



UNIVERSITEIT VAN PRETORIA  
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**A NON-INTRUSIVE IN-SERVICE MOTOR**

**EFFICIENCY ESTIMATION**

**TECHNIQUE**

by

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## SUMMARY

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### A NON-INTRUSIVE IN-SERVICE MOTOR EFFICIENCY ESTIMATION TECHNIQUE

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Optimising the energy use of electric motors presents a significant opportunity for reducing energy consumption in industry. A need exists for methods of accurately estimating the efficiency of motors without interrupting the motor driven process. This study describes the development of an accurate non-intrusive efficiency estimation technique for in-service induction motors. This method is based on a non-intrusive compensated slip method. A new motor speed estimation technique based on vibration signature analysis is developed and applied in the proposed efficiency estimation technique.

The performance of this method is verified through experimental data. Six other efficiency estimation techniques are implemented in this work. Their practical performance is compared to the proposed non-intrusive compensated slip technique. The proposed method of estimating motor efficiency is found to be accurate and easy to implement. The robustness of the non-intrusive compensated slip method to variations in the supply voltage is evaluated. The technique is robust to under-voltage and over-voltage power system conditions.

A comprehensive motor management strategy to reduce motor life cycle costs while increasing reliability is presented. This is an integrated approach based on the application of the speed and efficiency estimation techniques described in this study.



## LIST OF ABBREVIATIONS

<b>ANN</b>	Artificial Neural Network
<b>CZT</b>	Chirp-Z Transform
<b>DAQ</b>	Data Acquisition
<b>FFT</b>	Fast Fourier Transform
<b>IEC</b>	International Electrotechnical Commission
<b>IEEE</b>	The Institute of Electrical and Electronics Engineers
<b>MMF</b>	Magnetomotive Force
<b>MRAS</b>	Model Reference Adaptive System
<b>NEMA</b>	National Electrical Manufacturers' Association
<b>RCM</b>	Reliability-centred Maintenance
<b>SCADA</b>	Supervisory Control and Data Acquisition
<b>USB</b>	Universal Serial Bus
<b>VSD</b>	Variable Speed Drive



# TABLE OF CONTENTS

<b>CHAPTER 1 INTRODUCTION .....</b>	<b>8</b>
1.1 BACKGROUND AND CONTEXT .....	8
1.2 OBJECTIVES .....	9
1.3 CONTRIBUTIONS OF THIS DISSERTATION .....	10
1.4 ORGANISATION OF THIS DISSERTATION .....	10
<b>CHAPTER 2 A REVIEW OF MOTOR EFFICIENCY ESTIMATION TECHNIQUES.....</b>	<b>12</b>
2.1 INTRODUCTION .....	12
2.2 MOTOR LOSSES AND EFFICIENCY.....	12
2.2.1 Stator copper losses .....	13
2.2.2 Core losses .....	13
2.2.3 Rotor copper losses.....	14
2.2.4 Friction and windage losses .....	14
2.2.5 Stray load losses .....	14
2.3 REVIEW OF EFFICIENCY ESTIMATION TECHNIQUES.....	16
2.3.1 Segregated losses methods.....	16
2.3.2 Equivalent circuit methods.....	18
2.3.3 Slip methods.....	20
2.3.4 Air-gap torque methods .....	22
2.3.5 Current methods .....	23
2.3.6 Other methods .....	24
2.4 DISCUSSION .....	25
2.5 CHAPTER SUMMARY .....	26
<b>CHAPTER 3 REVIEW OF SPEED ESTIMATION TECHNIQUES .....</b>	<b>27</b>
3.1 INTRODUCTION .....	27
3.2 SPACE HARMONICS .....	28
3.2.1 Theoretical background .....	28
3.2.2 Speed estimation using air-gap eccentricity.....	30
3.2.3 Speed estimation using rotor slot harmonics .....	32
3.2.4 Extracting slot harmonics using the Chirp-Z transform .....	35
3.3 OBSERVER-BASED METHODS .....	36
3.3.1 Model reference adaptive system.....	37



3.3.2	Luenberger observer .....	38
3.3.3	Kalman filtering techniques .....	38
3.4	ARTIFICIAL NEURAL NETWORKS .....	39
3.5	CHAPTER SUMMARY .....	40
<b>CHAPTER 4 MOTOR SPEED ESTIMATION USING VIBRATION SIGNATURE ANALYSIS.....</b>		<b>41</b>
4.1	INTRODUCTION .....	41
4.2	SPEED ESTIMATION USING VIBRATION SIGNATURE ANALYSIS.....	42
4.3	EXPERIMENTAL SETUP .....	46
4.4	EXPERIMENTAL RESULTS AND ANALYSIS .....	47
4.5	CHAPTER SUMMARY .....	50
<b>CHAPTER 5 A NEW NON-INTRUSIVE MOTOR EFFICIENCY ESTIMATION TECHNIQUE.....</b>		<b>51</b>
5.1	INTRODUCTION .....	51
5.2	PRACTICAL EVALUATION OF EFFICIENCY ESTIMATION TECHNIQUES.....	52
5.2.1	Experimental setup .....	52
5.2.2	Experimental Results .....	59
5.2.3	Discussion .....	61
5.3	A NEW NON-INTRUSIVE SPEED ESTIMATION TECHNIQUE .....	62
5.3.1	Speed estimation technique.....	62
5.3.2	Motor efficiency estimation technique .....	62
5.3.3	Experimental setup .....	65
5.3.4	Experimental results .....	68
5.3.5	Discussion .....	79
5.4	CHAPTER SUMMARY .....	81
<b>CHAPTER 6 ERROR AND SENSITIVITY ANALYSIS .....</b>		<b>82</b>
6.1	INTRODUCTION .....	82
6.2	INFLUENCE OF SUPPLY VOLTAGE CONDITIONS.....	83
6.2.1	Voltage dips and under-voltages .....	83
6.2.2	Voltage swells and over-voltages.....	85



6.2.3	Voltage unbalance .....	87
6.2.4	Experimental setup .....	89
6.2.5	Experimental results .....	92
6.2.6	Discussion .....	97
6.3	MEASUREMENT ERROR ANALYSIS .....	98
6.3.1	Methodical error .....	101
6.3.2	Human error .....	101
6.3.3	Instrumental error .....	102
6.3.4	Statistical analysis .....	103
6.3.5	Error estimation .....	105
6.4	CHAPTER SUMMARY .....	107
<b>CHAPTER 7 APPLICATIONS TO MOTOR MANAGEMENT .....</b>		<b>108</b>
7.1	INTRODUCTION .....	108
7.2	ENERGY MANAGEMENT .....	109
7.3	MOTOR REPLACEMENT.....	111
7.3.1	Motor replacement strategy.....	111
7.3.2	Economic analysis .....	113
7.4	MOTOR MAINTENANCE .....	118
7.5	MOTOR CONDITION MONITORING.....	122
7.6	MOTOR MANAGEMENT.....	125
7.6.1	Strategy .....	125
7.6.2	People.....	125
7.6.3	Work management.....	125
7.6.4	Material management .....	125
7.6.5	Basic motor maintenance .....	126
7.6.6	Performance management.....	126
7.6.7	Technical support systems .....	126
7.6.8	Motor reliability .....	127
7.7	CHAPTER SUMMARY .....	128
<b>CHAPTER 8 CONCLUSION.....</b>		<b>129</b>



8.1 INTRODUCTION .....	129
8.2 DISSERTATION SUMMARY .....	129
8.3 CONTRIBUTION .....	130
8.4 RECOMMENDATIONS FOR FUTURE WORK.....	132
<b>REFERENCES .....</b>	<b>133</b>

# CHAPTER 1

## INTRODUCTION

### 1.1 BACKGROUND AND CONTEXT

The South African government's energy strategy acknowledges that energy has to be used in a way that supports the environment, society and economic development [1]. This is in line with international best practices. A new approach is required so as to ensure that energy is used efficiently. This reduces operating costs and minimises the adverse effects to the environment. Increasingly stringent international standards and government rebate programmes are introduced to promote energy efficiency.

Most of the electrical energy that is consumed by industrial countries is used to drive electric motors. This is as high as two thirds of the consumption in some countries [2]. Optimising the energy use of electric motors therefore presents a significant opportunity for reducing energy consumption. This can be accomplished by replacing inefficient motors with high-efficiency motors and making the motor-driven processes more efficient. An accurate method for estimating the efficiency of in-service motors is needed to determine the performance of installed motors. The efficiency of an installed motor can then be compared to a new energy-efficient motor. A decision on the replacement of a motor based on the life cycle costs can be made [3].

Induction motors are the most widely used type of electric motor in industry. They are popular because they are easier to control, cheaper to manufacture and relatively robust as compared to other motor types [4]. The focus of this work will be on induction motors. Estimating the efficiency of an in-service induction motor, without withdrawing it from service, remains a challenge in industry.

The efficiency of an electric motor is defined as the ratio of the mechanical output power to the electrical input power [5]. The electrical input power of a motor can be measured from the motor terminals. Measuring or calculating the mechanical output power of a motor that is already coupled to driven equipment is a complex undertaking. The torque and the rotor speed are required to calculate the output power. Once the motor is installed it is usually impossible to take measurements without stopping the motor-driven process and decoupling the motor from the equipment. This downtime results in financial losses due to lost production time.

Numerous methods for estimating the efficiency of in-service induction motors have been presented in literature. The methods vary in their level of intrusion and accuracy. Standard test procedures for determining the performance of motors also exist. These include the International Electrotechnical Commission (IEC) 61972, the IEC 34-2, the JEC 37, the CSA and the IEEE 112 test standard [6]. The most widely used standard in industry is the IEEE 112 standard. Most of the efficiency estimation techniques available require intrusive tests to be carried out on the motor. Further, it is expensive and impractical to implement in the field. The success of an efficiency estimation technique for an in-service motor depends on the accuracy, cost, ease of implementation and level of intrusion.

## 1.2 OBJECTIVES

The objective of this research is to develop and test an improved non-intrusive method for estimating the efficiency of an in-service induction motor. The focus is on developing an algorithm that will accurately estimate the efficiency based on electrical measurements taken at the motor terminals and vibration measurements measured on the motor frame. This will ensure a non-intrusive method. It will eliminate the need to perform intrusive tests that result in a disruption to the motor-driven process. This research must develop an estimation technique that is able to produce results to within 95% accuracy. The

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performance of the method is evaluated through structured experiments that test its accuracy under ideal and non-ideal supply conditions.

### **1.3 CONTRIBUTIONS OF THIS DISSERTATION**

In this dissertation, a robust non-intrusive motor efficiency estimation technique that will provide the desired accuracy under both ideal and non-ideal conditions is developed and tested. The approach followed in the development of the efficiency estimation technique requires the application of an accurate rotor speed estimation algorithm. A few techniques have been proposed for estimating the speed of an induction motor. A new motor speed estimation technique based on vibration signature analysis is developed and applied in the proposed efficiency estimation technique.

A survey of motor efficiency estimation techniques is presented. Several of the less intrusive motor efficiency estimation techniques are implemented. This is done to evaluate the performance of the proposed technique against these methods. The efficiency of the test motors is accurately measured to evaluate the accuracy of the estimation techniques.

### **1.4 ORGANISATION OF THIS DISSERTATION**

In Chapter 2, a comprehensive literature study of motor efficiency estimation techniques is presented. The strengths and limitations of each of the techniques are analysed. Chapter 3 presents a survey of speed estimation techniques. In this work, a new speed estimation technique is developed based on vibration signature analysis. A theoretical analysis and experimental implementation of this technique is presented in Chapter 4.

In Chapter 5, a non-intrusive compensated slip method for estimating motor efficiency is presented. The performance of the proposed method is evaluated against other non-intrusive methods.



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In Chapter 6, the sensitivity of the non-intrusive compensated slip method to supply voltage variation is evaluated. An experimental setup is developed to assess the robustness to supply voltage conditions. An error analysis of the technique is also presented in Chapter 6. In Chapter 7, the applications of the speed and efficiency estimation technique to motor management are discussed. Tools for economic comparison between two motors with different efficiencies are presented. A comprehensive motor-management strategy is proposed. Chapter 8 concludes the work that has been done in this dissertation. The contributions made through this work are highlighted and recommendations for future work are presented.

## CHAPTER 2

# A REVIEW OF MOTOR EFFICIENCY ESTIMATION TECHNIQUES

### 2.1 INTRODUCTION

Determining the efficiency of an in-service motor is crucial when a motor needs to be replaced or in making the decision to purchase a new motor [3]. In this chapter a review of non-intrusive methods for estimating the efficiency of on-line motors is presented.

Different methods have been presented in literature that vary in their level of intrusion and accuracy. In order to compare the methods that are available, they need to be tested against a common test standard. The most widely used standard in industry is the IEEE 112 standard [2].

This chapter begins with a definition of motor efficiency and the losses in an induction motor. A review of motor efficiency estimation techniques is presented. The efficiency estimation techniques are categorised according to the similarity of the approaches. Accuracy, cost, ease of implementation and safety are used to evaluate the different techniques.

### 2.2 MOTOR LOSSES AND EFFICIENCY

In induction motors not all of the electrical energy consumed is converted into the mechanical energy required for the application. A portion of the energy is lost within the motor. The efficiency ( $\eta$ ) of an electric motor is defined as the ratio of the mechanical output power to the electrical input power:

$$\eta = \frac{P_{output}}{P_{input}}. \quad (2.1)$$

There are five main types of losses that occur in an induction motor [5].

### 2.2.1 Stator copper losses

Stator copper losses occur as a result of the current in the stator windings. They are the ohmic losses given by (2.2), [4].

$$W_{st} = 3I_1^2 R_1 \quad (2.2)$$

where  $W_{st}$  is the stator losses,  $I_1$  is the stator current and  $R_1$  is the per phase stator winding resistance.

### 2.2.2 Core losses

Core losses are linked to the magnetic flux in the machine that is independent of the load. These losses occur as a result of the eddy currents in the iron and the magnetising hysteresis in the ferromagnetic core. Because of the cyclic magnetisation of the core, distributed voltages are induced along effective short circuit loops. Eddy currents flow around these loops within the core material [4]. The eddy currents cause ohmic losses on the surface of the rotor laminations. They also act to reduce the penetration of the flux into the rotor [7]. The magnetic flux varies as the applied stator voltage is changed. For a fixed stator voltage, the core losses in an induction motor will remain constant from no load to full load.

