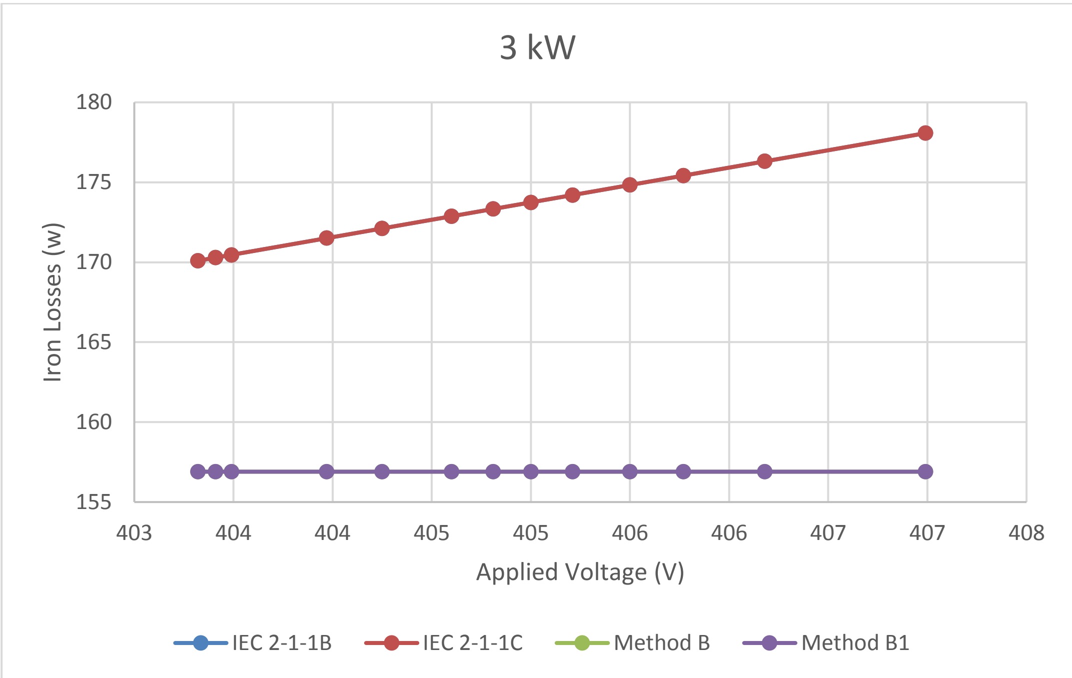
Motor Size @ 100% load	IEC method 2-1-1B	IEC method 2-1-1C	IEEE method B	IEEE method B1	IEEE method E1
5.5 kW	6.35%	6.35%	6.08%	5.84%	6.62%
7.5 kW	1.76%	1.76%	1.59%	1.78%	1.90%

Even though rotor resistance is the major reason why smaller machines have more losses leading to decreased efficiency, the figures in the above table offer an additional explanation as to why the efficiency of larger motors are higher than those of smaller machines.

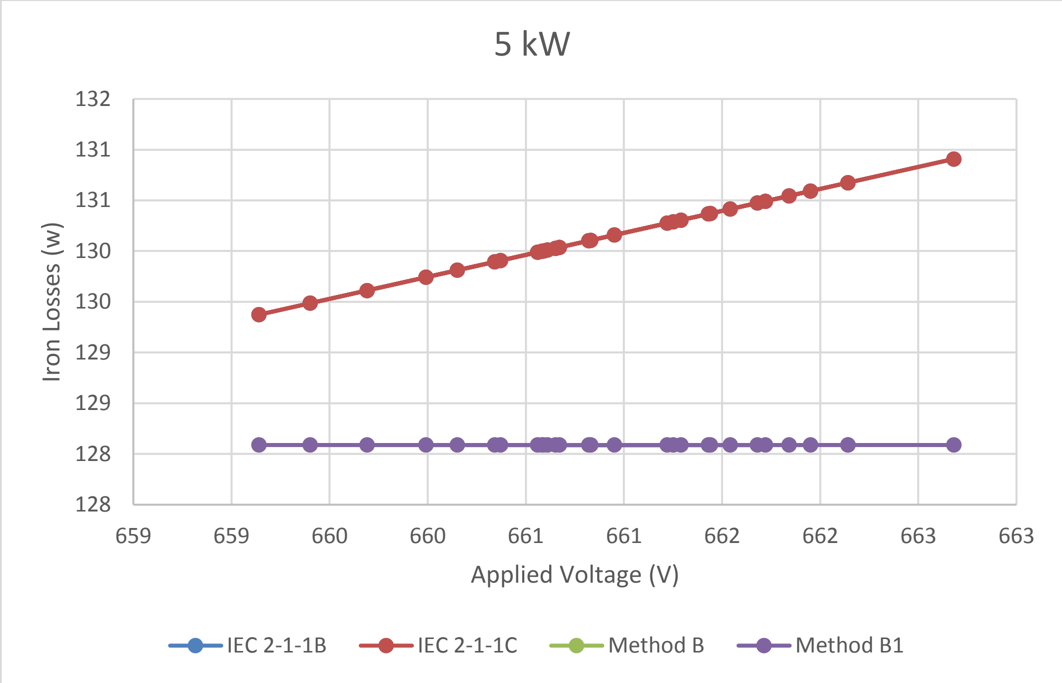
4.6 Excitation Losses at Rated Voltage

The IEEE 112 standard suggests that iron losses are load dependent, whereas the IEC 60034-2 standard uses the voltage, which takes the resistive voltage drop in the stator winding at the specific load into account when calculating the iron losses. Therefore, according to the IEC 60034-2 standard, iron losses are load dependent, with their maximum values produced when the load current is at its highest. The IEC 60034-2 standard, in its calculations, states that iron losses at full load are interpolated from the iron losses over the voltage curve at the required rated voltage. The following (three curves) show the iron losses, which are calculated at the rated voltage or load voltage of the motor.

a)



b)



c)

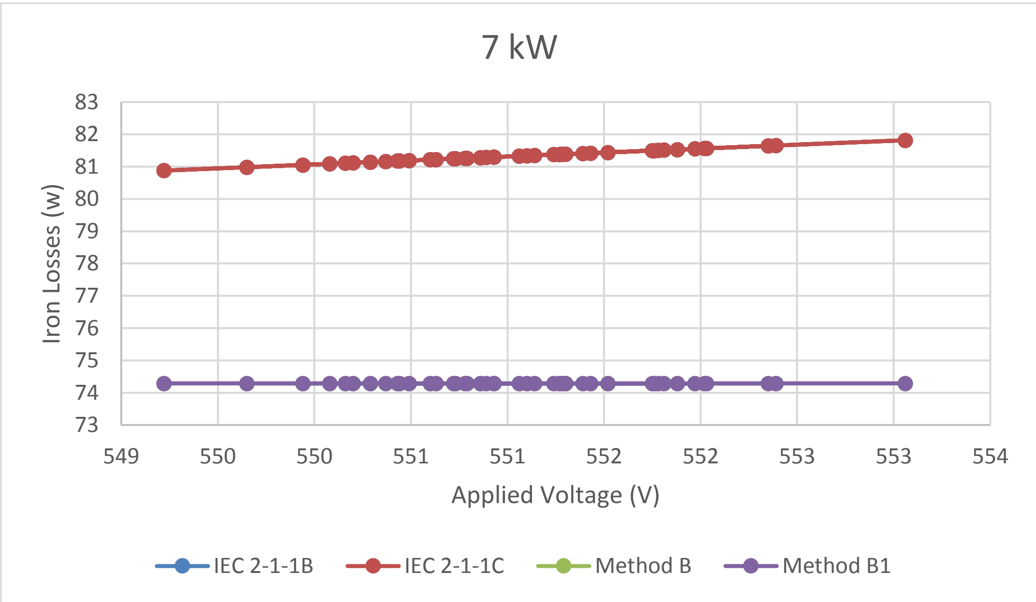
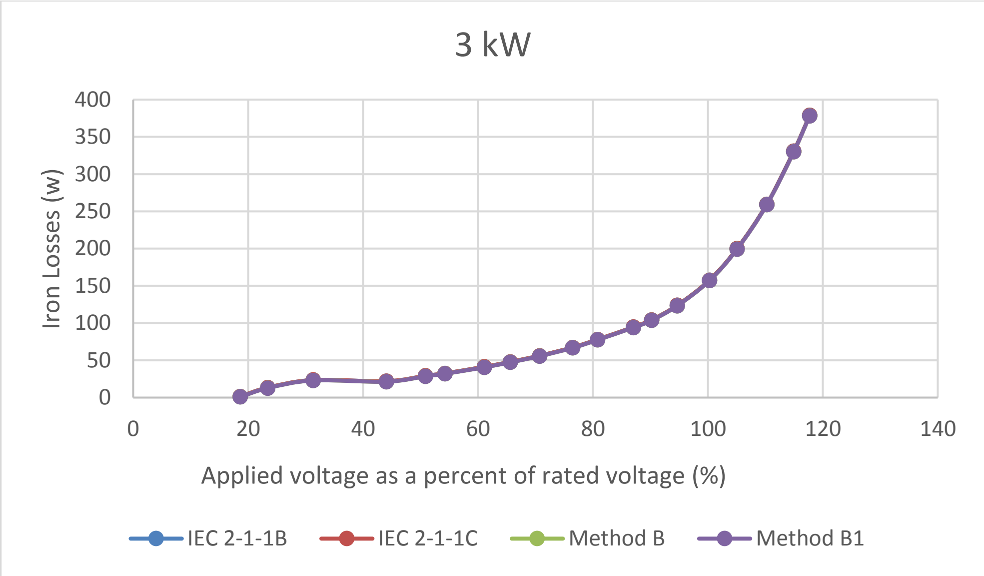


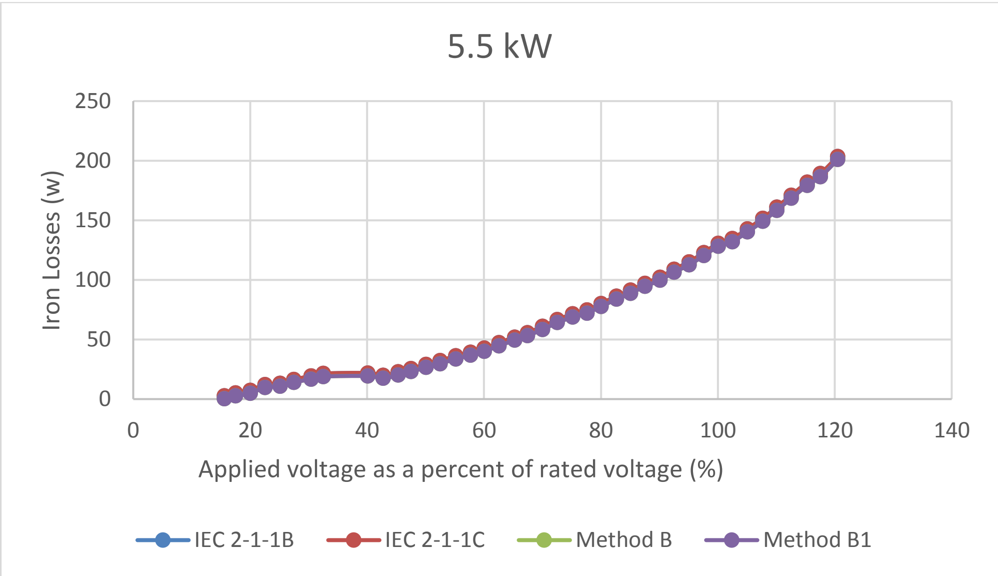
Figure 35: Iron losses at rated voltage for a) 3 kW, b) 5.5 kW, and c) 7.5kW induction motor respectively.