### 2.2.3 Rotor copper losses

The rotor copper losses occur as a result of the current flowing in the rotor. They vary with the slip of the motor. They are the ohmic losses given by (2.3), [4].

$$W_{rl} = 3(I_2')^2 R_2' \quad (2.3)$$

where  $W_{rl}$  is the rotor copper losses,  $I_2'$  is the rotor current and  $R_2'$  is the rotor resistance reflected to the stator reference.

### 2.2.4 Friction and windage losses

Friction and windage losses are the mechanical rotational losses that occur in the bearings and ventilation ducts. Because of their rotational nature, these losses are speed-dependent and are relatively constant from no load to full load. Depending on the design and construction of the motor, the components of these losses can be separated as follows [8]:

- A component of these losses that comes from frictional losses in the bearings in the motor. This can be calculated from the bearing type and the operating speed of the motor.
- The windage losses that occur as a result of the exterior cooling fan.
- The frictional air losses in the rotor due to air circulating in the ventilation ducts.

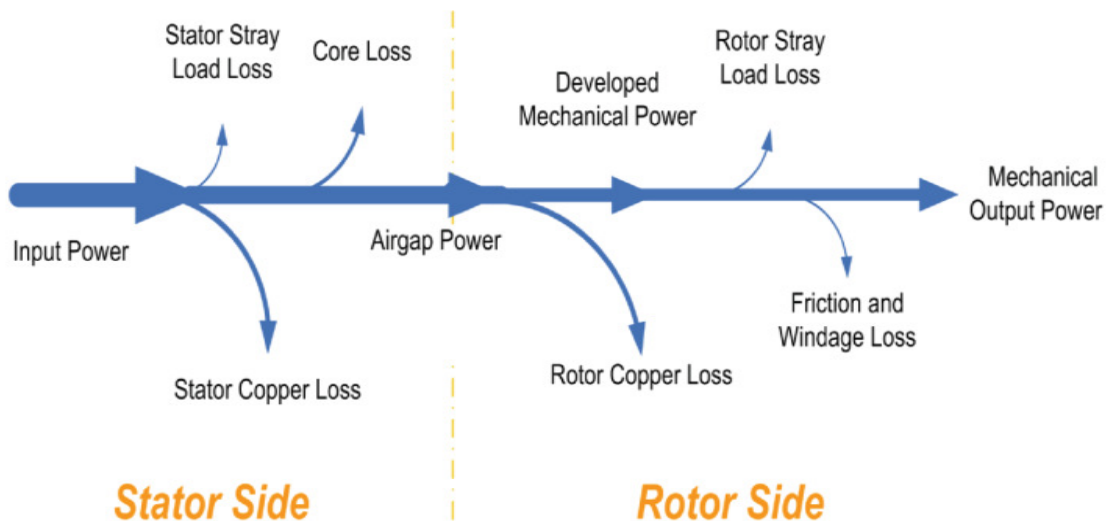
### 2.2.5 Stray load losses

Stray load losses are losses that are not accounted for. These losses vary with the driven load. The presence of significant stray load losses can result in abnormal heating and torque loss [9]. In such conditions it is prudent to derate the motor in order to prevent

damage or rapid failure. Stray load losses occur in induction motors due to a combination of the following [10]:

- Space harmonics that exist owing to motor structural imperfections in the slots, air gap and windings.
- Limitations in the ferromagnetic material used in the construction of the motor. This leads to saturation when the motor is in operation.
- Manufacturing imperfections that result in cross-bar currents flowing owing to the ineffective insulation of rotor bars.

The power flow of an induction motor is shown in Figure 2.1. From the diagram it is evident that the efficiency can be calculated by determining the output power or estimating the losses that occur in the motor. These are the main challenges in developing a non-intrusive on-line motor efficiency estimation technique. The electrical input power can be measured at the motor starter or motor terminals.



**Figure 2.1.** The power flow of an induction motor [11].

The efficiency of a motor will also vary depending on the supply voltage, the motor size, loading and operating speed.

## **2.3 REVIEW OF EFFICIENCY ESTIMATION TECHNIQUES**

Numerous motor efficiency estimation methods are proposed in literature. Many of the methods can be classified to fit into a few categories [12]. The methods that have been identified in this study are discussed based on the various categories they fit into. The differences will be highlighted and explained.

### **2.3.1 Segregated losses methods**

In the segregated losses motor efficiency estimation techniques, the magnitude of each of the components of the motor losses is estimated and the sum of these is subtracted from the input power that is measured from the motor input terminals. The difference is then the output power of the motor [13]. This class of method has been found to have an accuracy of within 2% of the actual efficiency. The major disadvantage is that it requires a no-load and full-load test in order to determine the motor loss components. This makes implementing them very intrusive. It will result in expensive plant downtime unless the tests can be performed during scheduled maintenance periods [14]. The segregated losses methods are therefore not truly non-intrusive.

There are a few variations of the segregated loss techniques, which will be mentioned below [12].

#### ***2.3.1.1 IEEE Standard 112 Method E1***

In order to apply this method, a no-load test has to be done [14]. Load tests also need to be performed with the motor loaded at six different load levels that range from 25 to 150% of

rated load. An assumed value based on IEEE 112 [15] is used to estimate the stray load losses based on the size of the motor. The assumed values are shown in Table 2.1. The resistance and slip measurements are adjusted to compensate for temperature changes.

**Table 2.1.** IEEE assumed values for stray-load loss.

Machine rating		Stray-load loss percentage of rated output
1–125 hp	1–90 kW	1.80%
126–500 hp	91–375 kW	1.50%
501–2499 hp	376–1850 kW	1.20%
2500 hp and greater	1851 kW and greater	0.90%

### ***2.3.1.2 Hirzel's Modified IEEE Standard 112 Method E1***

This method is similar to the standard IEEE method E1 [12]. It is less intrusive. One measurement is required for the load test and the no load test. This is performed at rated voltage, eliminating the need for a variable power supply.

### ***2.3.1.3 Ontario Hydro's Simplified Segregated Loss Method***

In the method proposed by Ontario Hydro, IEEE method E1 is simplified further by assuming a value for the friction, windage and core losses [14]. This makes this method even less intrusive as only a load test at rated voltage is needed to estimate efficiency.

### ***2.3.1.4 ECNZ Method***

This method is based on IEC 34-2 standard [12]. It is used to determine the efficiency of induction motors with power ranging from 5.5 kW to 750 kW. The voltage, current, speed and supply frequency have to be measured in order to apply the method. The stator resistance is measured in all three phases using current injection probes. The losses are estimated using measurements.

### 2.3.1.5 The Genetic Algorithm

In [3] a method using the genetic algorithm to solve nonlinear algebraic equation can be applied to the IEEE 112 standard segregated loss method. This method is less intrusive because the no-load test can be eliminated. The accuracy of this method is claimed to be within 3%.

There are a few other variations of the segregated loss method based on the above-mentioned techniques that have been commercialised. These include the Becnel, Kilgore, and Merrill's Modified IEEE Standard 112 Method E1, the Vogelsang & Benning Motor Analyzer Method, and the ANGUS Electronics Method [12].

### 2.3.2 Equivalent circuit methods

An induction motor equivalent circuit is shown in Figure 2.2 [16].  $R_1$  and  $X_1$  represent the stator resistance and leakage reactance,  $R'_2$  and  $X'_2$  represent the rotor resistance and leakage reactance.  $R_c$  and  $X_M$  represent the core resistance and the magnetising reactance of the machine.  $I_1$  and  $I_2$  are the stator and rotor currents, and  $s$  is the motor slip.

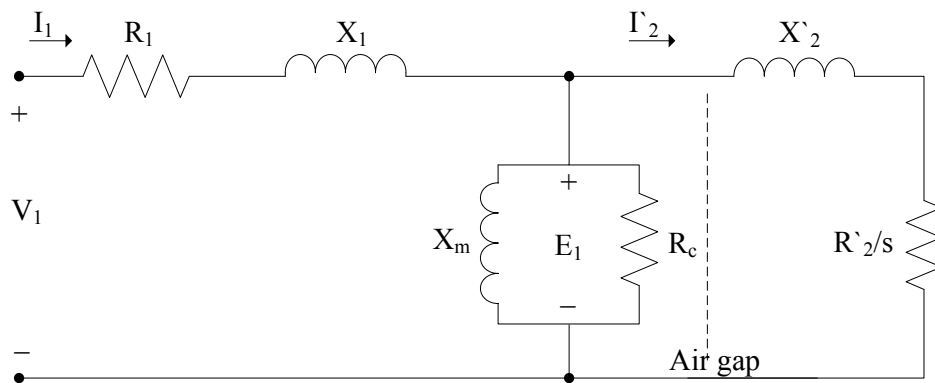


Figure 2.2. Induction motor per phase equivalent circuit (stator reference).

A few different approaches have been proposed for methods that are based on the equivalent circuit. One of the advantages of equivalent circuit techniques is that reasonably accurate efficiency estimates for the motor can be made for operating points at which the measurements were taken [12]. The accuracy of the methods can usually be increased by measuring the input current and slip at the operating point. The disadvantage of these techniques is that they are based on a per phase equivalent circuit. All the phases are assumed equal. This will introduce errors for an unbalanced system. A further disadvantage is that tests need to be performed in order to calculate the circuit parameters.

A discussion of these methods is presented below.

### ***2.3.2.1 IEEE Standard 112 Method F1***

In this method an impedance test, a no-load test and a variable voltage test need to be done to determine the parameters of the equivalent circuit. A value for the stray load losses is assumed according to the IEEE 112 standard. An iterative process is used to determine the parameters of the equivalent circuit.

### ***2.3.2.2 Ontario Hydro's Simplified Method F1***

The Ontario Hydro method requires a no-load and a full-load test [12]. The tests must be carried out at the rated voltage of the machine. The slip is also measured at the rated load of the motor. The practicality of this method is enhanced by eliminating the need for a variable voltage supply. The stray load and friction and windage losses are not taken into account in this method. A different iterative procedure is used to determine the equivalent circuit parameters.

### ***2.3.2.3 Locked Rotor Method***

Two locked rotor tests are used to determine the parameters of an equivalent circuit with two rotor loops [17]. A simplified version of the induction motor equivalent circuit is used to reduce the number of parameters that have to be determined. The models developed in the method ensure that high accuracy is achieved. The tests that have to be performed are very invasive. The circuit parameters are obtained from carrying out two locked rotor tests. Alternatively, a locked rotor impedance test and a load test can be done to calculate the circuit parameters. The tests would require the motor under test to be removed from normal operation.

### ***2.3.2.4 ORMEL96***

This technique only uses the nameplate data to calculate the parameters of a modified equivalent circuit. A speed measurement is required for this method. Assumed values are used to calculate the friction and windage losses [17]. The accuracy of this method is closely linked to the accuracy of the nameplate data. In cases where the nameplate data are inaccurate, this method will be unable to produce good results.

### ***2.3.2.5 Dr El-Ibiary's Equivalent Circuit Method***

In [18] an equivalent circuit method is applied. The method requires the measured input voltage, input current, stator resistance and the motor speed. The equivalent circuit parameters can be determined by using data measured from a no-load test and a single operating point. This method is claimed to be more than 99% accurate.

## **2.3.3 Slip methods**

The slip in an induction motor is directly proportional to the load that the motor is driving [4]. These models rely on measuring the speed of the motor. Their main advantage is their

simplicity [19]. A disadvantage of the methods is that the efficiency of a motor is not proportional to the loading of the motor. Further, the nameplate rating is not always very accurate.

### 2.3.3.1 Standard Slip Method

The standard slip method is given by (2.4), [14].

$$\eta = \frac{Slip}{Slip_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \quad (2.4)$$

The motor speed is measured to calculate the slip. The input power is calculated from measuring the terminal voltage and current.

### 2.3.3.2 Ontario Hydro's Compensated Slip Method

In the standard slip method, the effect of voltage on efficiency is not considered. Ontario Hydro [12] improves on this method by factoring the voltage into the calculation. This is shown in (2.5). In order to implement this method, the supply voltage has to be measured. The rated output power, voltage and slip are obtained from the motor nameplate or datasheet.

$$\eta = \frac{Slip}{Slip_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \cdot \left(\frac{V}{V_{rated}}\right)^2 \quad (2.5)$$

### 2.3.3.3 Slip Upper Bound Method

It has been show that the efficiency of an induction motor is bounded by (2.6) if stator losses are assumed to be negligible:

$$\eta \leq (1 - Slip) . \quad (2.6)$$

This method can only be used to estimate the maximum efficiency that a specific motor can attain [19].

### 2.3.4 Air-gap torque methods

The efficiency of an induction motor can be estimated by using air-gap torque equations [5]. These methods offer good accuracy but can still be intrusive.

#### 2.3.4.1 Air-gap Torque Method

In this method the efficiency is calculated by using the input voltage, current, rotor speed and shaft torque to determine the input and output power. The rotor speed and the stator resistance are needed to implement this method. A no-load test and speed measurements are needed. The rotor speed can be measured using speed sensors. This may require that the motor is decoupled for the sensor to be safely mounted. The stator resistance can be measured at the motor terminals using methods stipulated in the IEEE 112 test standard. Current and voltage transducers are required to measure the phase currents and the line voltages. Once this information has been obtained, the air-gap torque is calculated using (2.7), [5].

$$T_{ag} = \frac{\sqrt{3}P}{6} \left( (i_a - i_b) \int (v_{ca} + R_s(2i_a + i_b)) dt + (2i_a + i_b) \int (v_{ab} - R_s(i_a - i_b)) dt \right) \quad (2.7)$$

where  $T_{ag}$  is the air- gap torque,  $P$  is the number of poles,  $i_a$  to  $i_c$  are the phase currents,  $v_{ca}$  and  $v_{ab}$  are the respective line voltages. The output power is determined from the air-gap power by subtracting the friction and windage, rotor copper and stray load losses. The efficiency can be calculated using (2.8).

$$\eta = \frac{(T_{ag} \times \omega_r) - W_{fw} - W_{lr}}{P_{input}} \quad (2.8)$$

where  $\omega_r$  is the rotor speed,  $W_{fw}$  are the friction and windage losses and  $W_{lcr}$  are the rotor copper and stray load losses. The loss components can be estimated using one of the methods described in section 2.3.1.