4.7 Iron losses at variable voltage points

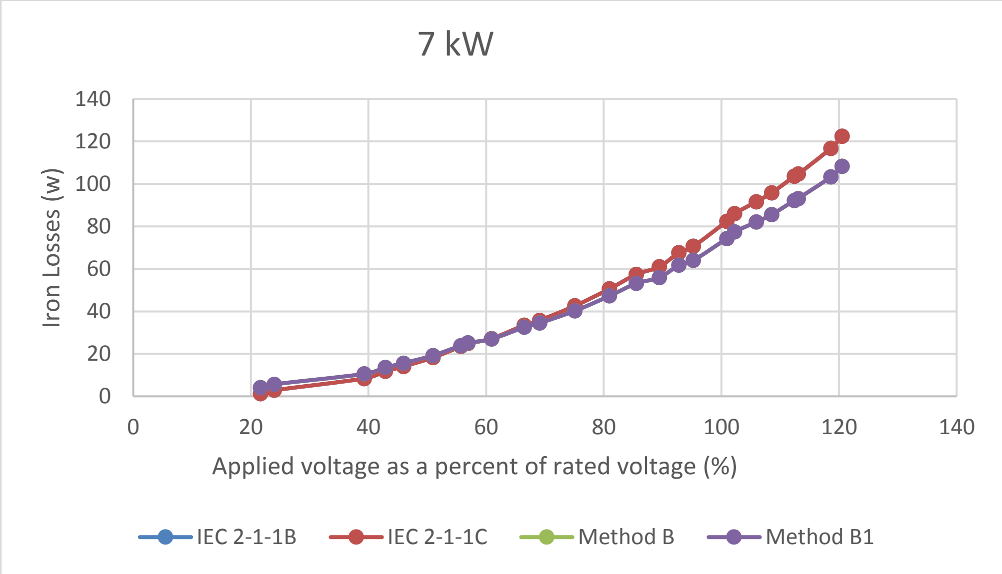
The characteristics shown below illustrate how iron losses, according to both standards, vary according to the applied voltage during the variable voltage test. In this test, the machine is operated at no-load with voltage applied to it from 125% of rated voltage to the minimum value where current will start to increase. The experiments carried out showed that iron losses exponentially increased in relation to applied voltage. Both standards list the same characteristics, hence showing a similarity, which is a positive step towards the harmonization of the standards.



a)



b)

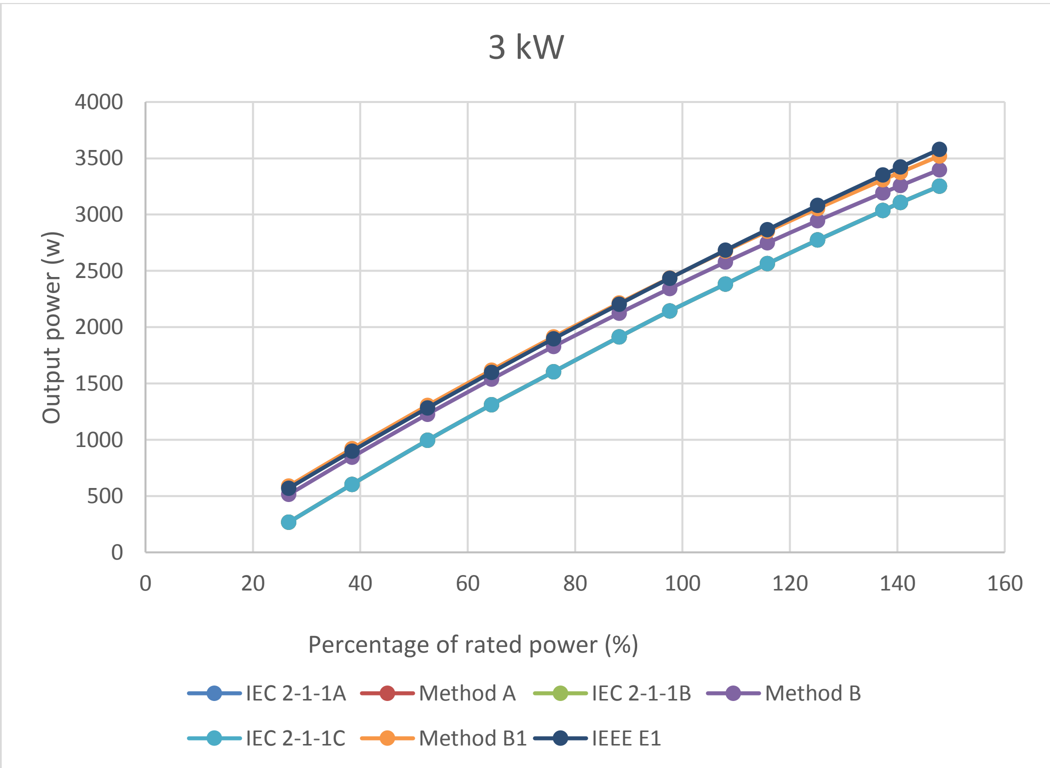


c)

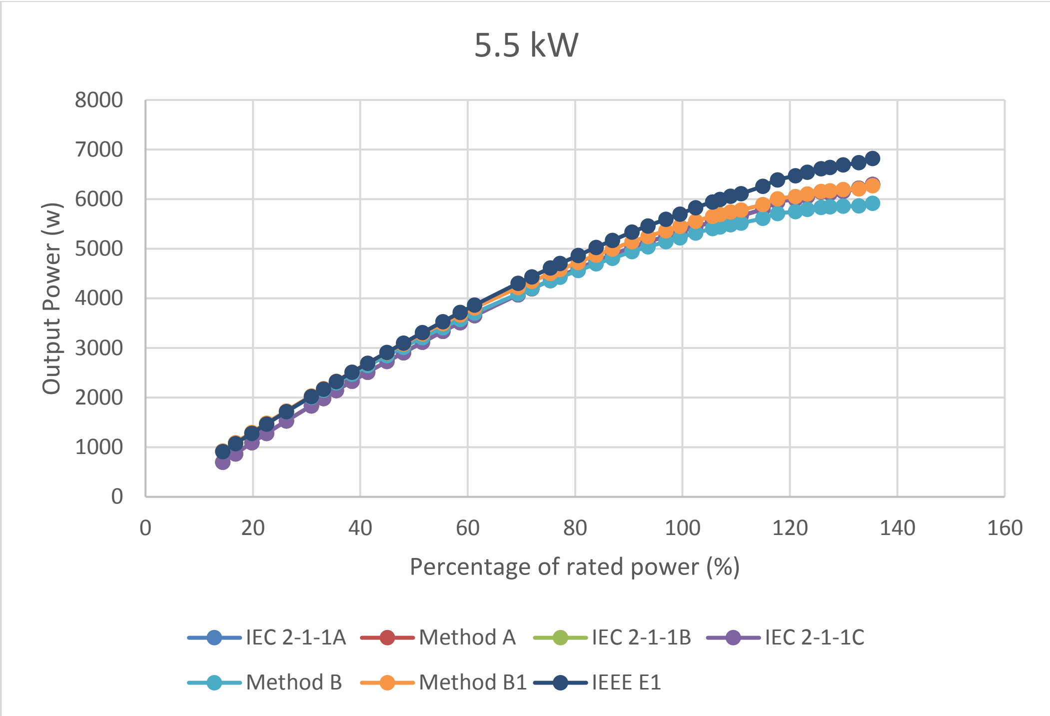
Figure 36: Iron losses at variable voltages for a) 3 kW, b) 5.5 kW, and c) 7.5 kW induction motor respectively

4.8 **Output Power**

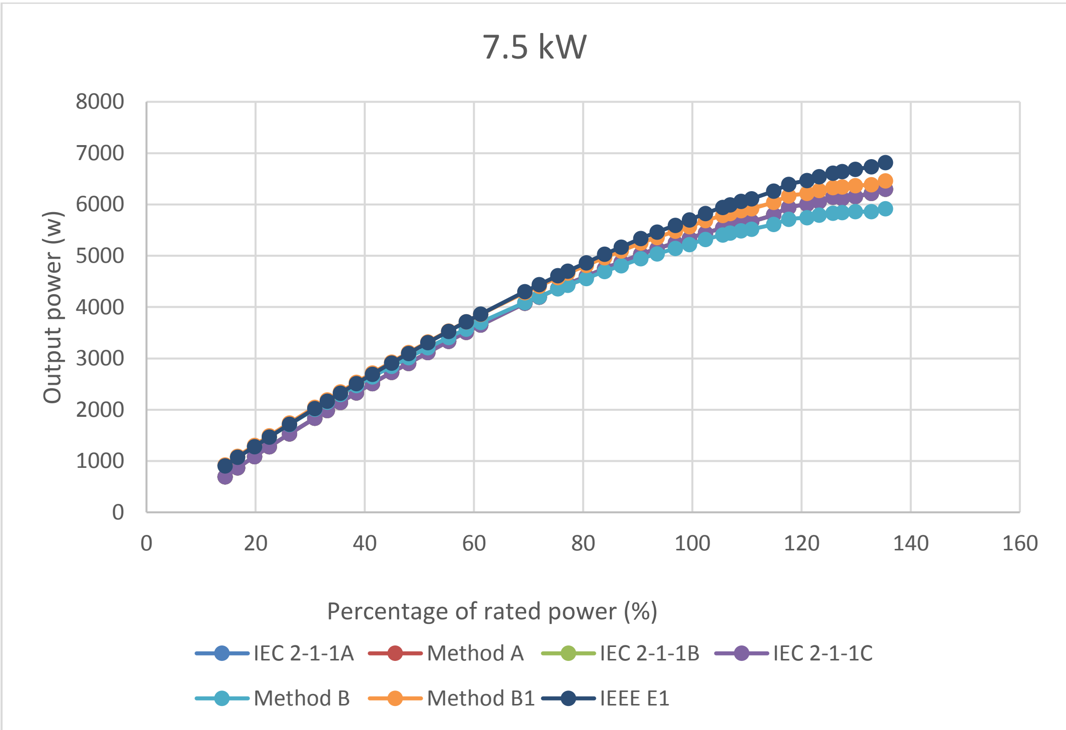
When the output power of the induction motor is measured using a torque meter and a calibrated dynamometer, the output power is the same for both standards. This similarity in the standards once more portrays a harmonization between the two standards. However, when output power is calculated using methods that are based on loss segregation, the values of the output power vary considerably. This results in discrepancies in the results.



a)



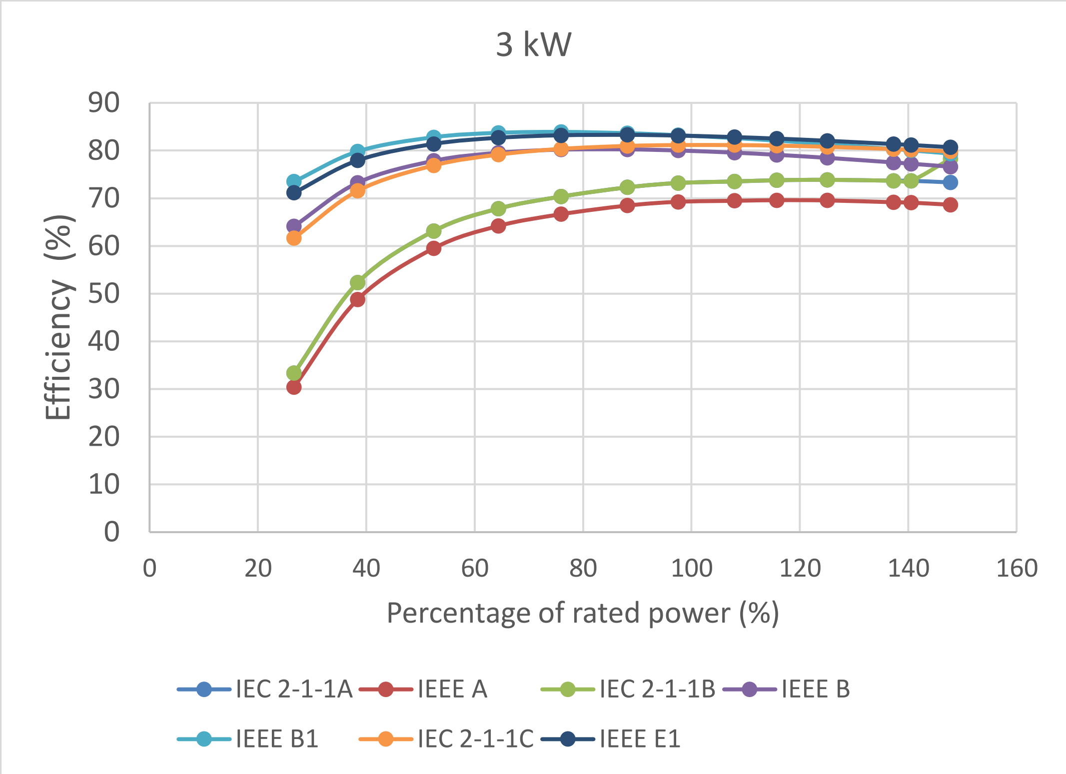
b)



c)

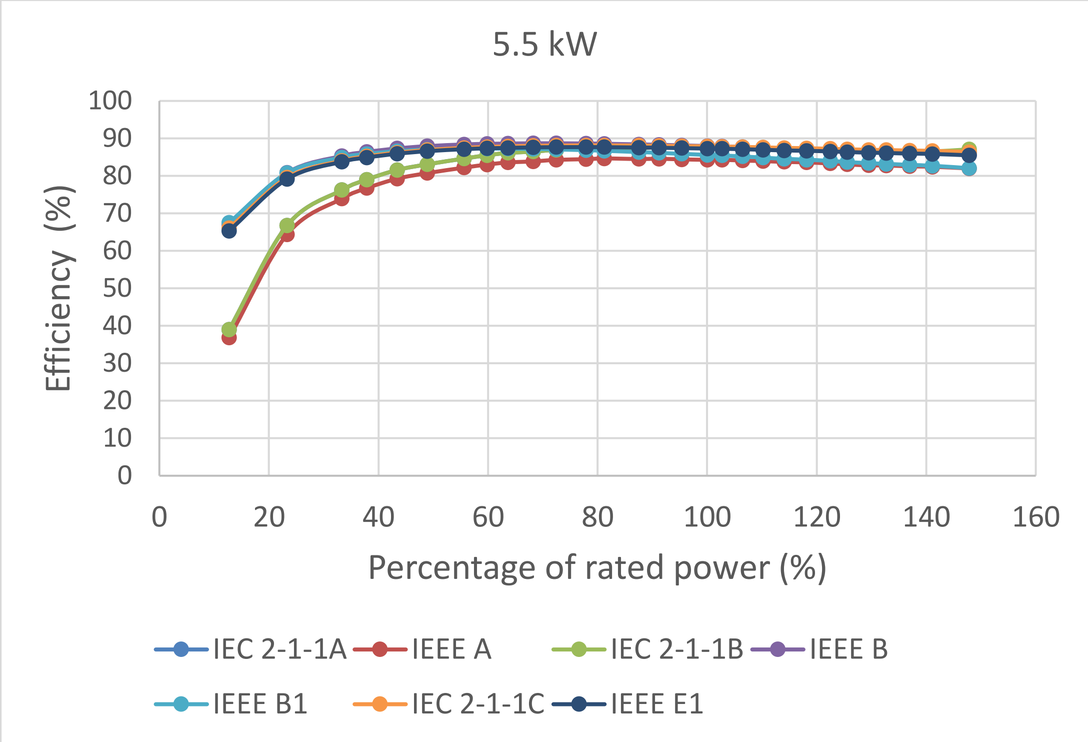
Figure 37: Output power at the various load points for a) 3 kW, b) 5.5 kW, and c) 7.5 kW induction motor respectively

4.9 **Efficiency**



a)

b)



c)

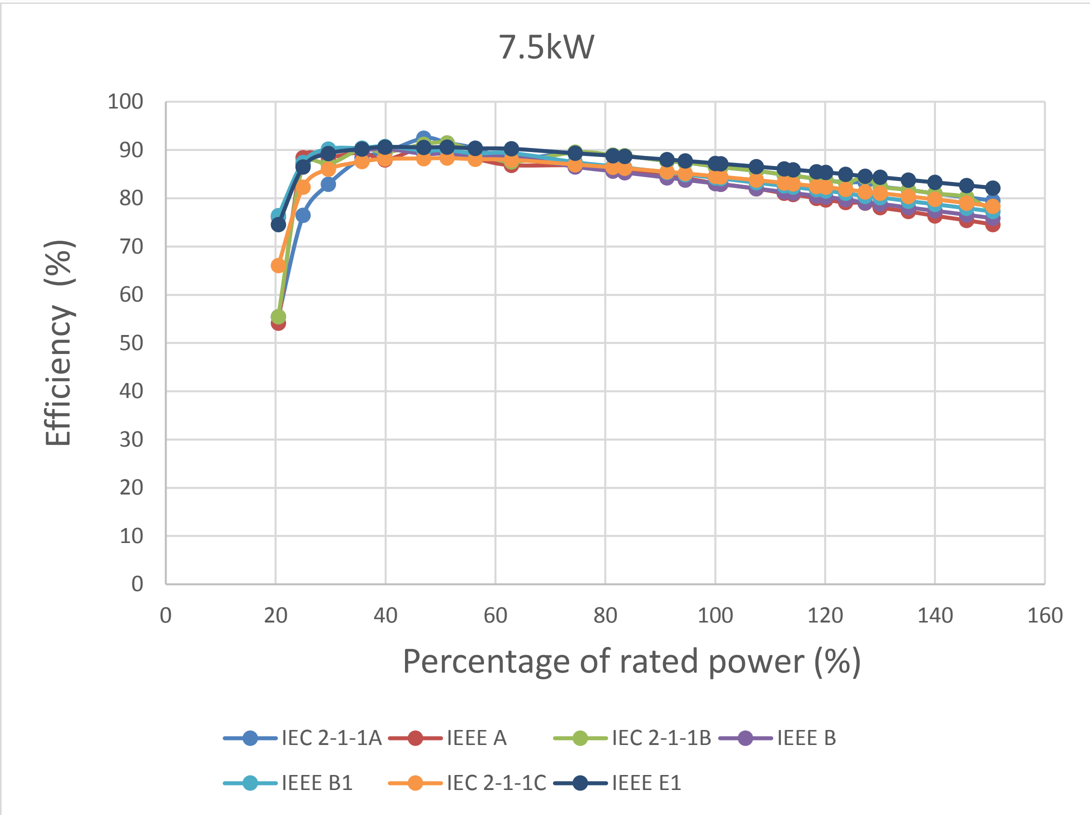


Figure 38: Efficiency calculations for the a) 3 kW, b) 5.5 kW, and c) 7.5 kW induction motors

The IEC 60034-2-1B and IEEE 112-A standards' efficiency values are at its lowest and bundled together. This is attributed to the methods' treatment of stray load losses. The two methods use the same approach to approximate temperature, and almost the same temperature approximations of windings, speed and slip correction are used. As a result, the efficiency values obtained are bundled together. The method used in the IEEE 112-A test method is a direct method with less temperature corrections, hence the losses are over-estimated, resulting in lower values of efficiency. IEEE 112-E1 test method has higher efficiency values due to the fact that it's estimation of stray load losses, which is 1.8% of rated input power, is very small. Efficiency values according to the test method from the IEEE 112-B1 standard used are also high because of the approach used to deduce winding temperature. Table 12 illustrates the values adopted in the winding temperature approximations.

A comparison between the 3 kW and 5.5 kW values shows that efficiency values for the former are more spaced and slightly lower when compared to the latter induction machine. This is owed to the fact that smaller machines have higher rotor resistances than larger machines, thus large values of efficiencies are expected from induction machines with higher ratings.

4.10 **Stray load Losses**

As previously mentioned, stray load losses are losses in an induction motor which cannot be accounted for using conventional methods. This section discusses the stray load losses when calculated according to the different methods in the standards. As observed in the following characteristics, the direct methods of determining efficiency from both standards are not shown. This is because direct methods do not consider stray load losses in their estimation of efficiency.

The data collected from the tests was used to calculate the value of stray load losses and the results obtained are graphically represented below. The test methods indicated the three sets of characteristic curves shown below, namely those presented by the IEC 60034-2-1B and IEEE112-B, IEC 60034-2-1C and IEEE112-E1, and IEEE 112-B1 test methods respectively. This is because these test methods share the same philosophy in calculating stray load losses. For example, the approach used to determine the temperature of the machine is the same for the IEC 60034-2-1B and the IEEE 112-B test methods. They also use the same approach of adopting certain temperatures for specific classes of motors when the motor windings are inaccessible for real time temperature recordings (Table 12). The IEC 60034-2 standard includes a temperature for motors in Class A, whereas the IEEE 112B omits a temperature value for induction motors with Class A insulation. The IEEE 112 standard recommends a temperature of 135 °C, in contrast to the 130 °C in the IEC 60034 standard. The same temperature correction of the winding temperature is used for the two test methods; thus, the final values of the stray load losses are approximately the same.

Table 13: Temperature correction according to IEC 60034-2 (a) and IEEE 112 (b) respectively

a)

Class of insulation system	Temperature in °C (Total temperature including 25°C reference ambient)
A	75
B	95
F	115
H	130

b)

Thermal class of the insulation system	Reference temperature °C
130 (B)	95
155 (F)	115
180 (H)	135

The second category comprises of the test methods used in the IEC 60034-2-1C and IEEE112-E1 standards. These have lower values for stray load losses. The approach used by these standards is an assigned or fixed allowance for stray load losses. The IEC 60034 standard recommends three formulae for different motor ratings, which are:

for $P_2 \leq 1$ kW $$P_{LL} = P_1 \cdot 0{,}025 \quad (4.1)$$

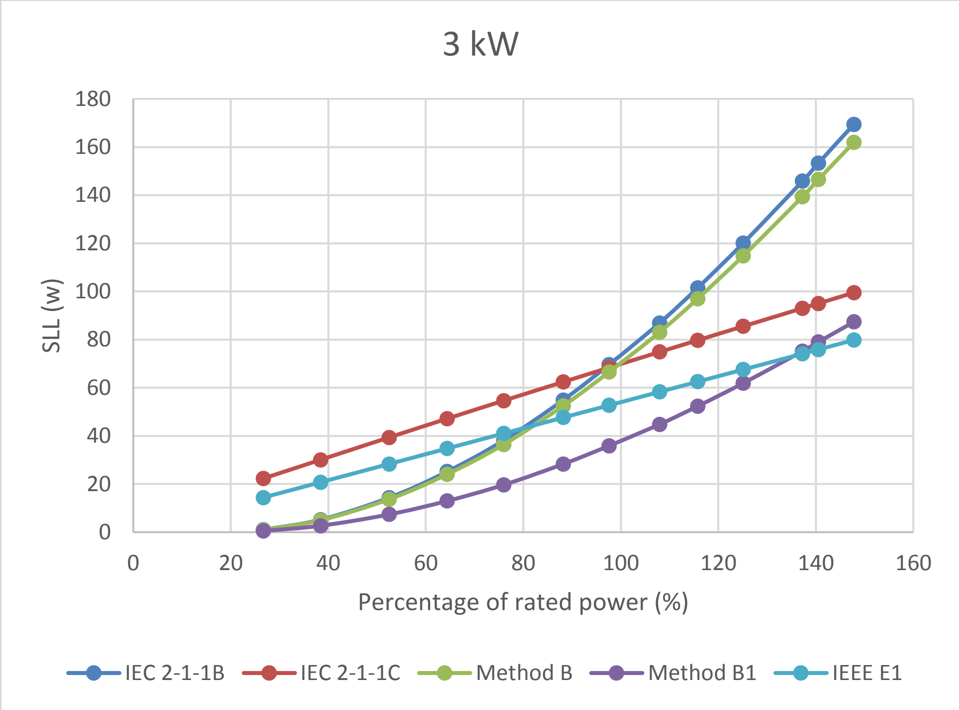
for 1 kW $\leq P_2 \leq$ 10 000 kW

$$PSLL = \left(0.025 - 0.005 * log10\left(\frac{Pout}{1kW}\right)\right) * Pin \quad (4.2)$$