#### **2.3.4.2 Modified Air-gap Torque Method**

The air-gap torque method can be modified to make it non-intrusive [11], [20]. This is accomplished by using advanced estimation techniques to determine the stator resistance and rotor speed. The rotor speed can be obtained from the slot harmonics in the stator current by using digital spectrum estimation. A detailed discussion of speed estimation techniques is presented in Chapter 3. The stator resistance can be obtained by using the online DC signal injection method. In order to implement the method, an external circuit must be introduced between the power supply and the motor terminal in order to inject a DC offset. This adds a level of complexity to the motor circuit. A structured way of switching in the DC circuit is required. This is because the introduction of the DC signal has an adverse effect on the performance of the motor. It causes torque distortion and increases power consumption.

Once suitable methods have been implemented, the motor efficiency can be determined from only measuring the terminal voltage and current. Equations (7) and (8) can then be applied to estimate the efficiency of the motor under test. The key advantages of the air-gap torque method are that it can be implemented online and the method could be robust to supply voltage variation. Its main disadvantages are that the method requires additional circuitry, which might not be as robust and reliable as the induction motor. This also increases the cost associated with implementing the method.

#### **2.3.5 Current methods**

Current-based motor efficiency techniques are among the least intrusive methods [12]. This is because only the input current of the motor needs to be measured. They are based

on the assumption that the load is directly proportional to the current. The efficiency achieved with this method is given by (2.9).

$$\eta = \frac{I}{I_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \quad (2.9)$$

The inherent weakness of this method is the effect of the no-load current. The presence of the no-load current often results in the method overstating the output power. As a result the estimated efficiency will be higher than the actual efficiency.

The accuracy of this method can be improved by factoring in the no-load current of the motor [19]:

$$\eta = \left( \frac{I - I_{no\ load}}{I_{rated} - I_{no\ load}} + \frac{I}{I_{rated}} \right) \left( \frac{P_{output,rated}}{2P_{input}} \right). \quad (2.10)$$

An alternative current method, that improves accuracy by factoring in the no-load current of the motor to give (2.11), can be used [14]:

$$\eta = \frac{2I - I_{no\ load}}{2I_{rated} - I_{no\ load}} \cdot \frac{P_{output,rated}}{P_{input}}. \quad (2.11)$$

### 2.3.6 Other methods

Various other methods have been proposed in literature. The shaft torque method [19] measures the speed and shaft torque to determine the efficiency. This is an accurate method but it is very intrusive for in-service motors. Other methods proposed offer a variation of the main methods. These include the Stanford empirical method [17], statistical methods [17], Ho and Chen's method [17], the Colin Grantham method [12], simulation techniques [21] and various commercially available instruments.

## 2.4 DISCUSSION

In evaluating the different efficiency estimation techniques, the accuracy, cost, ease of implementation and safety are important factors to consider. Most of the methods that are proposed are very intrusive. In order to perform no-load tests, locked rotor tests and variable load tests; the motor has to be taken out of normal operation. The tests that require a variable voltage supply are impractical because it may not be readily available at the required voltage and power rating. Conducting those tests will disrupt the normal operation of the plant. Measuring the rotor speed or shaft power requires instrumentation that is usually expensive. Further, it has to be installed directly on the shaft, which might be difficult to access. It will likely require that the motor-driven process be shut down for a period of time. The implementation of the above mentioned methods will be fairly difficult and costly.

The least intrusive efficiency estimation methods that were discussed are based on measuring the input power to the motor and using nameplate ratings. Estimated values are used to determine the efficiency. National Electrical Manufacturers' Association (NEMA) standards can allow a tolerance of up to 20% in the nameplate parameters. This tolerance introduces errors in methods that rely on nameplate data. Motor parameters change considerably with frequency and temperature. They also vary with changes in the supply voltage. The parameters of a motor deviate from the nameplate values when the motor is rewound. These factors therefore have a large impact on the accuracy of the methods. The other non-intrusive methods use fairly complex computation techniques. This makes field implementation difficult.

The methods that were used to validate the accuracy of the techniques are deficient in certain areas. Many of the tests conducted only consider new or used motors without any defects. The results are misleading, because some methods have built-in assumptions about



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the motor characteristics [22]. A robust technique must provide good accuracy when the supply conditions are not balanced or when there are defects in the motor.

## 2.5 CHAPTER SUMMARY

A review of motor efficiency estimation techniques has been presented. Although various techniques exist for estimating the efficiency of an in-service motor, many of the methods have a high level of intrusion. There is a trade-off between the level of invasiveness intrusiveness and the accuracy of the efficiency estimate. Most of the methods that have been commercialised use the more intrusive estimation techniques or rely on nameplate information. This has a negative effect on their accuracy. The few truly non-intrusive methods that are reasonably accurate require further development and testing to simplify and verify their practicality and accuracy.

## CHAPTER 3

# REVIEW OF SPEED ESTIMATION TECHNIQUES

### 3.1 INTRODUCTION

In the previous chapter the importance of motor speed in efficiency estimation techniques was highlighted. The development of a non-intrusive efficiency estimation technique relies on accurately obtaining motor speed. In this chapter a review of motor mechanical speed estimation techniques is presented.

The subject of speed estimation has been highlighted through the increased use of induction motor drives in industrial applications [23]. Research into speed estimation techniques has been spurred by the benefits of implementing non-invasive speed feedback in the control of low to medium performance motor drives [24].

It has been found that the installation of shaft-mounted speed sensors increases the cost of implementing a drive solution. It has the adverse effect of decreasing the reliability of the drive. The addition of a shaft-mounted sensor introduces an additional maintenance burden. This is to ensure that the sensor works within the design parameters. The performance of the drive is also highly dependent on the reliability and operation of the speed sensor. This reduces the robustness of the induction motor driven process. In many plants where induction motors are already installed, it is not always possible to retrofit a shaft-mounted sensor. Usually an expensive modification to the drive chain is required. The motors may also be operating in harsh environments that are not suitable for many speed sensors. The above-mentioned disadvantages of shaft-mounted speed sensors highlight the need for alternative methods of accurately determining the mechanical speed of a motor.

Speed estimation techniques that have been developed can be categorised into two main groups. The first group consists of methods that are based on applying signal-processing techniques to extract space harmonics from the stator supply voltage or current. Analogue techniques have historically been employed. The limitations in their performance at low frequencies and inability to detect low amplitude signals has led to digital signal processing being the preferred method for analysing the harmonics [25].

Observer-based methods use motor mathematical models to estimate the motor speed. These methods form the second group. The advantages and disadvantages of both of the approaches will be explored in this chapter.

## 3.2 SPACE HARMONICS

Various methods for estimating the mechanical speed of a motor using voltage or current spectral components have been presented in literature. In this section an overview of these methods is presented.

### 3.2.1 Theoretical background

In an induction motor that is fed from a sinusoidal source, the motor air-gap magnetic field contains a wide range of harmonics [26]. The different spectral components are commonly referred to as space harmonics or saliency harmonics [27]. These harmonics occur from [23]:

- The stator winding distribution,
- Stator slots,
- Air-gap eccentricity,
- Rotor slots, and
- Rotor winding distribution.

The spectral components that are produced as a result of the stator slots and winding distribution occur at integer harmonics of the stator supply frequency. They are not useful for speed estimation because they are superimposed onto the supply voltage and current harmonics. The rotor winding effects produce no detectable speed-related information. This is because they are uniformly distributed on the rotor surface.

Air-gap eccentricity and rotor slots produce spectral components that occur at harmonics of the rotor speed. These spectral components are superimposed on the supply voltage and current. They are detectable because they are inter-harmonics at the rotor frequency. Various signal-processing techniques have been presented to extracting the spectral components from the supply current or voltage. They are used to estimate the motor mechanical speed. The supply current is preferred for detecting space harmonics. This is because in drive-controlled motors the filtering behaviour of the stator windings results in a less noisy current signal as compared to the stator supply voltage. Current sensors are standard in many commercial drives. Methods based on the supply voltage require the installation of an additional voltage sensor [23].

The variation in the air-gap permeance and resultant current harmonics caused by rotor eccentricity and slotting is expressed by (3.1), [24].

$$f_{sh} = f_1 \left( (kR + n_d) \left( \frac{1-s}{P/2} \right) + n_w \right) \quad (3.1)$$

where  $f_{sh}$  is the space harmonic frequency;  $f_1$  the fundamental component of the supply frequency;  $k= 0,1,2..$ ;  $R$  is the number of rotor slots,  $n_d$  is the order of rotor eccentricity;  $s$  is slip;  $P$  is the number of poles and  $n_w$  is the air-gap millimetre harmonic order.

### 3.2.2 Speed estimation using air-gap eccentricity

Manufacturing tolerances, stator ovality, incorrect shaft installation and worn bearings can all result in a non-uniform air gap. This air gap non-uniformity leads to unbalanced magnetic forces when the motor is in operation. This results in air-gap eccentricity harmonics that induce corresponding harmonics in the stator windings [28]. These harmonics have two symmetrical spectral components that are side bands of the fundamental supply frequency. Their position relative to the fundamental supply frequency can be found by substituting  $k=0$ ,  $n_d = \pm 1$  and  $n_w=1$  into (3.1) to the following expressions [24]:

$$f_{ecc1} = f_1 \left( 1 + \left( \frac{1-s}{P/2} \right) \right) \quad (3.2)$$

$$f_{ecc2} = f_1 \left( 1 - \left( \frac{1-s}{P/2} \right) \right) \quad (3.3)$$

where  $f_{ecc1,2}$  are the lower and upper air-gap eccentricity side band frequencies.

Air-gap eccentricity-based speed estimation techniques rely on detecting the frequencies of the eccentricity components in the stator supply current. From (3.2) and (3.3) it can be seen that these frequencies are only dependent on the motor slip. They can also be detected at all motor loading conditions. The rotor frequency can be determined as follows:

$$f_{ecc1,2} = f_1 + f_{sl} \quad (3.4)$$

$$f_{ecc1,2} = f_1 - f_{sl} \quad (3.5)$$

where  $f_{sl}$  is the slip frequency. From (3.4) and (3.5) the slip frequency can be expressed as:

$$f_{sl} = |f_1 - f_{ecc1,2}|. \quad (3.6)$$

The rotor frequency is given by the following expression:

$$f_r = f_1 - f_{sl}. \quad (3.7)$$

The motor mechanical speed can be obtained by converting the frequency to revolutions per minute (RPM).

In order to extract the motor speed from the current signal it necessary to obtain the frequency components of the current signal. This is done by sampling the current signal and computing the Fast Fourier Transform (FFT) of the sampled signal. A peak search algorithm is employed to determine the eccentricity frequency components. It is suggested that the lower side band usually produces a larger amplitude signal in the current spectrum [29].

One of the main drawbacks of speed estimation based on air-gap eccentricity is that it is difficult to detect the eccentricity components. These are very close to the supply fundamental frequency. This results in spectral leakage and ambiguity, leading to inaccurate results [23]. Taking long data samples and using a digital Hamming window can assist in improving the frequency resolution and reduce spectral leakage [24]. Zero padding can also be used to improve the accuracy of peak detection algorithms. Long data samples increase the required processing time for the algorithm. The eccentricity frequency components are not always easily detectable due to their small amplitude.

### 3.2.3 Speed estimation using rotor slot harmonics

As an induction motor rotates, it produces air-gap permeance waves [25]. The spatial distribution of the air-gap permeance is determined by the number of rotor slots. These generated waves modulate the fundamental air-gap magnetomotive force (MMF) to produce two harmonic components of the air-gap flux with frequencies dependent on the rotor frequency. The magnitude of the flux harmonics remains consistent across all motor loading points [26]. This process is depicted in Figure 3.1. The flux harmonics produced owing to the rotor slots can be detected independently of motor operating temperature and stator supply frequency.

The interaction of the air-gap permeance and the fundamental MMF waves produces a resultant air-gap flux, given by [26].

$$B(\theta, t) = B_1 \cos(\omega_0 t - P\theta) + B_{r1} \cos \left[ \left( \frac{Z}{P} \omega_r + \omega_0 \right) t - (P + Z)\theta + \Psi_{r1} \right] + B_{r2} \cos \left[ \left( \frac{Z}{P} \omega_r - \omega_0 \right) t - (P - Z)\theta + \Psi_{r2} \right] \quad (3.8)$$

where  $\theta$  is the mechanical angle,  $t$  is time,  $\omega_0$  is the supply angular frequency,  $Z$  is the number of rotor slots,  $\omega_r$  is the rotor angular velocity, and  $\Psi_{r1}$  and  $\Psi_{r2}$  are phase angles. The above expression is equivalent to two opposing travelling waves in the air gap which induce a current harmonics in the stator. The single-phase induced current can be expressed as:

$$i_a(t) = \sum_{v=0}^2 A_v \cos(\omega_v t - \Psi_t) \quad (3.9)$$

where  $A_v$  is the amplitude,  $\Psi_t$  the phase of the  $v^{\text{th}}$  harmonic component. Expression (3.8) can be simplified to give [25]:

$$\omega_{sh1} = \frac{Z}{P}\omega_r + \omega_0 \quad (3.10)$$

$$\omega_{sh2} = \frac{Z}{P}\omega_r - \omega_0 \quad (3.11)$$

where  $\omega_{sh1,2}$  is the angular frequency of the forward and backward slot harmonics. The above expression is only applicable to a motor fed from a sinusoidal supply.

When the supply is non-sinusoidal, the rotor slot harmonics will interact with supply flux harmonics. The forward and backward angular frequencies of the induced rotor slot harmonics are then given by:

$$\omega_{sh1} = \frac{Z}{P}\omega_r + \alpha\omega_0 \quad (3.12)$$

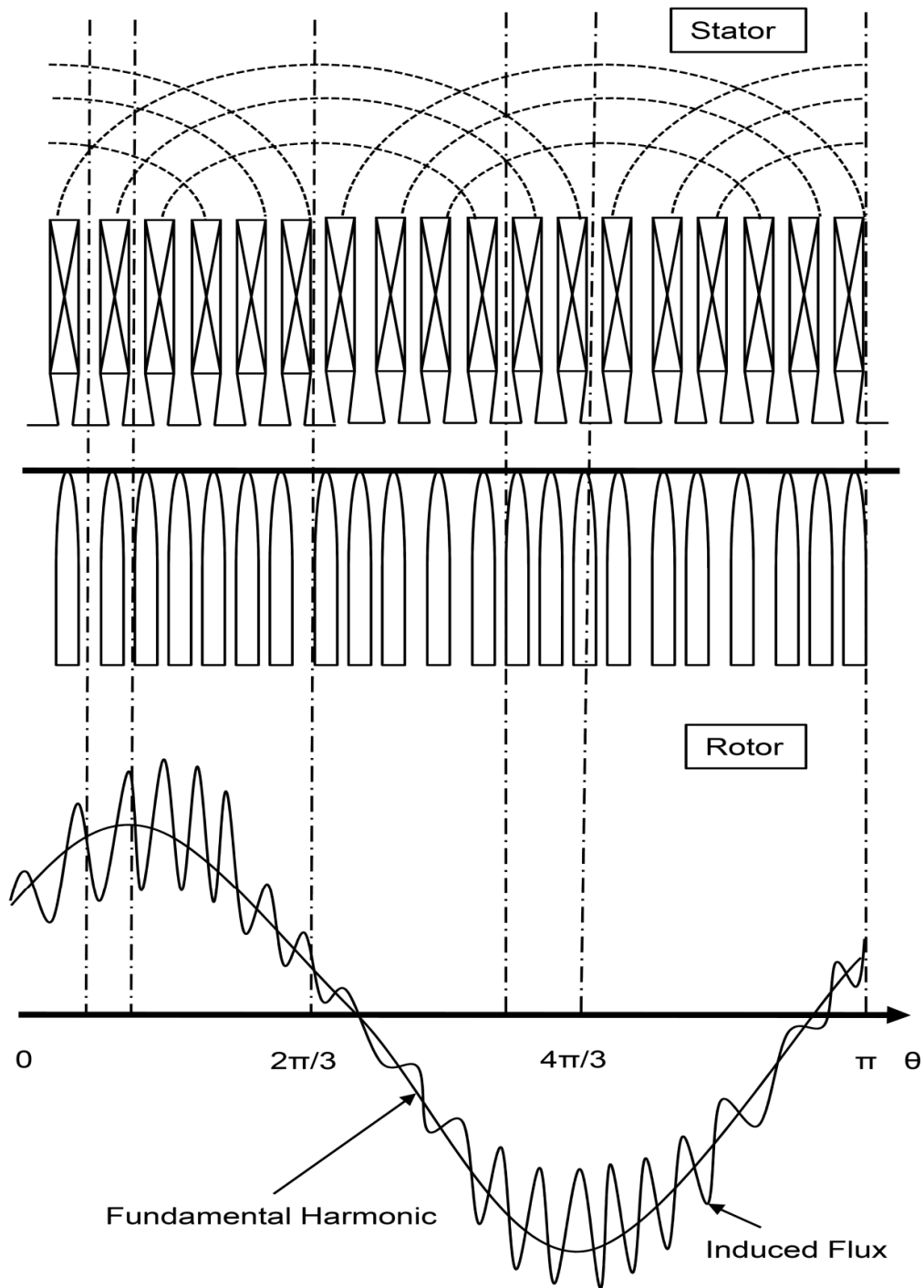
$$\omega_{sh2} = \frac{Z}{P}\omega_r - \alpha\omega_0 \quad (3.13)$$

where  $\alpha$  is the air-gap flux density harmonic. The rotor frequency can then be calculated using (3.14) and (3.15).

$$f_r = \frac{P}{Z}(f_{sh1} + \alpha f_0) \quad (3.14)$$

$$f_r = \frac{P}{Z}(f_{sh2} - \alpha f_0) \quad (3.15)$$

where  $f_{sh1,2}$  are the forward and backward slot harmonic frequencies.



**Figure 3.1.** Air-gap flux modulation caused by rotor slotting [23].

Speed estimation using rotor slot harmonics requires the extraction of frequency components from the stator supply current spectrum. An FFT can be applied to the sampled current signal to obtain the frequency components. From (3.14) and (3.15) it can be seen that the implementation of this method requires the number of rotor slots as an input. The number of rotor slots is usually not known for in-service motors. This presents a challenge in the implementation of speed estimation techniques based on rotor slot harmonics. Numerous search algorithms for identifying these harmonics are presented in literature [26], [23], [25], [27].

The main disadvantage of these techniques is that the search window for the rotor slot harmonics is large. When a large frequency search window is employed, a high sampling frequency is required to capture all the frequency components. This results in a low-frequency resolution from the FFT. Long data samples are required to provide sufficient resolution and resolvability to distinguish the rotor slot harmonics from the supply harmonics and noise. The large data samples result in long processing times.

### 3.2.4 Extracting slot harmonics using the Chirp-Z transform

In [23], it is proposed that the detection of rotor slot harmonics can be improved by using the chirp-Z transform (CZT) instead of the FFT. For drive-controlled motors, the current signal is non-stationary. This results in errors when an FFT is used to obtain the frequency components. One of the disadvantages of speed estimation techniques based on FFT-based rotor slot harmonics is that the large frequency window that is required resulted in a low resolution. The resolution for the CZT is given by:

$$\Delta f_{CZT} = \frac{f_w}{N} \quad (3.16)$$

where  $f_w$  is the frequency window and  $N$  the number of samples taken. This means that with the CZT a shorter observation window and a lower number of samples can be used to

obtain a high resolution. The spectral analysis for the rotor harmonic detection algorithm is performed in a shorter window. This results in higher execution speeds.

### 3.3 OBSERVER-BASED METHODS

The speed estimation methods discussed in this section are used in inferential control philosophies where the motor terminal quantities are measured and used with mathematical models of induction motors. The mathematical models used are known as state observers [30]. Induction motor models commonly used in observer-based techniques are based on the steady state model with either the rotor or stator as the reference. These models have simplifying assumptions. As a result of these assumptions, some of the motor dynamics are not adequately represented in the model [31]. Despite the un-modelled dynamics, some of the techniques available offer good stability and accuracy. Observer-based methods are commonly used to obtain the motor flux and speed for drive applications.

Observer-based methods have gained widespread attention for application with sensor-less field-oriented drives. They offer speed and torque feedback control capability from the terminal voltages and currents without the disadvantages of installing sensors [24]. Several observer-based methods have been presented in literature. They also have shorter processing times as compared to speed estimation based on current or voltage spectral components because they do not require processor-intensive signal-processing algorithms, such as the FFT.

Observer-based speed estimation techniques also have several drawbacks. They are inherently dependent on the motor parameters because they use a mathematical model of the motor. If the motor parameters are unknown, then intrusive tests will have to be performed to determine the required motor parameters. Motor parameters also vary with temperature and flux saturation [23]. The introduction of the stator current estimation error feedback improves the sensitivity of observer-based methods to parameters variation as

compared to open loop methods [32]. This is an added disadvantage of these methods. An observability analysis shows that the induction motor based on current models becomes unobservable when the stator voltage supply frequency approaches zero. This makes the observer-based methods unreliable when the motor operates with a low supply frequency [33].

A few different types of observer-based methods are discussed below.

### 3.3.1 Model reference adaptive system

Model reference adaptive system (MRAS) observer-based methods have been introduced to make the speed estimation more robust to motor operating point changes and parameter variations [34]. In this approach the motor is used as the reference model while the observer is made adaptive. An adaptive observer makes adjustments to correct for any variations that may be introduced through disturbances or process variations. Lyapunov stability analysis is done for the flux observer in order to derive the speed adaptation mechanism [35].

Speed-estimation techniques based on MRAS have been found to produce accurate results [33]. In order to maintain stability, the error between the estimated and measured terminal quantities is used in the feedback loop. This also results in improved accuracy. The estimation error is also fed to the speed estimation loop, which is part of the adaptation loop. A lagging estimate is fed back to the observer. This results in poor flux estimations at low stator supply voltage frequencies [35].

MRAS observer-based speed-estimation methods have the disadvantage of poor performance during torque and speed transients. The MRAS algorithm uses an integrator, which may result in the introduction of initial value and drift errors [33].



### 3.3.2 Luenberger Observer

In the Luenberger observer method, the errors between estimated and measured output variables are calculated. The error vector obtained is used to correct the estimated state variables [36]. When designing conventional Luenberger observers, the gain is calculated to ensure that the poles of the induction motor are proportional to those of the observer. The pole placement for the observer influences the accuracy and stability of the method. Good pole placement ensures that accurate flux estimates are obtained while maintaining good transient response across the entire operating speed range of the machine [37].

Placing the observer poles proportional to the motor poles can create instability in the control algorithm at high operating speeds. This is due to the large imaginary part of poles. Another drawback of Luenberger observers is that the gain contains speed-dependent terms which can have an adverse impact on accuracy [32].

### 3.3.3 Kalman filtering techniques

A source of errors in observer-based estimation techniques is their sensitivity to modelling errors and measurement noise. Kalman filters are designed to improve on these weaknesses through having high tolerance to noise and modelling limitations [33]. Traditional Kalman filters use complex computation. This makes their real-time application difficult [38]. Tuning of the filters' covariance matrices also adds another level of complexity. This makes the technique impractical for on-line speed estimation.

The extended Kalman filter (EKF) reduces the order of the traditional Kalman filter and simplifies the computational effort required to implement the technique [38], [33], [39]. The EKF can be implemented on microprocessors and used in real-time applications. Although the tuning of the EKF is simpler than that of the Kalman filter, it is still a challenge for on-line speed estimation. The order reduction has the disadvantage of

reducing the filter's robustness to parameter variations. It has been found that the speed estimation error increases with variations in the load torque and motor operating temperature [40]. The accuracy of the EKF at low frequencies is also poor in comparison to other state observer-based methods.

### 3.4 ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANN) are increasingly used in the control of motor drives [41]. They have a growing appeal because they have the ability to learn and continuously improve their performance. Neural networks offer several advantages over traditional tools. They have faster parallel computation when compared to conventional sequential computers. The distributed intelligence structure of ANN makes them more robust to input signal variations and increases their fault tolerance [42]. ANNs also have good noise immunity.

The application of ANN to rotor speed estimation is described in [43]. ANNs have been found to give accurate speed estimates across the entire operating speed range of an induction motor [44]. It must be noted though that the ANN-based estimator must be adequately trained with various patterns to obtain good performance. Simulated data based on a motor model are normally used for the off-line training of ANNs before use. This can result in poor performance when the motor operates in regions outside those used for training the algorithm [45]. The above-mentioned limitations with some ANN-based speed estimation techniques make them undesirable for use with in-service.

It has been proposed that another on-line speed estimation technique, such as rotor slot harmonics, can be used for on-line training of ANNs [45]. A two-layer back propagation neural network speed estimation method which does not require off-line training is proposed in [41]. A different on-line training ANN-based method is presented in [44].



### 3.5 CHAPTER SUMMARY

A comprehensive survey of speed estimation techniques has been presented. The strengths and weaknesses of the available estimation techniques were analysed. Methods based on space harmonics were found to be able to estimate the speed accurately in a non-invasive manner. They however have several weaknesses:

- it is difficult to detect the air-gap eccentricity components because they are very close to the supply fundamental frequency; and
- the frequency search window for the rotor slot harmonics is large, so a high sampling frequency is required to detect them.

Observer-based methods provide good speed estimation without requiring the installation of additional equipment. These methods are highly dependent on motor parameters, and these may vary due to changes in the motor's operating environment. Artificial neural networks provide an attractive alternative for estimating motor speed. They also have the disadvantage of requiring off-line training to produce accurate estimates.

## CHAPTER 4

# MOTOR SPEED ESTIMATION USING VIBRATION SIGNATURE ANALYSIS

### 4.1 INTRODUCTION

All rotating equipment produce some level of vibration, Electric motors are no exception. Vibration in electric motors occurs from the combination of mechanical and magnetic forces acting on the machine structure and the mounting of the motor [46]. The mechanical forces are produced as a result of unbalance in the rotating assembly. The rotating assembly consists of the rotor, shaft and bearings. The out-of-balance rotor forces have the same frequency as the rotor frequency. Although motor manufacturers attempt to design and manufacture motors with minimal vibration, the rotating assembly will always contain residual unbalance. This results in a vibration [47]. Magnetic forces are produced from the flux in the air gap. The air-gap flux also contains harmonics of the fundamental magnetic flux. The magnetic forces act radially on both the stator and rotor. These forces are known as Maxwell's forces [48]. The magnitude of motor vibration at any point is determined by the magnitude of the force and the mechanical response of the motor structure and mounting.

Motor vibration has been widely studied in the area of motor condition monitoring [49]. Various types of motor faults can be detected from the vibration signature of a motor. The faults occur at harmonics of the motor rotor frequency. The vibration signal of a motor contains a large amplitude component at rotor rotating frequency [29]. It is found to be prominent across all loading points.

A novel speed estimation technique based on motor vibration analysis is presented in this chapter. The chapter begins with a theoretical analysis of the proposed speed estimation

technique. Next, the vibration-based speed estimation technique is implemented using a National Instruments (NI) universal serial bus (USB) data acquisition (DAQ) device and custom LabVIEW software. Three different-sized induction motors are used for the tests. The experimental results are presented and analysed in the last section of the chapter.

## 4.2 SPEED ESTIMATION USING VIBRATION SIGNATURE ANALYSIS

The rotor speed can be determined by analysing the frequency components of the motor vibration signal. This is achieved by applying an FFT to the sampled motor vibration signal. The motor vibration signal is obtained from an accelerometer that is mounted on the motor. The amplitude of the rotor is the largest frequency component in the region of interest. The frequency of this signal is used to determine the rotor speed.