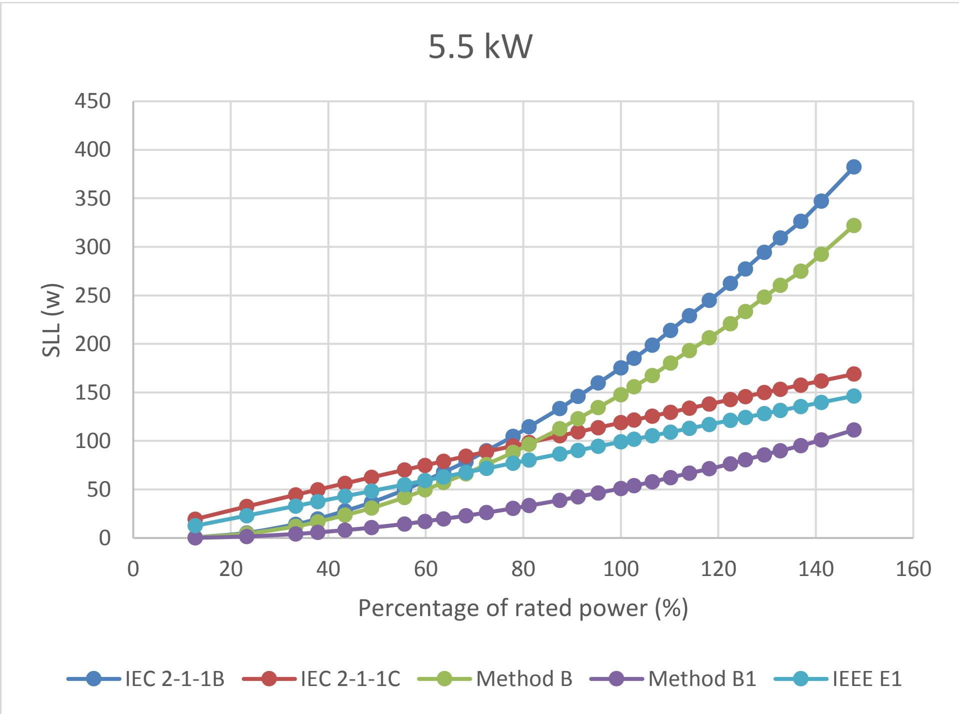
and for $P_2 \geq$ 10 000 kW $$P_{LL} = P_1 \cdot 0{,}005 \quad (4.3)$$

However, the IEEE 112-E1 test method recommends an assigned allowance of 1,8% for all motor ratings. The electric motors tested in this research are above 1 kW and less than 10 000 kW, hence this study used the second formula in the IEC 60034 standard. Even though the curves follow a similar shape and are closely spaced, the stray load losses for the IEEE 112-E1 test method are lower than those obtained from the IEC 60034-2-1C test method, because the method's assigned fixed allowance is an underestimation of the stray load losses.

Finally, the value of the stray load losses for IEEE 112-B1 is the lowest. This may be a result of the method's approach to temperature correction of the windings, which is not as strict as the IEC 60034-2-1B and IEEE112-B test methods.


3 kW
180
160
140
120
100
80
60
40
20
0
SLL (w)
0
20
40
60
80
100
120
140
160
Percentage of rated power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

a)


5.5 kW
450
400
350
300
250
200
150
100
50
0
SLL (w)
0
20
40
60
80
100
120
140
160
Percentage of rated power (%)
IEC 2-1-1B
IEC 2-1-1C
Method B
Method B1
IEEE E1

b)

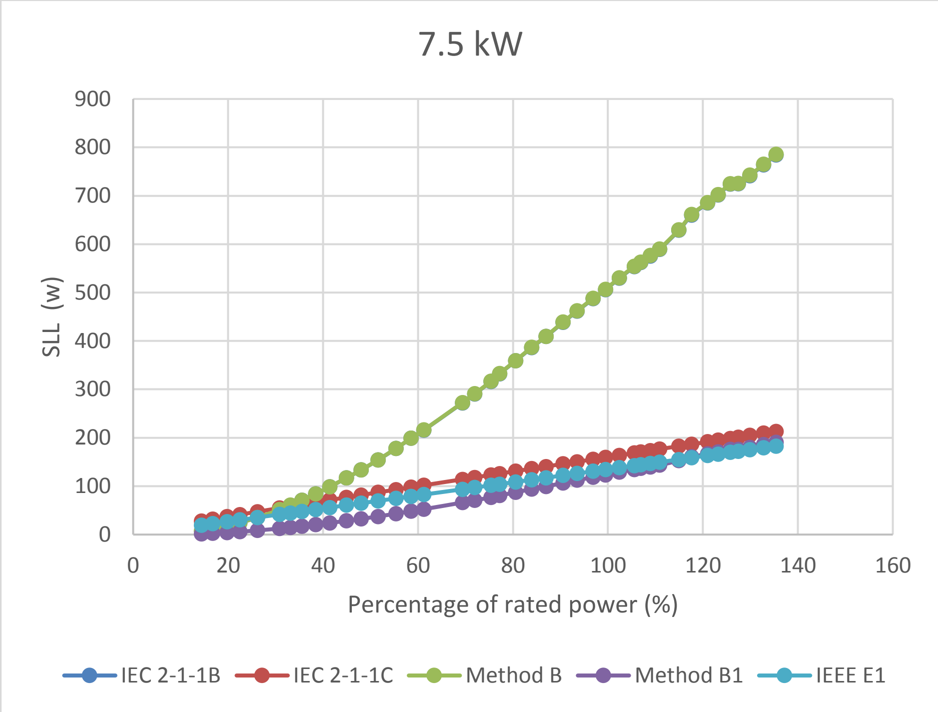
c) 

Figure 39: Stray load losses at various load points for a) 3 kW, b) 5.5 kW and c) 7.5 kW induction motors respectively

Figure 33 shows the different SLL values that are produced by the different standards when the machine is loaded up to 125% of rated load. IEC 60034-2B has the highest values of SLL because the segregation of losses eliminates errors.

The standards' comparison focused on the recommended test methods or preferred methods namely of summation of losses approach. However, there exist variations in the instrumentation specification, test conditions, differences in the testing procedures, and computation philosophies, thus resulting in different values of efficiency. For example, instrumentation specifications are generally similar, with an accuracy of ±0.1% to ±0.2 %. Instruments with this range of accuracy are readily available on the market. However, the IEEE 112B recommends measurements to be recorded from the full-scale reading of the instruments. This guarantees operation of the instrument within the proper portion of its range. Digital instruments on the market are an advantage as they automatically adjust their scales.

Furthermore, the test procedure contributes to the variances in the final value of calculated efficiency. IEEE 112B recommends the use of temperature sensor installed in the windings, whereas the IEC 60034-2-1 standard omits the installation of a temperature sensor. The disadvantage of not having a temperature detector is that it is difficult to know when the induction machine reaches its thermal stabilization.

Determination of motor winding resistance is another major source of discrepancies in final values of efficiency. IEEE 112B recommends that resistance be obtained from any of the phase-phase combinations whereas the IEC 60034-2-1 suggests the measurement of all phase-phase combinations. The IEC approach determines the individual resistance of each phase, but is impractical in the context of the time intervals in which readings should be taken since micro-ohm meters can only record the average of winding resistance of two phases in series for a star connected motor or the average for all three phases for a delta connected motor.

In the computation of results, the IEC standard makes use of winding resistance without the use of temperature sensor (Table 9), to determine the temperature of the induction machine and the conventional losses during the no-load and load tests. In IEC 60034-2-1, the resistance value measured before or at 100% loading shall be used for the 100% load point and higher load points. Load points less than 100% loading have resistances, which vary linearly with load, where the resistance value before commencing the test at highest load (that is, at 100% load) and 25% load are used to formulate the linear relationship.

Core losses according to the IEC 60034-2-1, incorporate the voltage drop in stator conductors, resulting in a curve depicting variable iron losses for the load test. This contrasts with the IEEE 112B standard, which considers core losses to be constant. Where measurements and calculations are carried out for small motors using core losses, which include voltage drop, the resulting motor efficiency is higher. Should the same approach be used for machines rated above 5 kW, the difference is small. Moreover, when iron losses are considered to be load independent, small induction machines with large stator resistance are likely to have negative stray load losses [41].

These were the main differences between the test methods compared in the two standards, the IEC 60034-2-1 and IEEE 112B. Recommendations to harmonize the standards will be presented in the following chapter.

4.11 Summary

In this chapter, test results for different test methods for 3 kW, 5.5 kW and 7.5 kW induction motors have been presented and analysed. The raw data from each electric motor was used to calculate the different loss components of the electric motors. Finally, the value of efficiency was then computed using the different philosophies recommended by the standards for the different test methods. The results showed that the test procedures are almost the same, with slight variations. These variations results in approximately 4% difference in the actual output at rated power. Moreover, the results of the tests generally show two approaches to calculating the different loss components, except for the treatment of stray load losses. A large variation in the stray load loss characteristics is a result of the different approaches used in the various methods to calculate the losses. These discrepancies in the calculated test results of the three motors indicate that there is a need to harmonize the standards, especially in the calculation procedures and the approach to quantifying the stray load losses.

5 CONCLUSION

5.1 Conclusion

The literature survey presented in Chapter 2 of this research indicates that electric motors consume approximately 65% of the domestic and industrial energy. As a result, energy efficiency is a priority to consumers, manufacturers and legislators. The chapter gave a general discussion of the asynchronous induction motor, a brief history, evolution, construction, and operating principle of the induction motor. Various loss components, including their origins, were discussed. Methods and ways to mitigate or reduce these losses were presented, with emphasis being placed on the stray load losses. Efficiency of electric motors can be improved if the measurement test methods produce results, which reflect the exact energy consumed by the machines. However, international and national standards are not harmonized as shown by the comparison done in chapter 3 and the results discussed in chapter 4.

Chapter 3 showed that there exist several methods within the standards to measure the efficiency of electric motors. Test methods can be categorised under direct and indirect methods. This research focused on the direct and indirect methods found in the IEEE 112 and IEC 60034-2 standards. However, the theoretical comparison focused on the complete standards, bringing out similarities and differences in aspects like instrumentation, test conditions, procedures, and assumed or allocated percentage values of stray load losses.

Chapter 4 presented a comparison of the standards based on the same raw data of the electric motors, with calculations adopted from the various standards. Values of efficiency were calculated using the direct and indirect methods from the two standards. The direct methods used were those from the IEEE 112-A and IEC 60034-2-1A standards. Indirect methods used for experiments were from the IEC 60034-2-1B, IEC 60034-2-1C, IEEE 112-B, IEEE 112-B1, and IEEE 112-E1 standards. Measurement results obtained from 3 kW, 5.5 kW and 7 kW induction motors confirmed the differences in efficiency values between the main methods within the two major international standards.

It was shown that winding temperature plays a critical role in the determination of the efficiency of the induction motors. Hence, most of the variations originated from the determination of the winding temperature. The main difference between the IEC 60034-2-1 and IEEE 112B standards is the determination of the winding temperature (Table 9). IEC standard suggests interpolating between recorded resistances, that is between 25% and 100% load points, and the IEEE advocates temperature detectors installed in the windings of the machine. Winding temperature is critical as it results in larger stray load loss values when it is underestimated or small stray load loss values when overestimated. This in turn under-estimates or over-estimates the final value of efficiency.

Core losses also contribute to final value of stray load losses. When the value of iron losses is considered to be load independent, as in the IEEE standard, it results in different values of stray load losses and efficiency values. The iron losses at rated voltage and no load are independent of load according to the same standard. On the contrary, the IEC standard states iron losses at a specific load point are calculated from the curve at the voltage U_r, which accounts for the resistive drop in the stator winding.

Furthermore, the assigned allowance or fixed allowance of the stray load losses contributed more to the discrepancies of the calculated efficiency of the electric motors.

5.2 **Recommendations**

One of the main objectives of this work was to highlight the major differences between the given standards, with the intentions of making recommendations, which can result in the harmonization of the standards. Chapter 3 presented the differences in the instrumentation, power supply, test procedure and test conditions and calculation of the results during the calculation of efficiency. Chapter 4 had an analysis of the results obtained from the various computation philosophies. In this section, the identified discrepancies will be highlighted, and recommendations made to harmonize the standards.