The rotor frequency can be obtained by using a peak detection algorithm. The search area is narrowed by selecting a boundary that corresponds to the minimum and maximum expected frequency. This is derived from the motor's nameplate-rated speed. The motor's rated speed is used to obtain the minimum rotor frequency, (4.1). The synchronous speed is used to obtain the maximum frequency, (4.2).

$$f_r^{min} = \frac{n_r}{60} \quad (4.1)$$

where  $f_r^{min}$  is the low frequency boundary and  $n_r$  is the motor's rotor speed in rpm;

$$f_r^{max} = \frac{2f_s}{P} \quad (4.2)$$

where  $f_r^{max}$  is the upper frequency boundary and  $P$  is the number of poles. The peak search is then limited to the frequency range expressed in (4.3). The minimum and maximum boundaries of the search window can be increased by 5% to account for speed

variation that can occur as a result of supply voltage variation. This also accounts for motors that are operated in overload conditions, resulting in a drop in the operation speed.

$$f_r^{min} \leq f_r \leq f_r^{max} \quad (4.3)$$

When selecting the sampling frequency and the number of samples for the FFT, (4.4) should be taken into consideration [50].

$$\Delta f = \frac{f_s}{N_{fft}} \quad (4.4)$$

where  $\Delta f$  is the frequency resolution,  $f_s$  is the sampling frequency and  $N_{fft}$  is the number of samples used in the FFT. It can be seen from (4.4) that the resolution of the vibration frequency component of the rotor speed obtained from the FFT can be improved by taking longer data lengths for a given sampling frequency.

The rotor speed in rpm can be calculated from the rotor frequency by using the time conversion factor expressed in (4.5).

$$\eta_r = 60 \times f_r \quad (4.5)$$

where  $\eta_r$  is the motor's rotor speed in rpm and  $f_r$  is the rotor frequency in Hz. A flowchart of the speed estimation technique is shown in Figure 4.1.

The method can be modified for use with motors fed by variable frequency drives. The frequency range for detection can be determined dynamically by measuring the supply voltage at the motor terminals. The supply voltage frequency is the stator frequency in (4.2) to determine the upper boundary of the expected speed. From the motor nameplate ratings, the rated slip can be calculated as:

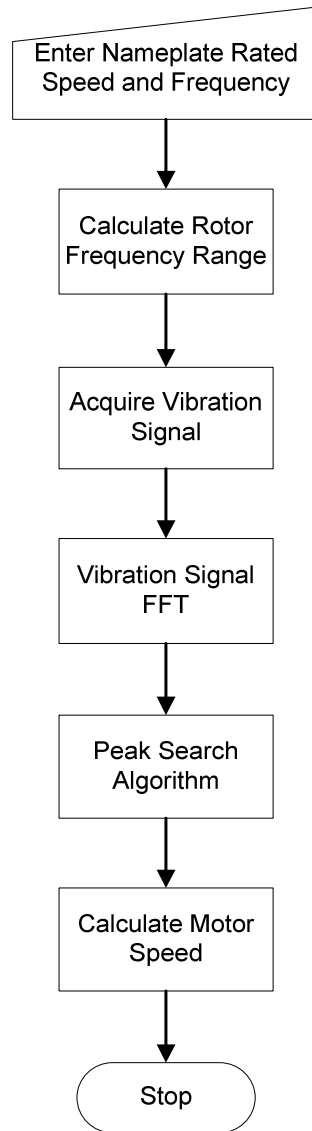


$$n_s = \frac{120f_s}{P} \quad (4.6)$$

$$s = \frac{n_s - n_r}{n_s} \quad (4.7)$$

where  $n_s$  is the synchronous speed of the stator magnetic field. The minimum frequency for the search window is the given by (4.8).

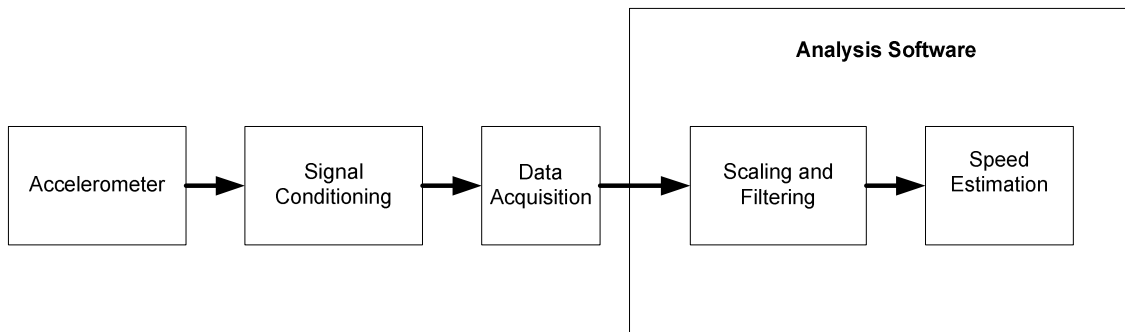
$$f_r^{min} = f_r^{max}(1 - s) \quad (4.8)$$



**Figure 4.1.** Vibration signature motor speed estimation technique flowchart.

### 4.3 EXPERIMENTAL SETUP

The experimental setup that was used for the speed estimation tests consisted of three test motors, a DAQ device, an accelerometer, a DC generator and a computer. The three test motors were 3 kW, 11 kW and 15 kW squirrel cage induction motors. All the test motors were 380 V, 4 pole and 50 Hz machines. An NI USB 6251 Bayonet Neill-Concelman connector DAQ device was used to sample the vibration signal. The motors were loaded using the DC generator. A block diagram of the experimental setup is shown in Figure 4.2.



**Figure 4.2.** Experimental setup block diagram.

A signal-conditioning circuit was used to supply the accelerometer with a 20 mA excitation current. A magnetically mounted ICP accelerometer with a sensitivity of 100 mV/-G was used to measure the motor vibration. Software was developed in LabVIEW for the signal analysis. The vibration signal was sampled at 100 kHz for 10 s and a second test was done at each loading point using a 20 s data sample to improve the frequency resolution. Using (4.5) and substituting the sampling frequency and number of samples, the frequency resolution for the tests can be calculated as follows:

$$\Delta f_1 = \frac{f_s}{N_{fft}} = \frac{100000}{1000000} = 0.1 \text{ Hz.}$$

The 20 s data sample is calculated to provide a frequency resolution of 0.05 Hz. The frequency resolution can be improved by reducing the sampling frequency. It can be shown that the selected sampling frequencies and data lengths will produce a maximum error of 6 rpm at no load. This error is within the transducer's tolerance. A rotary encoder with an edge counter was used to determine the motor speed, which is used for comparison.

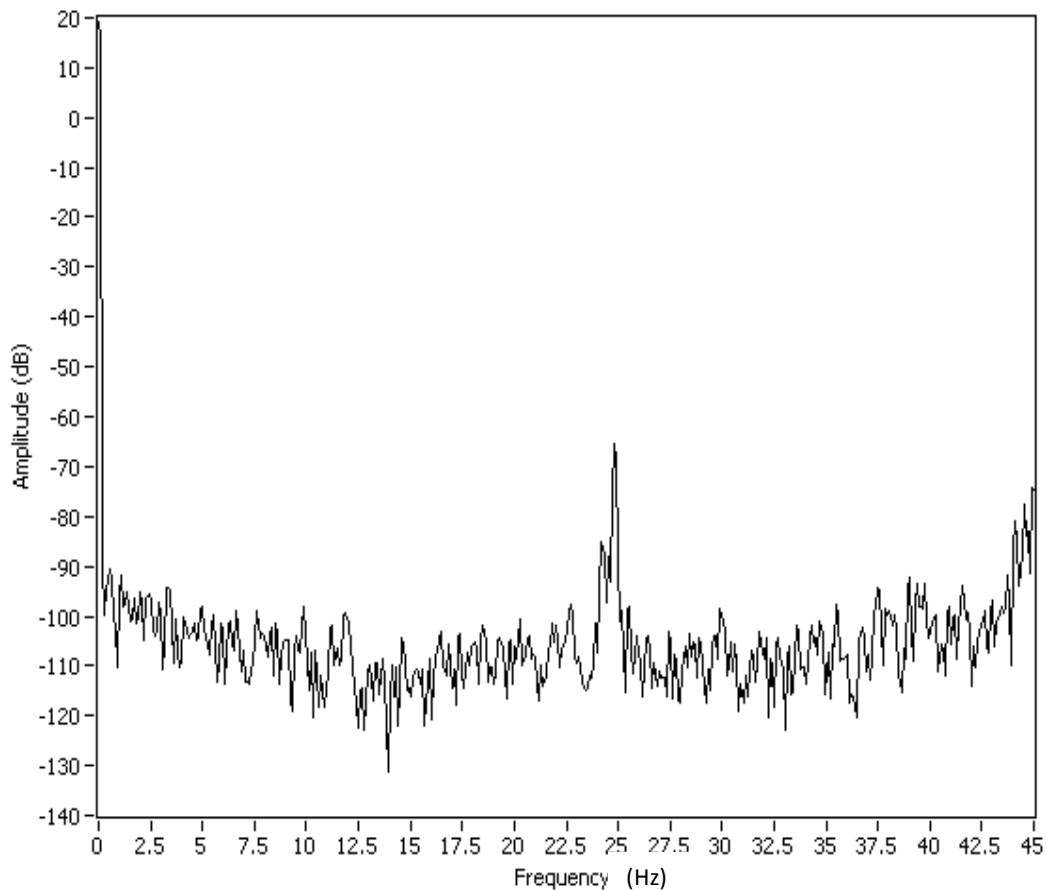
#### 4.4 EXPERIMENTAL RESULTS AND ANALYSIS

The vibration signal of the motor was measured at no load and full load for the three test motors. Analysis of the frequency components contained in the vibration signal shows that there is a high amplitude component at the rotor frequency. This can be seen in Figures 4.3 and 4.4 where there is a shift in the position of the peak from no load to full load.

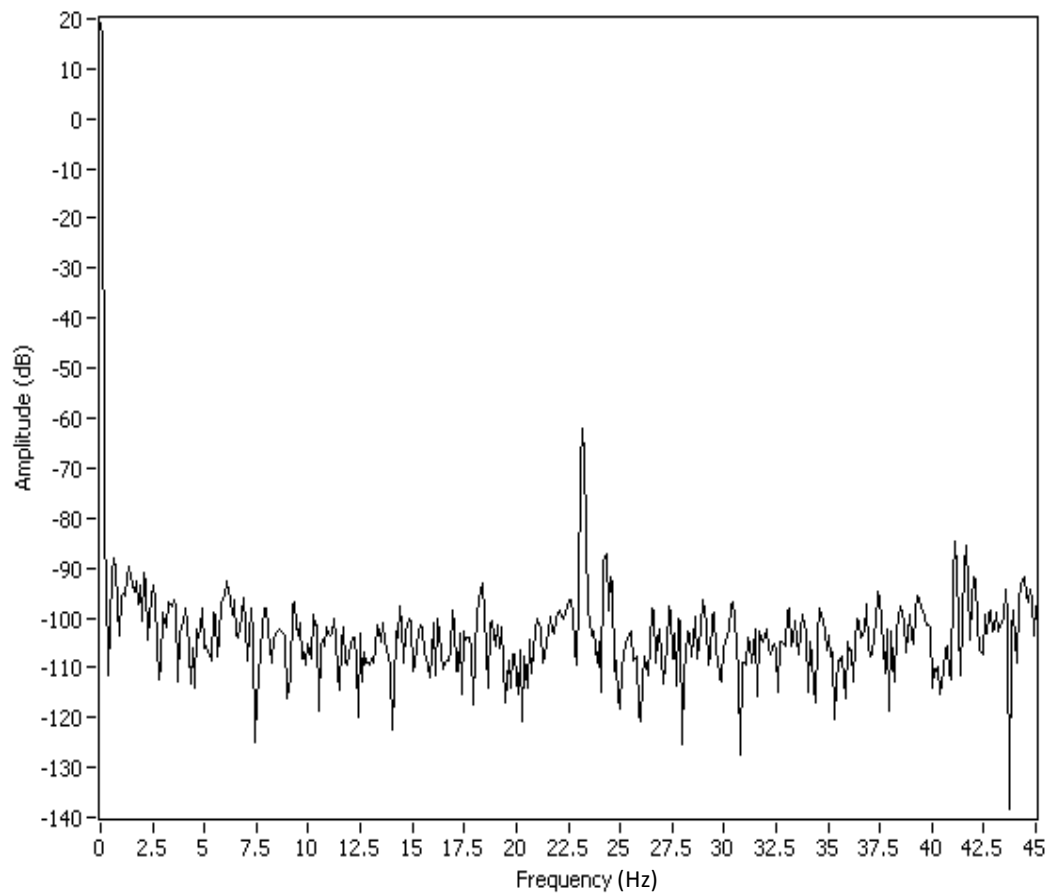
A comparison of the speed estimates and measured speed for the three test motors is shown in Table 4.1. The motor speed was measured using a rotary encoder for comparison. The experiments were repeated three times at each loading point. The results were found to be consistent. The accuracy of the speed estimate can be improved by increasing the frequency resolution of the vibration signal through a reduced the sampling rate or taking longer data samples.

The vibration signature analysis technique for estimating the mechanical speed of a motor is preferred to the methods presented in Chapter 3. This is because of its high accuracy and ease of implementation. The vibration component at the rotor frequency has high amplitude across all motor loading conditions. It is not influenced by the motor supply conditions. This signal can be detected in both new motors and used motors. The rotor frequency signal of interest is not located close to any other signal. Errors due to spectral leakage are not introduced. The signal will always be lower than the stator supply frequency. This means that low sampling frequencies are required. A low sampling frequency can produce a high resolution without taking long data samples. This results in a

fast computation time as compared to other FFT-based techniques. A further advantage of using low sampling frequencies is that relatively cheap analogue-to-digital conversion circuitry can be used. The motor vibration signature is not parameter-dependent, unlike observer-based methods. As long as the motor is rotating, the signal will exist under all supply conditions since it results from the mechanical unbalance in the rotating assembly. The method has the drawback of requiring an accelerometer. This increases the initial cost of the method. The benefits achieved outweigh this shortcoming.