Instrumentation

Instrumentation specifications are similar in both standards. However, the uncertainty of measurement on the recorded values can be a positive addition to the IEC standard as it only used by the IEEE standard. The use of digital instruments can also be incorporated into the standards as these automatically adjust their scale based on the reading.

Test Procedure

The main differences in the test procedure is the availability of a temperature sensor. The IEC 60034-2-1 standard makes it optional to have a sensor whereas the IEEE 112B standard requires the presence of a sensor on or in the motor. For medium voltage and low voltage motors already on the market, it may not be easy to install temperature detectors, or it will pose extra expenses to incorporate the sensors. Hence, the approach used by IEC standard will be a better option in terms of harmonization. Temperature detectors can be more useful to high voltage machines.

IEC standard states that motor resistance value shall be obtained by reading all three line-line combinations of the terminals whereas the IEEE recommends any of the three. Due to the improved modern manufacturing methods, motor windings are likely to be more balanced, hence equal resistances on the windings. The recommendation would be to record all combinations if an automated data acquisition system is used, as it is the only solution, which can read so many readings in the stipulated time range. Alternatively, the median of the three values should taken and used in conjunction with temperature rise.

Bearing temperature stabilization before the no-load test can be neglected in the IEEE standard, only if the no-load test is done after the load test. It will save time during the test, as the machine would have run for hours during thermal equilibrium test rated load.

Finally, the IEC 60034-2-1 recommends tests at eight fixed load points whereas the IEEE 112 recommends a minimum of six variable load points. It is recommended to have eight fixed points, and allowing the machine to stabilize for ten seconds at each load point, thereby avoiding recording transient values.

Calculation of results

The correlation coefficient used when plotting the residual losses curve should be 0.95 or better for both standards. This value indicates the quality of the test carried out. With the right equipment and following the recommended procedure, the coefficient can be easily attained; hence the IEEE standard can adopt it and be on the same platform as the IEC standard.

IEC standard corrects friction and windage losses to the change in the synchronous speed of the motor during a load test, but IEEE standard neglects that correction. The difference for this correction may be marginal, but it is the small differences that have a cumulative effect on the final value of stray load losses and efficiency. Hence, the IEEE standard can also adopt the same correction of friction and windage losses.

In the IEEE calculations, input power is not subjected to temperature correction, which contrasts with the IEC standard. The IEEE does apply temperature correction to other losses, hence correcting input power according to the IEC standard will further align the standards.

5.3 **Further Studies**

The impact of power quality on the efficiency of electric motors was not within the scope of this work. The effect of harmonics in current and voltage, voltage unbalance, and power factor which are a reality in practical cases in industry and domestic applications was not incorporated in this study. The use of electronic solid-state equipment by other users on the same network distorts the alternating current waveform. Voltage instability, which includes unbalance and over-voltages may also have an impact on the final value of efficiency. The extent to which these phenomena affect stray load losses and efficiency are areas open for open further studies. If those parameters are taken into consideration, the results are likely to show further variations.

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APPENDIX A

INDUCTION MOTOR EFFICIENCY TEST METHODS: A COMPARISON OF STANDARDS

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Abstract

The efficiency data provided by manufacturers is measured or calculated according to different national and international standards. These standards use different means to incorporate the stray load losses and use different test methods; thus, the efficiency values obtained from different testing standards can vary. This leads to problems in competition and a potentially confusing situation for manufacturers and customers [1]. Hence, there is a need to compare the standards and highlight the possible variations leading to these differences, their causes and recommend where possible, solutions on how they can be eliminated.

1 INTRODUCTION

Energy efficiency has been a matter of global interest in the past two decades. Resources are being channelled towards developing and improving the efficient use of electrical energy. Energy prices have been rising and countries are struggling to meet the ever increasing demands of their consumers. Most electrical energy is consumed by electrical drives.

Determining induction motor efficiency is of prime importance to three groups of people namely, the manufacturers, customers and legislators [2]. Stray load losses (SLL) must be accurately determined during efficiency testing.

Customers are concerned with the total energy loss a machine makes or the efficiency of a machine, as this will determine the running cost of the machine. Therefore, the accuracy of declared machine efficiency is paramount and efficiency values, which obscure the real losses, are misleading [3]. Knowing the exact value of motor losses is not only important for saving energy, but also to keep the motor heating within specified limits to ensure maximum machine life [4]. Furthermore, legislators need to be enlightened so that they enact policies that promote efficient energy conversation, and if need be, even put up incentives, which encourage the manufacture and acquisition of more efficient electrical machines. A brief survey of motors, which enter the South African market, will highlight the importance of having accurate efficiency values.

2 SOUTH AFRICA'S LOCAL MARKET

South Africa's electric motor industry market is largely supplied by Brazilin, European and Chinese manufacturers. It is important to know which standards are being used to measure/calculate the efficiency of motors being supplied to the local market.

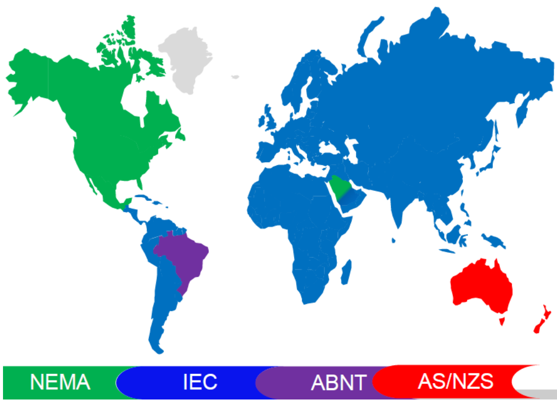

Figure 40: International standards used in different parts of the world [6]

Machines of the same rating, but from different manufacturers usually have different efficiency values. It results from the variations found in the methods used to determine the efficiency.

The work presented in this paper focuses on a comparison of standards. Losses in motors and differences in the test methods will be discussed, which give rise to different efficiency values between the standards.

3 LOSSES IN MOTORS

Induction machine losses can be subdivided into conventional losses (iron losses, ohmic losses, friction and windage losses) and SLL, in the stator and rotor, under load and no-load conditions. Figure 2 gives a summary of losses and their respective locations.

3.1 Conventional losses

The conventional losses are:

a) Ohmic losses in the conductors that are a function of the current and resistance, they increase rapidly with the load current and can be reduced e.g. by increasing the cross sectional area of the stator and rotor conductors,

b) Iron losses that occur mainly in the steel laminations of the stator and the rotor due to hysteresis and eddy currents, varying with flux density and frequency. They can be reduced e.g. by using thinner laminations, sharp punching tools or laser cutting and improved magnetic materials,

c) Mechanical losses are due to friction in the bearings and – in case of slip ring machines – brush friction losses, the ventilation and windage losses. They can be decreased by using low friction bearings, improved and optimized ventilation and fan design.

3.2 Stray load losses

The stray load losses result from stray flux, the step-like (non-sinusoidal) distribution of the air gap flux density due to the arrangement of the winding and the cage in the slots, inter-bar currents [5] and mechanical imperfections in the airgap. The eccentric field induced voltages in the parallel paths of the stator windings give rise to equalizing currents, which also contribute to SLL. They can be reduced by optimal design and careful manufacturing [6].

The main components of stray load losses in squirrel-cage induction motors are:

a) Fundamental-frequency stray load losses in the stator which consist of:

i) Skin effect (first and second order) in the stator winding,

ii) Stray load losses in the end region of the stator and rotor windings due to axial flux components, and

iii) Eddy current losses especially in high saturation areas in the stator housing and in metallic parts e.g. the bearing brackets.

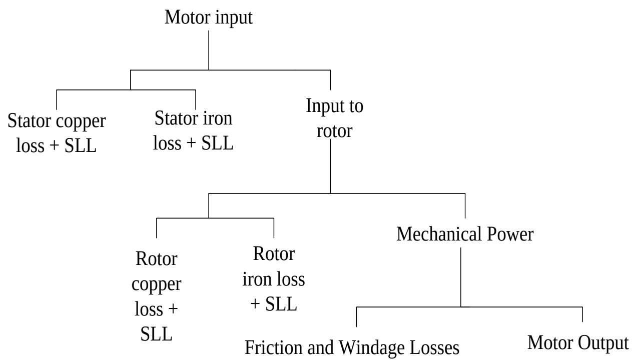

Figure 41: Induction motor losses

b) Higher frequency stray load losses in the rotor and stator include:

i) The skin effect in the rotor cage, harmonic rotor currents due to the third space harmonic caused by iron saturation,

ii) The losses due to inter-bar currents in cages with skewed rotor slots,

iii) The tooth pulsation losses in the rotor and the stator caused by the distortion of the air gap flux density distribution due to the slot openings,

iv) The surface losses in the rotor and the stator,

v) The losses in the stator winding due to harmonic currents and circulating currents in delta connected stator windings due to the third space harmonic caused by iron saturation, and

vi) The iron losses in the stator core due to the third space harmonic caused by the distortion of the field distribution due to iron saturation.

Induction motor efficiency test methods use different methods to determine efficiency, which are basically classified under direct or indirect methods and are affected by how the stray load losses are accounted for.

4 EFFICIENCY DETERMINATION METHODS

The methods of efficiency determination vary greatly in terms of their complexity, overall performance and the suitability for the plant conditions. Manufacturers provide efficiency values on the nameplates of their machines. This data is calculated or measured using different national or international standards.

These standards use different methods and assumptions to incorporate the stray load losses, thus the efficiency values obtained from different testing standards can differ by several percent. This leads to problems in competition and to a confusing situation for customers [1].

The IEEE/ANSI, IEC and AS/NZS standards are leading the process of critically evaluating the efficiency and the stray load losses in induction motors. These standards currently provide several methods and procedures for efficiency measurements in accordance with the type and the machine rating, with the desired accuracy, etc. In the direct (input-output) method the mechanical power is determined through an accurate measurement of speed and torque and used in [12], [13] and [7]. In the indirect method (segregation of losses) the loss components are determined individually and used in [12], [13] and [7]. The Calorimetric method is also used in the Australian standard [7]. This method is accurate, but very expensive and time consuming. The IEC 60034 standard [13] has an additional Eh-Y test to determine SLL. Previous versions of the IEC standard proposed a fixed allowance to represent SLL, for example 0.5% of input power. Both [12] and [13] require no-load, full-load, and part-load tests. The IEEE approach requires no-load tests over a range of voltages and a wider range of loads for the part-load conditions. The AN/NZS standard is closer to the IEC standard, thus the focus is of this comparison on the IEEE and IEC standards.

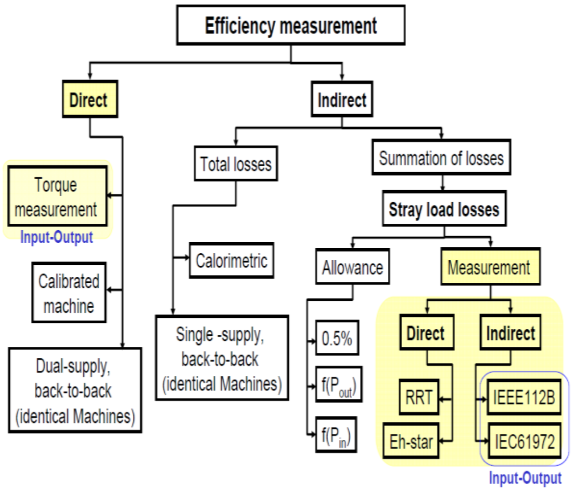

Figure 42 Test Methods [10]

Some methods of efficiency measurement and losses determination are presented in Figure 3. Differences in the standards are found in the test conditions and can be classified into four categories listed below:

4.1 Power Supply

The maximum deviation from rated voltage during testing of the machine is critical because efficiency varies with voltage [8] and differs between standards (see table 1).

Table 1: Power supply variations

Parameter	IEEE	IEC	AN/NZS
Max. THD (%)	5	1.5[1]	-
Max. Voltage Unbalance (%)	0.5	0.5[2]	-
Max. Deviation from Rated Voltage (%)	-	-	0.5
Max. Deviation from Rated Frequency (%)	0.1	0.1	0.3

4.2 Instrumentation

Instrumentation requirements are generally the same, although IEC speed accuracy may need to be averaged against the other standards to bring about same results (see table 2).