**Figure 4.3.** FFT of the no-load motor vibration signal-11 kW motor.



**Figure 4.3.** FFT of the full-load motor vibration signal-11 kW motor.

**Table 4.1.** Motor Speed Estimation Results

<b>15 kW Motor</b>			
<b>No load</b>			
<b>Frequency (Hz)</b>	<b>Speed Estimate (rpm)</b>	<b>Measured Speed (rpm)</b>	<b>Error (%)</b>
25.01	1500.6	1502.3	0.11
<b>Full Load</b>			
24.37	1462.0	1454	0.55
<b>11 kW Motor</b>			
<b>No load</b>			
24.95	1497.0	1498	0.07
<b>Full load</b>			
24.41	1464.4	1463	0.09
<b>3 kW Motor</b>			
<b>No load</b>			
24.82	1489.1	1491	0.13
<b>Full load</b>			
23.20	1392.2	1396	0.27
<b>Average</b>			0.20

#### 4.5 CHAPTER SUMMARY

A new method for estimating the speed of an induction motor based on vibration signature analysis was introduced. The experimental results obtained from implementing the technique show that it produces highly accurate speed estimates. The method is truly non-intrusive. This makes it suitable for online use without disrupting the motor-driven process.

## CHAPTER 5

# A NEW NON-INTRUSIVE MOTOR EFFICIENCY ESTIMATION TECHNIQUE

### 5.1 INTRODUCTION

A review of motor efficiency estimation techniques was presented in Chapter 2. A trade-off exists between the level of invasiveness of the method and the accuracy of the efficiency estimate. The methods that were used to prove the accuracy of some of the techniques have limitations in certain areas. Most of the efficiency estimation methods require intrusive tests to be carried out on the motor. This is expensive and impractical to implement in the field. The success of an efficiency estimation technique for an in-service motor depends on the accuracy, cost, ease of implementation and level of intrusion.

A non-intrusive method of accurately estimating the motor speed is presented in this chapter. This method is based on the compensated slip method. In this method the motor terminal voltage and the motor speed is measured. The motor speed is estimated using the motor vibration signature. The vibration signal of the motor contains a component at the frequency of the rotor mechanical speed. The speed is obtained from the vibration signal using the technique that was developed in Chapter 4.

The chapter begins with the practical implementation of six of the motor efficiency estimation techniques that were discussed in Chapter 2. The performance of these methods is evaluated against the measured efficiency of the motor under test. An analysis of the results is then presented.

An experimental setup was developed to test the proposed techniques. Three test motors were used in the evaluation of the techniques. The efficiency of each test motor was measured. The results that were obtained were compared with the new method.

## 5.2 PRACTICAL EVALUATION OF EFFICIENCY ESTIMATION TECHNIQUES

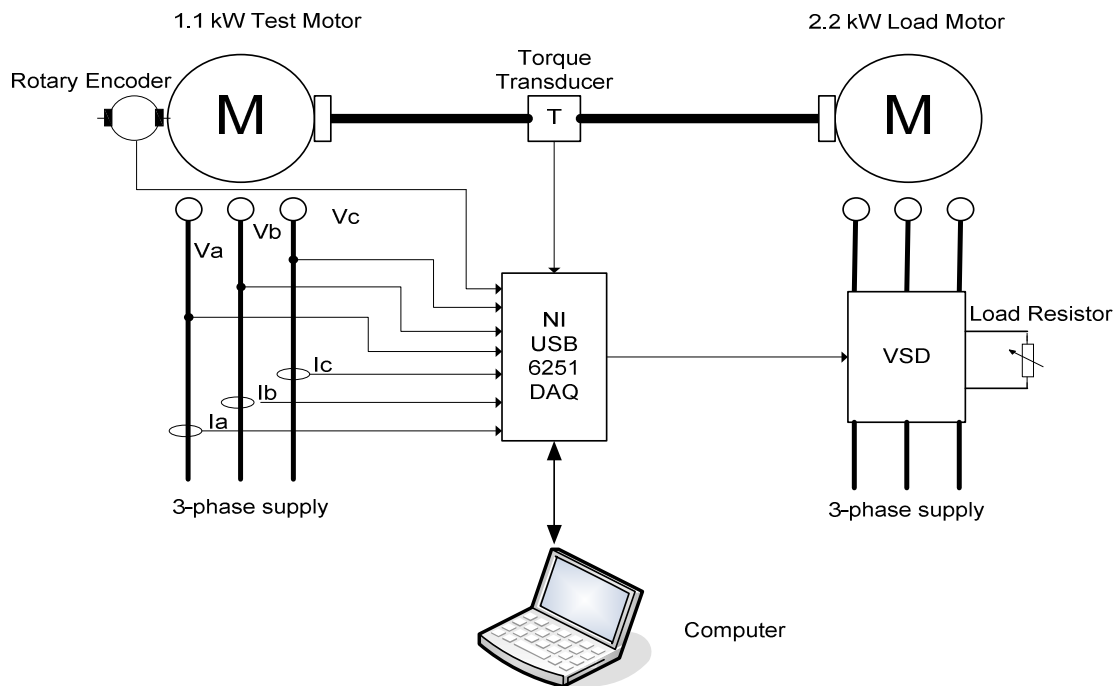
### 5.2.1 Experimental setup

An experimental setup was developed to test the performance of selected motor efficiency estimation techniques. Figure 5.1 shows a block diagram illustrating how the methods were implemented. A torque transducer and tachometer were used to measure the shaft torque and rotational speed. Current and voltage probes were used to measure the input current and voltage in each phase. The signals were sampled at 20 kHz each using an NI USB 6251 DAQ device. All of the selected methods were implemented in software using LabVIEW. A test setup was developed that can continuously calculate the efficiency of the test motor using all the estimation methods concurrently under varied load and supply conditions. At the end of each test a report is generated that plots the efficiency curves obtained from each estimation technique.

A 1.1 kW, 2 pole, 380 V, 50 Hz standard efficiency induction motor was used for the experiments. The motor parameters are shown in Table 5.1. The motor was loaded at different points ranging from no load to full load. The actual output power was calculated using the shaft torque and motor rotational speed from the torque transducer and tachometer. Equation (5.1) was used to calculate motor output power [49].

$$P_{output} = T_{shaft} \cdot \omega_r \quad (5.1)$$

where  $T_{shaft}$  is the shaft torque and  $\omega_r$  is the rotor speed. The calculated output power was used in (5.1) to determine the efficiency of the motor at each operating point. The resultant efficiency curve was used to benchmark the performance of the motor efficiency estimation techniques.



**Figure 5.1.** Block diagram of experimental setup.

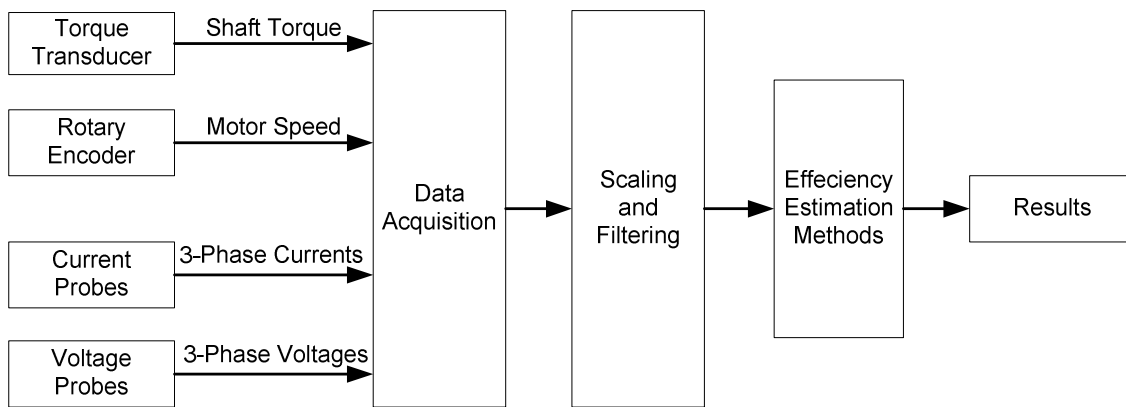
To load the test motor, the load motor drive is set to a supply frequency such that the synchronous frequency is slower than the rotor frequency. The slip speed is therefore negative. It results in reverse MMFs being generated in the air gap. This results in torque being generated in the direction opposite to the rotor rotation; a braking torque is generated at the motor shaft [51]. The load induction motor is operated in regeneration mode. In this operating mode, negative electromotive forces are induced in the stator phases. They have

the effect of reducing the voltage at the inverter input. The generated power is dissipated across a resistor to maintain stability in the operation of variable speed drive (VSD).

**Table 5.1.** Test motor data.

Motor Parameters	Test motor	Load Motor
Rated output power (Watts)	1100	2200
Phase	3-phase	3-phase
Rated voltage (Volts)	220/ 380	220/ 380
Rated current (A)	4.34/ 2.51	7.6/ 4.4
Rated speed (rpm)	2745	2845
Rated frequency (Hertz)	50	50
Rated slip	0.085	0.052
IEC design	N	N

In Figure 5.2 a functional block diagram of the implementation of the motor efficiency estimation techniques is shown.



**Figure 5.2.** Experimental setup functional block diagram.

### 5.2.1.1 Equivalent Circuit Methods

The equivalent circuit for the test motor was determined the blocked-rotor and a no-load test [50]. Circuit analysis equations for calculating the output power were used to determine the output power at each loading point. The test motor used for the experiments does not have terminals for accessing the stator windings for winding temperature measurements. The IEEE standard test procedure for induction motors stipulates that resistance measurements should be corrected to an ambient temperature of 25 °C [15]. This is done in order to account for the variation in resistance due to changes in operating temperature. The equivalent circuit parameters that were used in the application of this method are shown in Table 5.2.

**Table 5.2.** Test motor equivalent circuit parameters.

Motor parameter	Value
Stator resistance ( $R_1$ )	6.059 $\Omega$
Rotor resistance ( $R_2$ )	6.65 $\Omega$
Stator reactance ( $X_1$ )	10.018 $\Omega$
Rotor reactance ( $X_2$ )	10.018 $\Omega$
Core resistance ( $R_c$ )	4441.08 $\Omega$
Magnetising reactance ( $X_m$ )	113.38 $\Omega$
No-load current	1.44 A

### 5.2.1.2 Slip Methods

The slip method and the Ontario Hydro's compensated slip method were implemented using (5.2) and (5.3). The slip was calculated using the measured motor speed and the measured synchronous frequency.

$$\eta = \frac{Slip}{Slip_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \quad (5.2)$$

$$\eta = \frac{Slip}{Slip_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \cdot \left( \frac{V}{V_{rated}} \right)^2 \quad (5.3)$$

where  $\eta$  is the estimated motor efficiency,  $V$  is the input voltage and  $V_{rated}$  is the motor's rated input voltage.

### 5.2.1.3 Current Methods

The standard current method as expressed in (5.4) was implemented. Both of the improved current methods were also implemented using (5.5) and (5.6). The no-load current used is obtained from the motor's datasheet.

$$\eta = \frac{I}{I_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \quad (5.4)$$

where  $I$  is the measured input current and  $I_{rated}$  the motor's rated current. The above equation results in an output power estimate that is higher than the actual load. It is proposed [21] that this can be corrected by using (5.5). This factors in the no-load current. This method is referred to as the improved current method 1 in the presentation and analysis of the experimental results.

$$\eta = \left( \frac{I - I_{no\ load}}{I_{rated} - I_{no\ load}} + \frac{I}{I_{rated}} \right) \left( \frac{P_{output,rated}}{2P_{input}} \right) \quad (5.5)$$

An alternative current method that improves accuracy by factoring in the no-load current of the motor to give (5.6) for the efficiency can be used [19]. This method is referred to as the improved current method 2 in the presentation and analysis of the experimental results.

$$\eta = \frac{2I - I_{no\ load}}{2I_{rated} - I_{no\ load}} \cdot \frac{P_{output,rated}}{P_{input}} \quad (5.6)$$

A flowchart of the test software is shown in Figure 5.3. In order to limit the inrush current of the test motor during the starting transient, the load motor is first started and set to run at the rated speed of the test motor. Once the load motor has reached the required operating speed, the test motor is started. The test motor starts at a simulated no-load condition. The test motor is loaded at each point and allowed to stabilise. Once the motor has stabilised, measurements are obtained from the transducers. The different efficiency estimation algorithms are applied to the same data set. This allows for accurate comparison of the different techniques under exactly the same conditions. The results are saved to file and then displayed on the user interface. The loading point is varied from no load to full load.

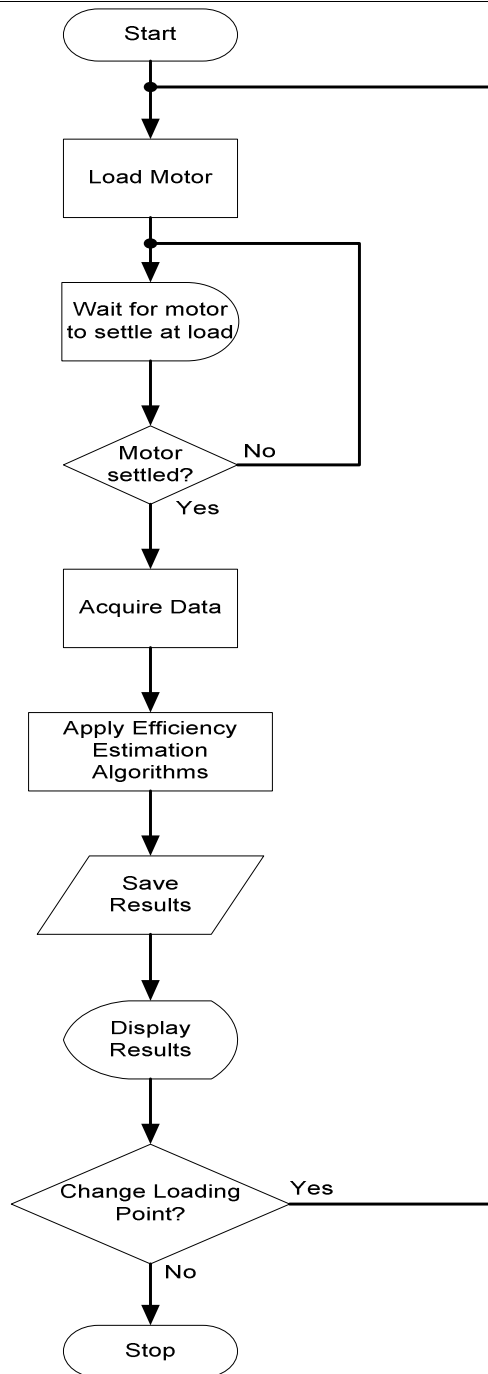


Figure 5.3. Flowchart of the test software.