Table 2: Instrumentation

Parameter	IEEE	IEC	AS/NZS
Instrument transformer (%)	±0.3	±0.3	±0.3
Power (%)	±0.2	±0.2	±0.2
Voltage (%)	±0.2	±0.2	±0.2
Current (%)	±0.2	±0.2	±0.2
Torque (%)	±0.2	±0.2	±0.2
Speed (rpm)	±1	±0.1	±1
Frequency (%)	±0.1	±0.1	±0.1
Resistance (%)	±0.2	±0.2	±0.2
Temp (°C)	±1	±1	±1

4.3 Test Procedure

The IEC gives an option to use resistance or temperature detectors while the AS/NZS has no room for temperature measurements as shown in Table 3. Temperature variations influence the skin effect in the motor conductors, thus altering efficiency results. When bearing loss stabilization is not done, the test shall be performed in a specific order where the load test is followed by the no-load test.

4.4 Computation of Results

Table 4 highlights similarities and differences in the computation of results. Higher efficiency values are expected when voltage drop is considered, although there will not be a significant difference for large motors.

Moreover, human error is a source of getting different results when testing for efficiency. Repeatability of tests and execution of the tests contribute to human error. Different people running the same test using same standard and test bench will yield different results [9].

Table 3: Test Procedure

Step	IEEE	IEC	AS/NZS
Motor Temperature by detector	Yes	Optional	No
Measurement of motor resistance value	Any of 3	All 3	All 3
Temperature test at rated load	Yes	Yes	Yes
Measurement of motor temperature during load test	$T_{detector}$	$R_{stator\ before}$ $R_{stator\ after}$	$R_{stator\ before}$ $R_{stator\ after}$
Load test	Yes	Yes	Yes
Bearing loss stabilization	Yes	No	Yes
No-load test points	Min 6 Variable values	8 Fixed Values	Min 6 Variable values
Measurement of motor temperature during no-load test	$T_{Detector}$	$R_{stator\ before}$ $R_{stator\ after}$	$R_{stator\ before}$ $R_{stator\ after}$

The main difference of the mentioned methods, beside measurement equipment and setup, is the determination of the stray load losses. Stray load losses are difficult to predict analytically and measure accurately, because they constitute only a small fraction of the total power losses in an induction machine.

The most used methods can be subdivided in:

a) Direct measurement of SLL:

i) Reverse rotation test in [10] method E and [11]

ii) Eh-star method in [13]

b) Indirect measurement of SLL:

i) Input-output method with loss segregation (residual loss method) in [12] and [11]

ii) Calorimetric method with segregation of losses is used in [7].

Measurement of SLL using input-output test in the residual loss method in IEC 60034-2 Ed. 4 and IEEE 112B, calorimetric and reverse rotation test (RRT) methods need calibrated measurement equipment of high accuracy and a coupled load. Furthermore, it is time and energy consuming. On the contrary, the Eh-star method is an economical alternative test.

Table 4: Computation of results

Step	IEEE	IEC	AS/NZS
Calculation of motor rated load resistance	$t \leq t_{table}$	$t = t_0$	$t \leq t_{table}$
Calculation of motor load points resistance	Based on $T_{detector}$	$R_{stator\ before}$ $R_{stator\ after}$ $R_{stator\ linear}$	$R_{stator\ before}$ $R_{stator\ after}$ $R_{stator\ average}$
Core losses computation considering voltage drop in the stator	Yes	Yes	Yes
Correlation coefficient of the residual losses	0.90	0.95	0.95
Correction of windage / friction losses	No	Yes	No
Correction of input power	No	Yes	No
Coefficient for temperature correction	234.5	235	235

5 A COMPARISON OF THE TEST METHODS

5.1 *Direct Methods for Total Loss*

This method is used in [12] and [11].

Advantages

i) Real physical behaviour due to the direct losses assessment from the input-output test.

ii) [11] considers the load dependent-iron losses.

Disadvantages

i) IEEE112 method B considers iron losses to be independent of the load, thus affecting small motors (with big stator resistance) more.

ii) [12] method B and [13] considers the friction and windage losses to be independent of the changing speeds during the load test, leading to

a small error in the SLL especially for motors with higher slip values.
iii) Coupling of the machine with the load and use of the dynamometer is necessary.
iv) Since the losses are the differences of nearly equal/output power quantities, the upper limit of efficiency to be evaluated with sufficient accuracy should be 95% to 96%.
v) Procedure takes considerable time.

5.2 *Indirect Methods for Total Losses*
a) Reverse Rotation Test
Advantages
i) Physically correct determination of the fundamental SLL in the stator at the removed rotor test except neglecting of small iron losses.
Disadvantages
i) The consideration of load-dependent friction and windage losses affects the efficiency determination, e.g. method E in [12] and [13], but not the SLL.
ii) Accuracy of instrumentation is important as load has to be coupled to a calibrated dynamometer.
iii) No real physical load situation of the machine.
iv) At the slip $s=2$ the magnetisation current is small, so low main flux and no main flux iron saturation. The zig-zag stray flux dominates.
v) Different harmonic slip in the 5^{th} and 7^{th} air gap field harmonic causes different SLLs.
vi) RRT generally yields high SLLs
vii) Two test procedures are generally needed.
b) Eh-star method
Advantages
i) No coupling of the machine with the load and no dynamometer needed.
ii) Simple and short test.
iii) No difference of nearly equal power quantities to be measured, so no efficiency limits.
i*v)* Main flux too small, though it is bigger than RRT due to the positive sequence system.
Disadvantages
i) No real physical load situation of the machine.
ii) Complicated theory.
iii) Auxiliary power resistor R_{eh} and maybe a switch for the symmetric start-up are necessary.
iv) Loss component due to three times stator frequency circulating current in delta-connected winding, caused by the saturation harmonic, is not included.
c) Equivalent No-Load Method
Advantages
i) No coupling of the machine with load and no dynamometer are necessary, thus less expensive and saves time.
ii) Method is not complicated.
iii) Fundamental current effects, e.g. current displacement, are considered.
Disadvantages
i) Rotor fundamental current is missing, so the SLL are bigger than at rated condition.
ii) Machine is highly saturated during test, so the main flux dependent SLL are bigger than at rated condition.
iii) Voltage must be higher than the rated voltage to reach the rated current at no-load.
iv) Resistive losses must be measured accurately.
v) High frequency losses mainly localized in the rotor, so the rotor fundamental current may be of minor influence [12].

The direct method for calculating efficiency (measurement of the input and output power) suffers from measurement uncertainty, therefore it is limited for motors of lower efficiency. The indirect method is less sensitive to measurement errors and seems to be, depending on the measurement accuracy of the total power losses P_d, useful also for higher efficiency machines. In the efforts to improve the efficiency of the induction machine the stray load losses should be taken into account accurately. Due to the unavoidable measurement errors, the indirect determination of the stray load losses by measuring the input and output power is generally not accurate enough for the small value of the stray load losses at high efficiencies. Therefore, the direct measurement methods of the stray load losses could be useful at high efficiencies, but difficult to execute. A simple and fast test, like the eh-star method, is required for the stray load losses measurement, e.g. during the process of the optimisation of the motor design.

6 CONCLUSION

Recently most standards were revised as illustrated by the minor differences tabulated in this document. However, small differences still exist, mainly in the way stray load losses are measured and these give rise to inconsistent efficiency results. Furthermore, different people running the same tests under the same conditions will yield different results, a consequence of human error [9]. There is need to work towards a full harmonization of the standards so as to create a level global platform.

Moreover, it will result in improved energy conservation.

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8 BIOGRAPHIES

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APPENDIX B

Induction Motor Efficiency Test Methods: A Comparison of Standards

S Deda and JA de Kock

Abstract—Improved efficiency is the task of the hour. Environmental challenges, which include climate change, global warming and greenhouse gas emission have been fuelling the need to increase energy efficiency in electrical rotating machinery. Furthermore, there is a need to establish a level platform for motor manufacturers globally where they can produce electric machines according harmonized standards. Not only does this establish trust with the market, but it allows legislators to enact policies which promote energy conservation and facilitate governments to provide incentives to organizations which make energy efficiency their priority. A comparison of induction motor efficiency test methods according to the IEC 60034-2-1 and IEEE 112 standards is presented in this paper. A standard DOL squirrel cage induction motor rated at 5.5 kW is tested according to the IEC and IEEE preferred standards. Data collected from tests carried out on the 5.5 kW 4-pole motor is used to calculate the efficiency for the various IEC and IEEE tests. The data obtained shows a similar variation in values of efficiency, stray load losses and excitation losses for the same machine, but calculated using different standards. These differences result from how stray losses are treated and calculated in the standards. As a result, there is a need to harmonize the international standards.

***Index Terms*—Energy efficiency, induction motors, induction motor test standards, induction motor test methods.**

The greater part of losses that influence the efficient conversion of electrical to mechanical energy occur in the windings and magnetic cores of the machine. During the design stage of an induction machine, losses are calculated using analytical methods. Once manufactured, tests are carried out to determine the losses. This validation process should produce results whose variance is small. Standards allow for different methods to be used to determine the losses. Loss segregation and input-output methods are the two major categories under which all the test methods fall. This section discusses the losses found in the induction motors, and state some of the analytical methods of calculating the losses.

Losses are commonly classified based on their location, that is, winding losses (stator and rotor), core losses (stator and rotor), and the friction and windage losses [1]. The difference between the summation of the above stated losses, input and output power gives rise to what are termed the stray losses. Stray load losses (SLL) are difficult to compute and account for. Previous literature and work done on the investigation of stray losses indicates that electromagnetic losses in the winding and core are responsible for stray losses. Electromagnetic losses consist of fundamental and harmonic losses (space harmonic losses, and time harmonic losses), all found in the stator and rotor of the machine. The scope of this research will not include time harmonics as they are found in static convertor fed systems.

Resistance/Ohmic Losses

Resistance losses are also termed copper losses although they affect aluminium and other losses [2]. As stated above, ohmic losses are located in the stator and rotor winding of the induction machine. These losses are a result of current flowing in conductors and are defined by the following relationship:

$$P = I^2R \qquad (1)$$

The magnitude of resistance losses is directly proportional to the square of current, hence they are load dependent. Actually, ohmic losses depend on the effective resistance of the winding under rated frequency and operating flux conditions. An alternating magnetic flux is generated by alternating current flowing through the conductors resulting in a phenomenon known as the skin effect. The skin effect also affects the effective resistance of conductors and will later be discussed in detail. Effective resistance results in higher loss values as compared to the measured DC resistance.

Electrical resistance of conductors also increases with temperature as there will be more collisions within the conductor [3]. The equation (2) describes the relationship between change in temperature and corresponding resistance output.

$$R = R_{ref}[1 + \alpha(T - T_{ref}) \qquad (2)$$

Hence, it is important to correct resistance values to operating temperatures when carrying out efficiency tests so as to get accurate results.

Resistance losses in the stator windings can be minimized by using more copper, increasing the size of slots and a longer core, i.e. fewer turns. This in turn will decrease stator winding resistance. A major setback of this approach is the resulting increase in cost and difficulty in construction. Coil overhang can be decreased, reducing winding resistance but it poses the same difficulty of construction and increases inrush current [4].

Rotor losses are reduced by using larger cage bars and lesser turns in the stator, as well as increasing the size of end ring. Furthermore, decreasing slip by means of increasing the flux density in the air gap results in lower resistance losses. Unfortunately, these measures may result in increased inrush current and reduced starting torque [4], [5].

Iron losses

Iron losses are dependent on supply voltage and frequency. Eddy currents flowing in the conductors and core magnetization resulting from fluctuating flux densities greatly influence these losses. In induction machines, the losses are limited principally to the stator iron.