### 5.2.2 Experimental Results

In this section the results that were obtained are presented. Figure 5.4 shows a plot of the efficiency curves that were obtained after implementing the motor efficiency estimation techniques.

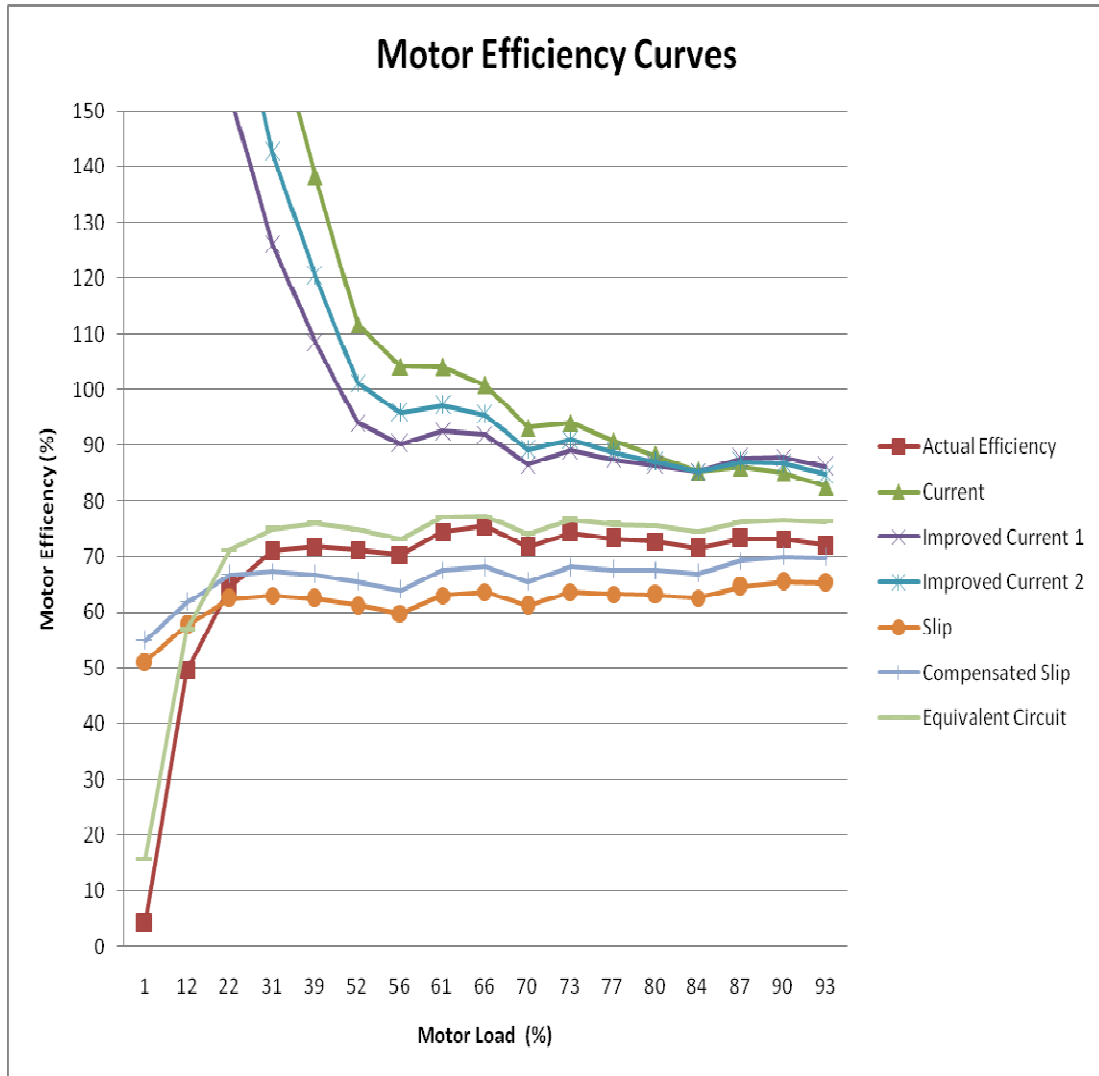


Figure 5.4. Motor efficiency curves.

**Table 5.3.** Percentage error in efficiency estimation techniques

<b>Motor Load</b>	<b>Equivalent Circuit Method</b>	<b>Slip Method</b>	<b>Compensated Slip Method</b>	<b>Current Method</b>	<b>Improved Current Method 1</b>	<b>Improved Current Method 2</b>
0.77%	283.24%	1140.25%	1231.03%	15443.99%	10505.49%	12491.92%
11.54%	14.65%	16.34%	24.51%	508.48%	322.40%	397.24%
21.69%	10.11%	3.44%	3.32%	228.53%	136.47%	173.50%
39.41%	5.62%	13.02%	7.07%	92.55%	50.95%	67.69%
51.65%	5.08%	14.02%	8.13%	56.83%	31.99%	41.98%
56.40%	3.99%	14.93%	9.01%	48.08%	28.34%	36.28%
61.37%	3.41%	15.29%	9.22%	39.84%	24.27%	30.53%
73.22%	3.28%	14.35%	8.28%	26.59%	19.84%	22.55%
93.21%	5.89%	9.42%	3.05%	14.70%	19.69%	17.68%
Minimum	2.33%	3.44%	3.05%	14.70%	18.85%	17.68%
Average above 50%	3.97%	13.33%	7.24%	28.99%	21.97%	24.79%
Average above 75%	4.37%	11.81%	5.62%	18.84%	19.49%	19.23%

Table 5.3 above shows the percentage error for each of the tested motor efficiency estimation methods. The average error for each method was calculated for loading points above 50% and 75% of the rated load. The minimum error for each method is also shown in Table 5.3.

### 5.2.3 Discussion

The actual efficiency curve that was obtained from the tests is consistent the standard efficiency of an induction motor of this size. From Figure 5.4 it can be seen that the current methods produce estimates that are higher than the actual motor efficiency. This is because they provide load estimates that are higher than the actual load. The slip methods have efficiency estimates that are lower than the actual efficiency. The current methods were very inaccurate for loading points below 50% of the motor's rated load. The slip, compensated slip and equivalent circuit methods follow the actual efficiency curve across the full operating range of the test motor. The techniques showed improved performance as the loading point approached the motor's rated output power. The method with the best results was the equivalent circuit method. This was followed by the compensated slip method. The best estimate from the equivalent circuit method was within 2.33% of the actual efficiency. This was within 3.44% for the compensated slip method. The average accuracy for the equivalent circuit method for motor operating points above 50% of the rated load was found to be within 3.97% of the actual efficiency. The compensated slip method was the most accurate when the motor was operating at loading points above 75% of rated load. An average accuracy of within 5.62% was obtained.

The current methods were the easiest to implement for on-line motor efficiency estimation. They demonstrated their highest accuracy for operating points above 75% of rated load. Their average accuracy was within 20% of the actual efficiency. This indicates that they are not useful in determining the potential energy savings that can be obtained by replacing an installed motor with a high-efficiency motor. The compensated slip method showed good results. It has the disadvantage of requiring speed measurements that might be intrusive. The most accurate method was the equivalent circuit method. This method is found to be very intrusive.

### **5.3 A NEW NON-INTRUSIVE SPEED ESTIMATION TECHNIQUE**

A new non-intrusive speed estimation technique is developed in this section. The method is implemented in an experimental setup.

#### **5.3.1 Speed estimation technique**

An accurate speed estimation technique based on motor vibration signature analysis is applied in the developed motor efficiency estimation techniques. The rotor speed is determined by analysing the frequency components of the motor vibration signal. This is achieved by applying an FFT to extract the frequency components of the sampled motor vibration signal. The rotor frequency is then obtained by using a peak detection algorithm and narrowing the search area by selecting a boundary that corresponds to the minimum and maximum expected rotor frequency. The boundary is derived from the motor's nameplate-rated speed. This technique is discussed in detail in section 4.2 of the previous chapter.

#### **5.3.2 Motor efficiency estimation technique**

The novelty of this method for motor efficiency estimation lies in a non-invasive speed estimation technique being used. The speed estimation technique is used together with the Ontario Hydro compensated slip method. This allows for a non-intrusive efficiency estimation technique that can be applied to test motors while they are in service. The motor-driven process is not interrupted because a magnetically mounted accelerometer and clamp-on current and voltage transducers are required to implement the method. The speed estimation technique can be adjusted for implementation with motors driven by VSDs.

A flowchart of the implementation of the non-intrusive motor efficiency estimation technique is shown in Figure 5.5. The technique starts with the user/operator entering the

required nameplate data. In order to implement the method, the rated speed, supply frequency, rated output power and supply voltage is required. The nameplate data are used to calculate the upper and lower frequency boundary for the peak search. The three-phase stator currents, three-phase stator voltages and radial vibration signal are obtained from the transducers. Three-phase current and voltage measurements are preferred. This allows for accurate computation of the input power even under unbalanced supply conditions. It should however be noted that single-phase measurements of the current and voltage can also be used. In this case the assumption of a balanced supply is made. The input power is calculated using the measured input currents and voltages. An FFT of the vibration signal is calculated to obtain the frequency components. A peak search algorithm is performed in the calculated frequency window. The frequency of the determined peak is the rotor frequency. The motor mechanical speed is detected from the rotor frequency. An FFT of one phase of the stator voltages is calculated to obtain the fundamental frequency of the supply voltage. The synchronous frequency of the air-gap field is calculated using the fundamental supply frequency. An accurate calculation of the motor slip at the specific operating point is obtained. The motor efficiency is estimated using (5.3).

A practical implementation of the motor efficiency estimation technique is presented in the next section.

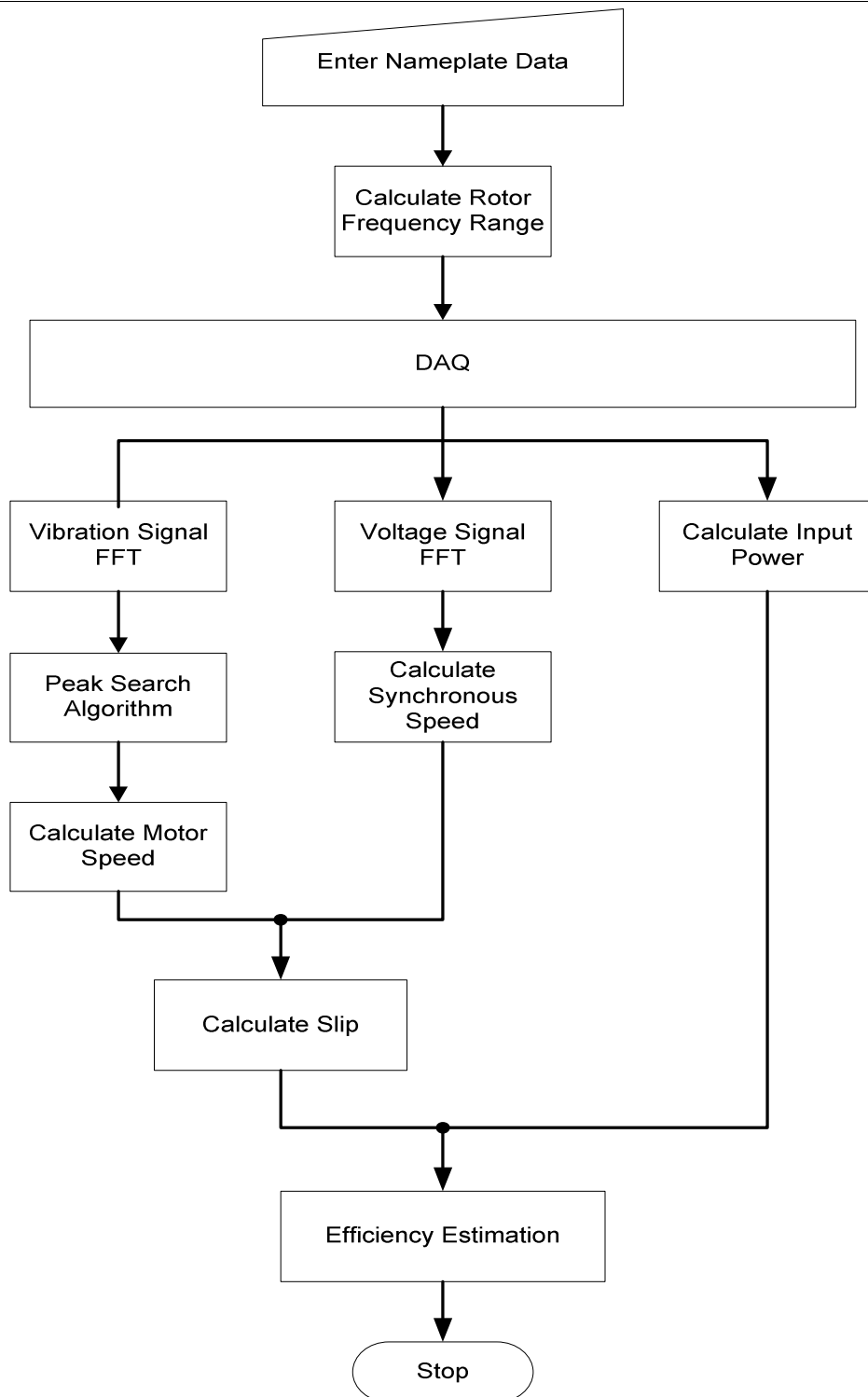


Figure 5.5. Flowchart of motor efficiency estimation technique

### 5.3.3 Experimental setup

In this section the experimental setup developed for evaluating the performance of the non-intrusive motor efficiency estimation technique is presented. Figure 5.6 shows the block diagram of the experimental setup. In this setup, a shaft-mounted torque transducer and rotary encoder were used to measure the shaft torque and rotational speed. The input current and voltage in each phase were measured using current and voltage probes. A magnetically mounted accelerometer is used to measure the vibration on the motor under test. The signals were sampled using an NI USB 6251 DAQ device connected to a laptop computer. Custom software was written in LabVIEW to implement the motor efficiency estimation techniques.