The following equations highlight how iron losses are dependent on supply voltage and frequency. In both equations, when the constants are changed accordingly, frequency and flux density can be replaced by speed and voltage respectively.

iii) Eddy-current loss

$$P_e = K_e(B_{max} f \partial)^2 \qquad (3)$$

where ∂ = *lamination thickness*

B_{max} = *maximum flux density*

f = *supplied frequency*

K_e = *proportionality constant*

iv) Hysteresis Loss

$$P_h = K_h f B_{max}^2 \qquad (4)$$

where K_h = proportionality constant

Iron core losses are considered to be constant. However, the variation of load current considerably alters the space distribution of flux density in the machine, hence increasing core losses. This increment in losses is classified as part of stray load losses (SLL). The use of a lengthier core and better lamination alloys can reduce iron losses [5].

Windage and Friction Loss Components

Depending on the rating of the electric motor, improvements in the heat transfer system facilitates a reduction in the windage losses. Friction losses can also be reduced by the use of lower friction bearings and better lubrication on moving parts of the motor.

Stray Load Loss Components

Stray load losses (SLL) in an induction machine consist of the difference between the total input power and the calculated sum of the I^2R loss (stator and rotor), core losses, windage and friction losses, and the output power. Changes in the flux distribution and eddy currents in the machine conductors cause the load current to generate these losses. These changes can be a result of restrictions in the design and manufacturing process of the motor. Firstly, steel used in the manufacturing of laminations has limitations, which causes it to saturate when the motor operates at or above a certain threshold. Secondly, manufacturing imperfections can also lead to the generation of stray load losses. Defective insulation of rotor cage bars cause cross bar currents also leading to SLL [6].

Standards specify different methods for the determining efficiency. Beside differences in test bed setup and equipment, the major difference in the standards is the determination of stray load losses. This difference gives rise to different values of efficiency for the same motor tested using different standards. In this study, the IEC 60034-2 and IEEE 112 standards will be compared and the test methods looked at are:

i) IEC 60034-2-1A
ii) IEC 60034-2-1B
iii) IEC 60034-2-1C
iv) IEEE 112-A
v) IEEE 112-B
vi) IEEE 112-B1
vii) IEEE 112-E1

i) and iv) are known as input-output methods, ii) and v) are segregation of losses, also known as residual loss method, iii) and vii) is the assigned allowance, and vi) uses a fixed assigned temperature for the calculation of losses.

It was not within the scope of this study to exhaust all the test methods as it required installation of test equipment, which was beyond the limits of the allocated budget.

The main difference in the mentioned methods, beside measurement equipment and setup, is the determination of the SLL. SLL are difficult to predict analytically and measure accurately, because they constitute only a small fraction of the total power losses in an induction machine. Methods commonly used to measure SLL are classified under direct methods or indirect methods.

Direct methods include:

- IEEE 112E [7] and IEC 60034-2-1-1F [8] both known as Reverse rotation methods
- IEC Eh-star method [8].

Indirect measurement includes the input-output method in IEC 60034-2, IEEE 112-B and B1 and the Calorimetric method in the Australian Standard, AS 1359.102.2.

The input-output method requires calibrated equipment and load, demanding time, energy and high accuracy as opposed to the Eh-star method, which does not need coupling the machine to a load and dynamometer.

In this section, measurement results for a 5.5 kW motor is presented and calculations for efficiency, conventional losses and SLL are compared. The same raw data will be used, but used according to the IEC and IEEE standard procedures. It will be shown that using the same data, the different standards produce different results. The origins of these different results will be identified in the following section.

Performed measurements

Test carried out in this study include:

1) Rated load temperature rise test.
2) Load test at different load points
3) No-load test with variable voltage points
4) Resistance tests.

The equipment used to record data with high accuracy included a power analyser, N4L model PP5530 that logged the electrical data in real time during the tests, a resistance meter RM025T to log the cold and hot rundown resistance of the windings, and a Magtrol TMB 311/431 inline torque/speed meter. These instruments exceed the uncertainty of measurement requirements of IEC60034.

4.1.1 Rated Load Test

IEEE 112 and IEC 60034-2 recommend that rated load temperature test be carried out to establish the steady state temperature rise. Rated load is applied to the machine until the rate of change is 1 K or less per half hour.

4.1.2 Load Test

IEEE 112 recommends that six readings be taken at load points from 25% to 150%, whereas the IEC 60034-2 states load points from 25% to 125%. Hence the study could use the same data for calculations.

4.1.3 No-load test with variable voltage points.

The induction machine is run at no-load to achieve separation of no-load losses and readings taken at voltages ranging from 125% to a point where further reduction in voltage increases the current according to the IEEE 112. IEC 60034-2 recommends voltage readings between 110% and 30% of the rated voltage. IEC 60034-2 specifies that voltage values between 30% and 60% and 90% and 110% be used to calculate the P_{FW} and P_{Fe} respectively. In contrast, the IEEE 112 uses the same voltage to calculate the no-load losses without specifying two ranges.

4.1.4 Resistance

To determine accurate resistance values, both standards recommend that resistance readings be taken immediately after the machine is shut down and values recorded at 10 s intervals. The actual resistance value at shutdown is the extrapolated value (see Figure 1).

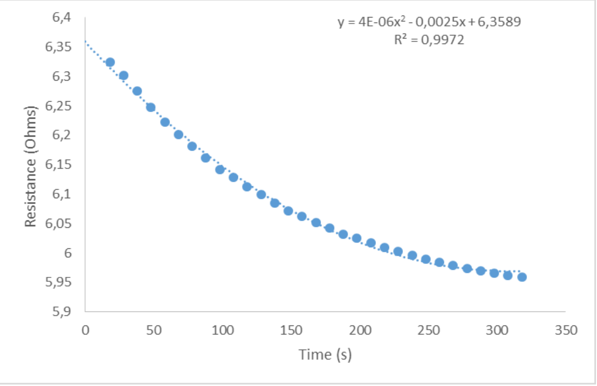

Figure 1. Winding resistance decay immediately after machine shutdown.

The cold resistance for the 5.5kW motor was 5.139 Ω, but after running the machine to thermal equilibrium at rated load and extrapolating the resistance curve, the resistance at shutdown is 6.3821 Ω. A variation in the resistance values alters the stator, rotor and stray load losses, and ultimately results in an efficiency change.

In computing the final values of the stray load losses, both standards in their methods of Residual losses/segregation of losses recommend a linear regression analysis. However, the regression coefficient for the IEC 60034-2 and IEEE 112 standard should be at least 0.95 and 0.9 respectively. A value lower than that indicates that collected data is not satisfactory, problems with instrumentation or the procedure has not been followed accordingly. The data collected from this study was used to plot the different final values for the above stated methods and the regression coefficients, 0.9907 and 0.9862 were obtained for IEC 60034-2 and IEEE 112 respectively. Figure 2 and Figure 3 illustrate the uncorrected and corrected values of the stray load losses plotted against torque squared.

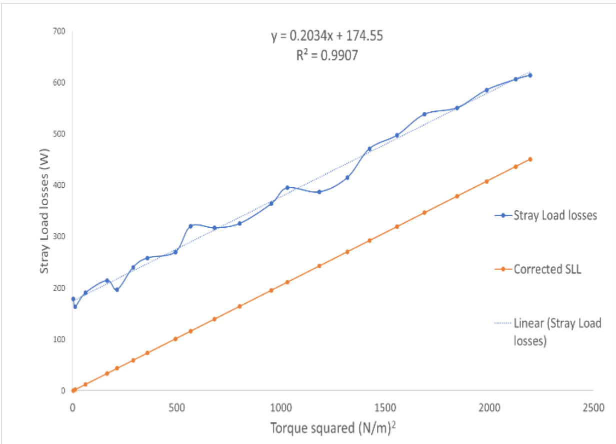

Figure 2. IEC 60034-2-1-1B Stray load losses final computation.

On the contrary, the IEEE 112-B1method corrects the final values according to a specific temperature resulting in a low regression coefficient as is shown in Figure 4.

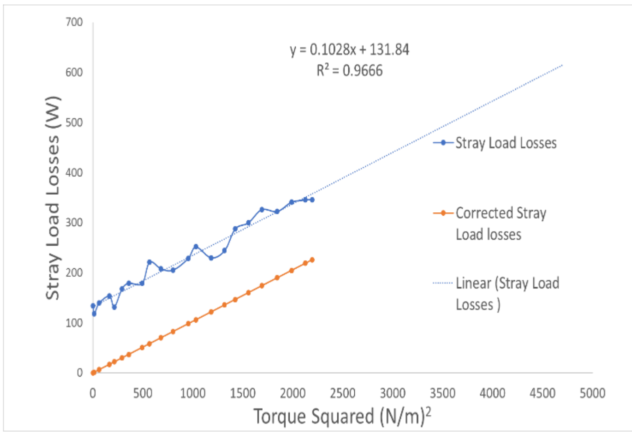

Figure 3. IEEE 112-B Stray load losses final computation

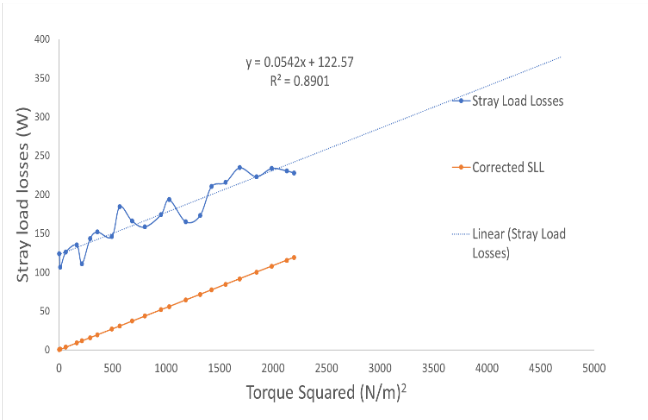

Figure 4. IEEE-B1 Stray load losses final computation

Figure 2 shows the different SLL values that are produced by the different standards when the machine is loaded up to 125% of rated load. IEC 60034-2B has the highest values of SLL because the segregation of losses eliminates errors.

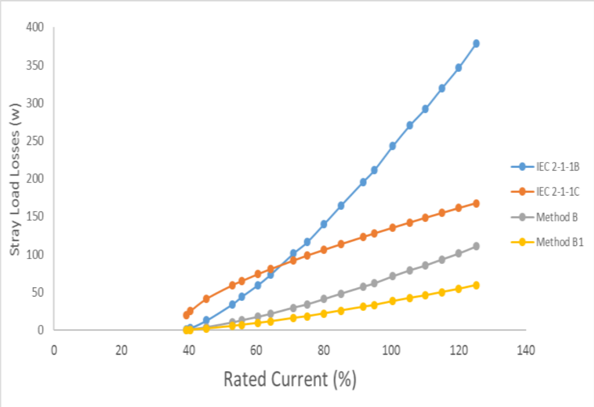

Figure 5: SLL calculated according to different standards/methods

Curves for IEC 60034-2C and IEEE 112-E1 representing assigned allowance have SLL values closely spaced. IEC 60034-2C recommends the assumed value of the stray load losses for ratings: 1 kW < P_{out} < 10000 kW to be given by:

$$PSLL = \left(0.025 - 0.005 * log10\left(\frac{Pout}{1kW}\right)\right) * Pin \quad (5)$$

However, the IEC 60034-2C assigned values result in higher values of SLL than the 1.8% of rated power recommended by the IEEE method E1.

Stator and Rotor Copper Losses

Stator copper losses are the same for the IEC 60034-2B and 2C. IEEE 112-B and B1 have the same values as well. However, the two standards' values show a large disparity. This is mainly due to the approach used to calculate these values.

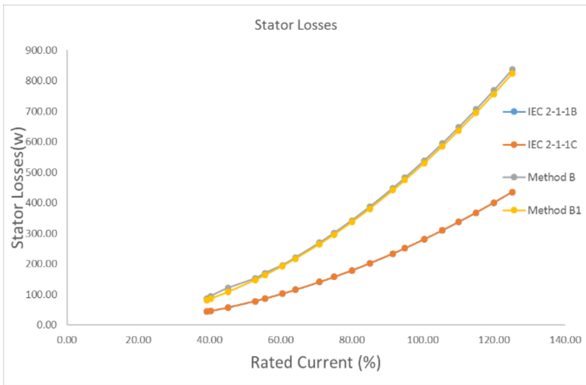

Figure 6. Stator losses according to different standards/methods

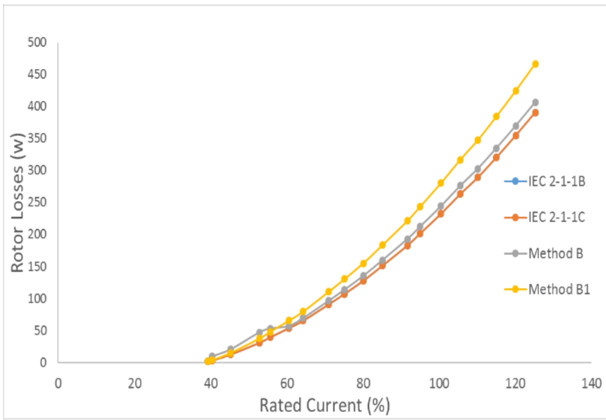

Figure 7. Rotor losses calculated according to different standards/methods

Output power versus load

Figure 8 illustrates how the output power is approximately the same for all the methods when a torque meter and calibrated dynamometer is used, which is a positive similarity in the standards.

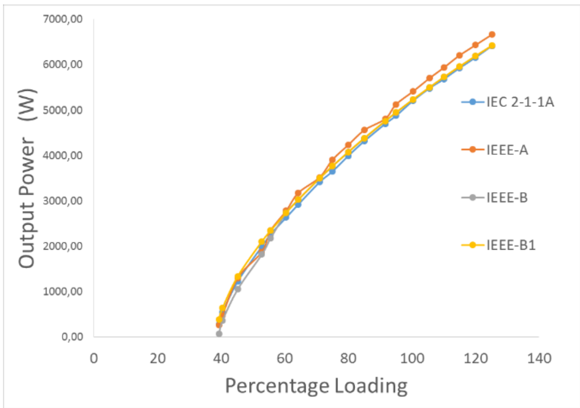

Figure 8. Output power according to the different standards

No-Load Losses

IEEE 112 considers the iron losses to be load independent, whereas the IEC 60034-2 uses the voltage, which takes the resistive voltage drop in the stator winding into account when calculating iron losses. Hence, according to the IEC 60034-2, iron losses are load dependent, having their highest values when the load current is at maximum. According to the same standard, the iron losses at full load are interpolated from the iron losses over the voltage curve at the required rated voltage. Figure 9 illustrates the curves obtained from the different standards. However, the IEEE 112 standard uses a constant value calculated when the rated voltage of the induction motor is applied during the no load test.

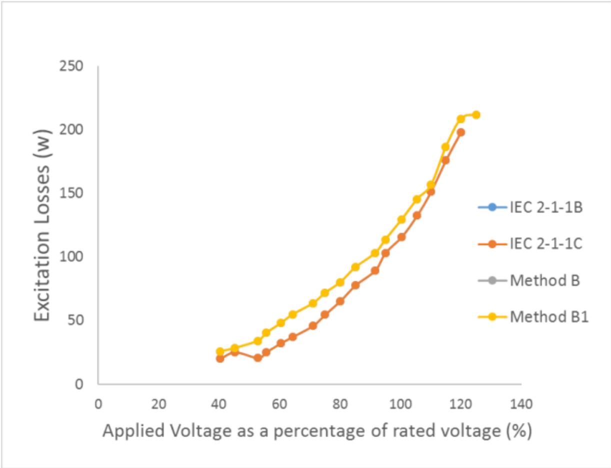

Figure 9. Excitation losses according to the IEEE 112 and IEC 60034-2-1 method.

Friction and Windage Losses

Both standards in the various methods consider the friction and windage losses to be constant. IEC 60034-2 method separates the voltage percent curve for friction/windage losses from the Fe losses curve. This results in a slightly higher value of F_{Fw} as compared to the IEEE method, which gives a constant value.

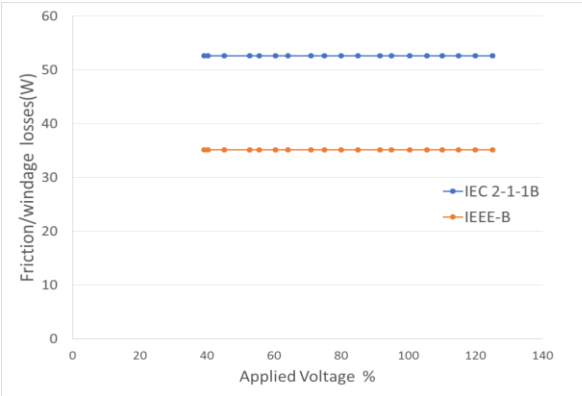

Figure 10. Friction and Windage losses calculated according to the IEC 60034-2 and IEEE 112standard.

Evaluation of Efficiency

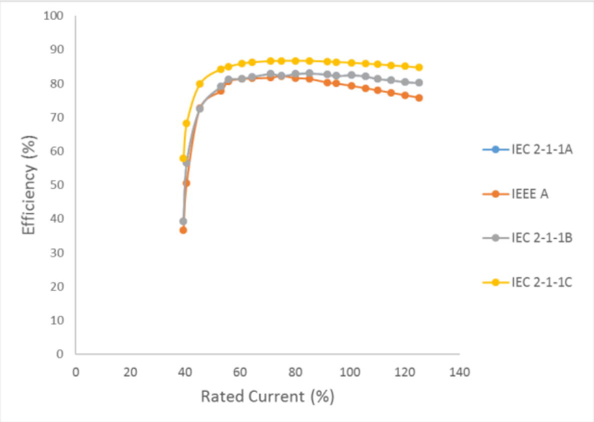

Figure 11. Final values of Efficiency from the various test methods.

IEC 60034-2-1A and 2B are basically almost the same whereas the IEC 60034-2 2C is higher by an average of 3%. This large variation is mainly due to the assigned value of SLL. SLL determination is mainly responsible for the differences that are seen in the final determination of efficiency.

Test procedures in standards are almost the same, with some variations. These variations result in 4% difference in the actual output at rated power. If the IEEE method A result is discarded, the other results are within 0.4% from one another. The results of the tests generally show two approaches to calculating the different loss components, except for the treatment of the SLL. These disparities in the calculated test results of the 5.5 kW motor indicate that there is need to harmonise standards, especially in the calculation procedures and the approach to quantifying the stray load losses.

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Presenting author: The paper will be presented by Simon Deda.

APPENDIX C

		Ranges								
Load Test		voltage V	current A	CT Accura	Current Accuracy A		% Accuracy		Combined Accuracy of CT and Power Analyzer	
Voltage	Current	1	0.1	0.000273	0.000901	-0.000901	0.0107	-0.0107	0.000941641	0.000941641
380.87	8.40350	3	0.3		0.000862	-0.000862	0.0108	-0.0108	0.000904047	0.000904047
	8.01000	10	3		0.000802	-0.000802	0.0108	-0.0108	0.00084704	0.00084704
	7.41010	30	10		0.000763	-0.000763	0.0109	-0.0109	0.000810643	0.000810643
	7.02470	100	30		0.000702	-0.000702	0.0110	-0.0110	0.000753314	0.000753314
	6.41300	300	100		0.000664	-0.000664	0.0110	-0.0110	0.000717482	0.000717482
	6.02720	1000	300		0.000561	-0.000561	0.0112	-0.0112	0.000623752	0.000623752
	5.00080	3000			0.000546	-0.000546	0.0113	-0.0113	0.000609982	0.000609982
	4.84730				0.000503	-0.000503	0.0114	-0.0114	0.000571711	0.000571711
	4.41590				0.000467	-0.000467	0.0115	-0.0115	0.000540456	0.000540456
	4.05730				0.000403	-0.000403	0.0118	-0.0118	0.000486068	0.000486068
	3.41500				0.000368	-0.000368	0.0120	-0.0120	0.000458109	0.000458109
	3.07250				0.000341	-0.000341	0.0122	-0.0122	0.00043656	0.00043656
	2.80070				0.000061	-0.000061			0.000279244	0.000279244

1. Input power accuracy calculations

Power Factor SUM PPA1	Watts SUM PPA1	VA SUM PPA1	RMS Current SUM PPA1	Watts accuracy	Watts accuracy	% Accuracy	% Accuracy	Combined accuracy of Power Analyzer and CT	
0.847	8132.2	9601.6	8.4035	8.103665	-8.09929	0.099649	-0.0996	8.103665	
0.8444	7763.1	9193.4	8.01	7.750119	-7.74593	0.099833	-0.09978	7.750119	
0.8407	7121.3	8470.4	7.4101	7.128144	-7.12428	0.100096	-0.10004	7.128144	
0.8364	6735.1	8052.4	7.0247	6.762382	-6.75871	0.100405	-0.10035	6.762382	
0.8261	6061.4	7337.4	6.413	6.131604	-6.12826	0.101158	-0.1011	6.131604	
0.8175	5650.4	6911.8	6.0272	5.752197	-5.74905	0.101802	-0.10175	5.752197	
0.7799	4466.9	5727.2	5.0008	4.680468	-4.67786	0.104781	-0.10472	4.680468	
0.7719	4285.1	5551.7	4.8473	4.518746	-4.51621	0.105453	-0.10539	4.518746	
0.7424	3752.8	5054.8	4.4159	4.055026	-4.05272	0.108053	-0.10799	4.055026	
0.708	3290.3	4647.5	4.0573	3.664074	-3.66196	0.11136	-0.1113	3.664074	
0.6104	2389.1	3913.9	3.415	2.933098	-2.93131	0.12277	-0.1227	2.933098	
0.5207	1833	3520.4	3.0725	2.511735	-2.51013	0.137029	-0.13694	2.511735	
0.4001	1282.1	3204.1	2.8007	2.131817	-2.13036	0.166275	-0.16616	2.131817	

3) Speed Accuracy measurements

motor speed	speed accuracy		% Accuracy		Summation in Quadrature
1442	0.14458	-0.14458	0.010026	-0.01003	0.144588
1448.892	0.145269	-0.14527	0.010026	-0.01003	0.145277
1444.985	0.144878	-0.14488	0.010026	-0.01003	0.144886
1453.724	0.145752	-0.14575	0.010026	-0.01003	0.14576
1455.287	0.145909	-0.14591	0.010026	-0.01003	0.145916
1461.184	0.146498	-0.1465	0.010026	-0.01003	0.146506
1466.797	0.14706	-0.14706	0.010026	-0.01003	0.147067
1468.716	0.147252	-0.14725	0.010026	-0.01003	0.147259
1471.274	0.147507	-0.14751	0.010026	-0.01003	0.147515
1474.471	0.147827	-0.14783	0.010026	-0.01003	0.147835
1483.495	0.148729	-0.14873	0.010026	-0.01003	0.148737
1491.524	0.149532	-0.14953	0.010025	-0.01003	0.14954
1494.437	0.149824	-0.14982	0.010025	-0.01003	0.149831

4) Torque Accuracy measurements

motor torque	Accuracy		% Accuracy		Summation in Quadrature
46.45471	0.073227	-0.07323	0.157632	-0.15763	0.073243
44.26758	0.072134	-0.07213	0.162949	-0.16295	0.072149
40.76592	0.070383	-0.07038	0.172651	-0.17265	0.070399
38.47182	0.069236	-0.06924	0.179965	-0.17997	0.069252
34.74779	0.067374	-0.06737	0.193894	-0.19389	0.067391
32.32703	0.066164	-0.06616	0.204669	-0.20467	0.066181
25.44334	0.062722	-0.06272	0.246515	-0.24652	0.06274
24.30333	0.062152	-0.06215	0.255733	-0.25573	0.06217
21.06345	0.060532	-0.06053	0.287378	-0.28738	0.06055
18.22187	0.059111	-0.05911	0.324396	-0.3244	0.05913
12.54588	0.056273	-0.05627	0.448537	-0.44854	0.056293
8.946124	0.054473	-0.05447	0.608901	-0.6089	0.054494
5.468249	0.052734	-0.05273	0.96437	-0.96437	0.052755