The test motors are loaded using a DC generator. A three-phase controlled inverter is used to convert the generated power to AC and feed it back into the supply grid. The load torque for the induction motor under test is varied by using a current controller to adjust the armature current set point of the DC generator. The controller also synchronises the generators' output power to the grid frequency and phase.

Three induction motors were used to evaluate the performance of the non-intrusive compensated slip motor efficiency technique. All the motors were three-phase, 50 Hz rated frequency and 380 V input voltage. The datasheet parameters for the test motors are summarised in Table 5.4.

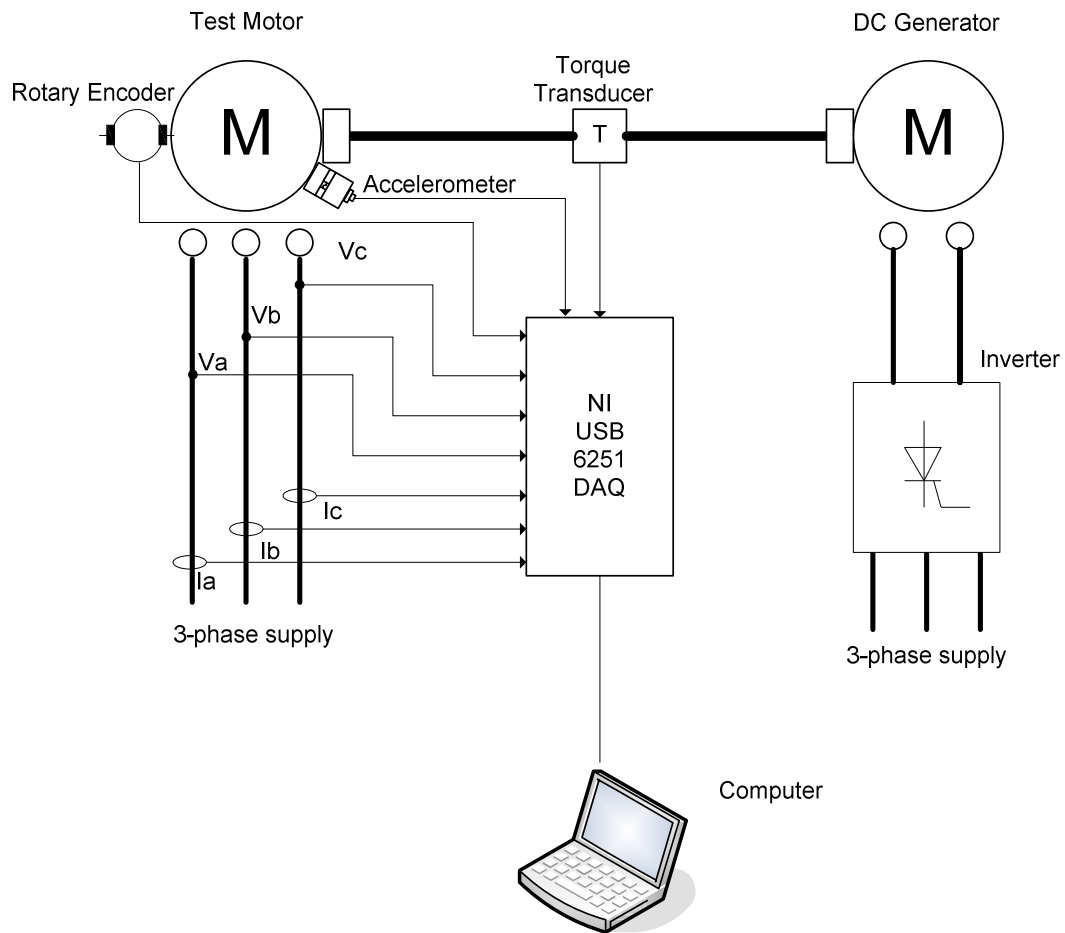
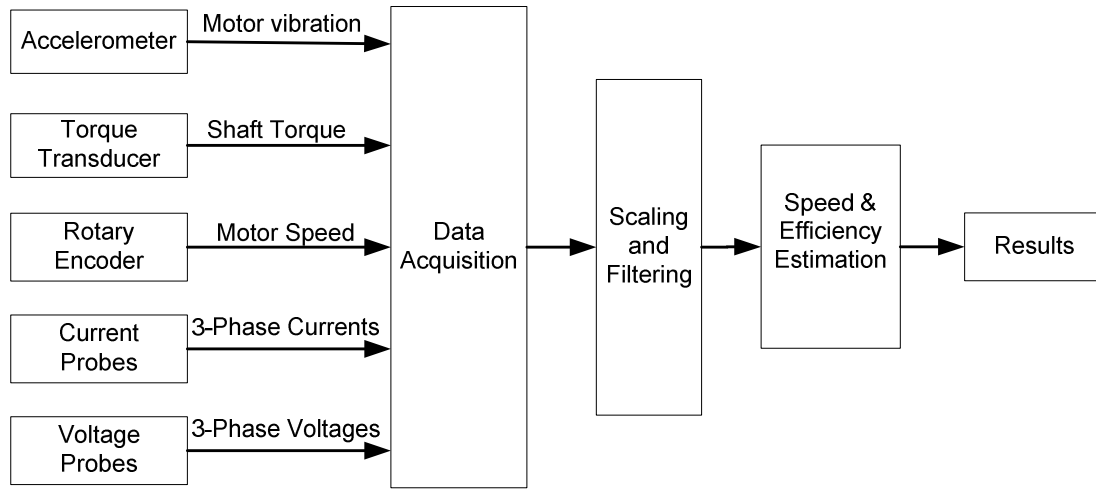


Figure 5.6. Block diagram of experimental setup.

**Table 5.4.** Test motor data.

<b>Motor Parameters</b>	<b>Motor 1</b>	<b>Motor 2</b>	<b>Motor 3</b>
Rated output power (Watts)	3000	11000	15000
Phase	3-phase	3-phase	3-phase
Rated voltage (Volts)	220/ 380	380/ 660	380/ 660
Rated current (A)	11.4/ 6.63	22.9/ 13.2	30.0/ 17.3
No-load current (A)	5.70/ 3.30	10.0/ 5.76	12.0/ 6.91
Rated speed (rpm)	1390	1455	1455
Rated frequency (Hertz)	50	50	50
Rated slip	0.073333	0.03	0.03
IEC Design	N	N	N

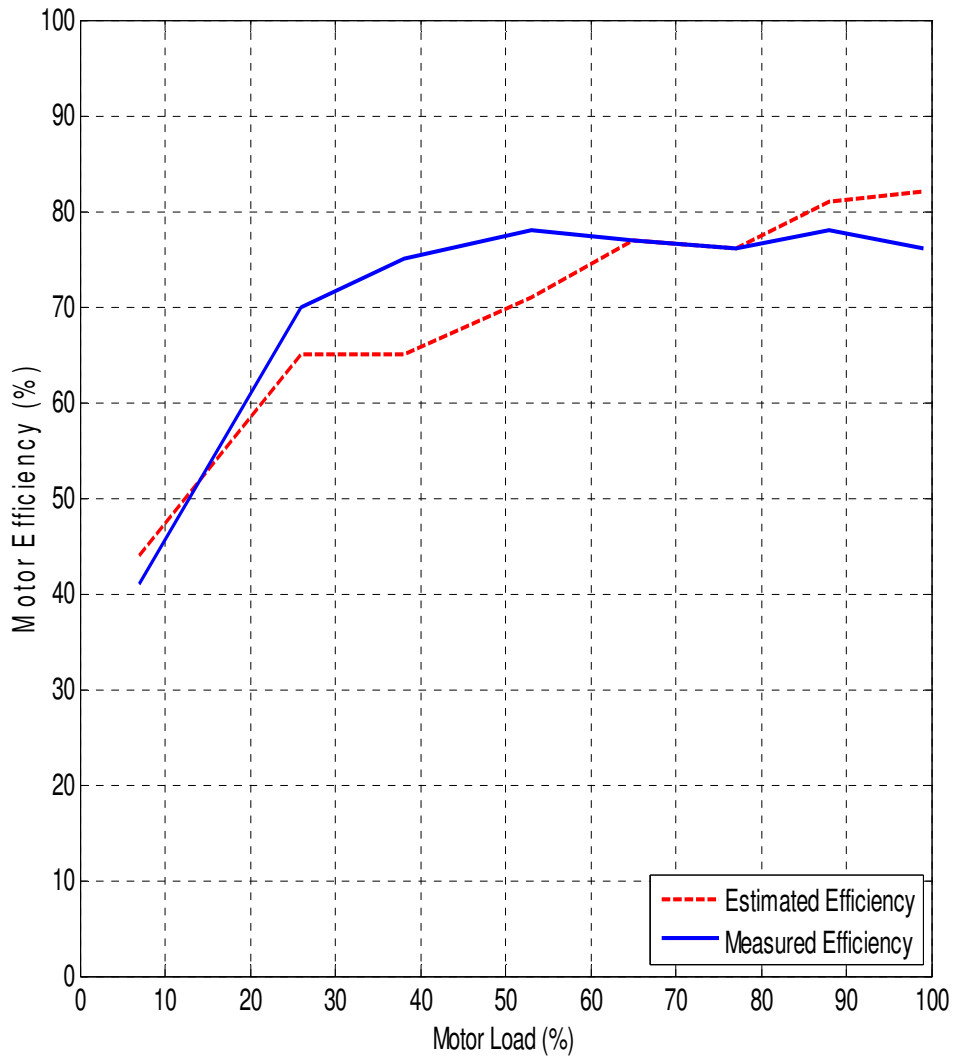
In Figure 5.7 a block diagram depicting the functional units of the experimental setup is shown. The motor vibration, shaft torque, motor speed, stator phase current and voltages are measured by their respective sensors. The analogue signals are converted to digital signals through the DAQ device with an anti-aliasing filter. The digital signals are scaled using the scaling factors used in the sensors. A low pass filter is used to filter high-frequency noise in the signals obtained. The speed and efficiency estimation algorithms are then applied. The results are displayed and saved to file.



**Figure 5.7.** Experimental setup functional block diagram.

### 5.3.4 Experimental results

The results that were obtained from the implementation of the non-intrusive efficiency estimation technique are presented in this section. The values used in this section are the mean values. Each test was repeated several times in order to get the best estimate. In Figures 5.8 to 5.10, the efficiency curves show a comparison of the estimate obtained with the new against the measured efficiency for each of the three test motors. Figures 5.11 to 5.13 show plots of the efficiency estimation curves obtained using the slip method, current method, improved current method 1, improved current method 2 and the non-intrusive compensated slip method. The measured efficiency curve is also included in the graphs. Figures 5.14 to 5.16 show plots of the measured efficiency and the power factor for each of the test motors across all the loading points.



**Figure 5.8.** 3 kW motor efficiency curves.

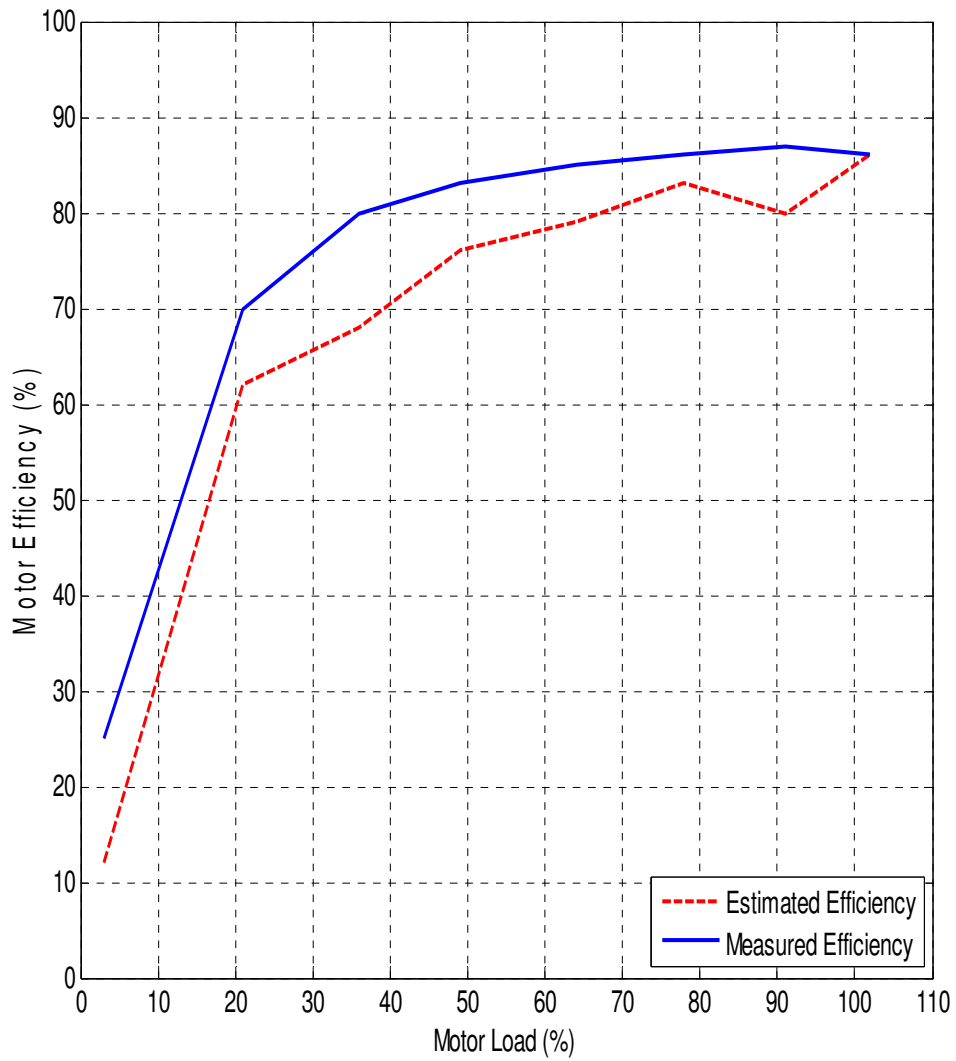
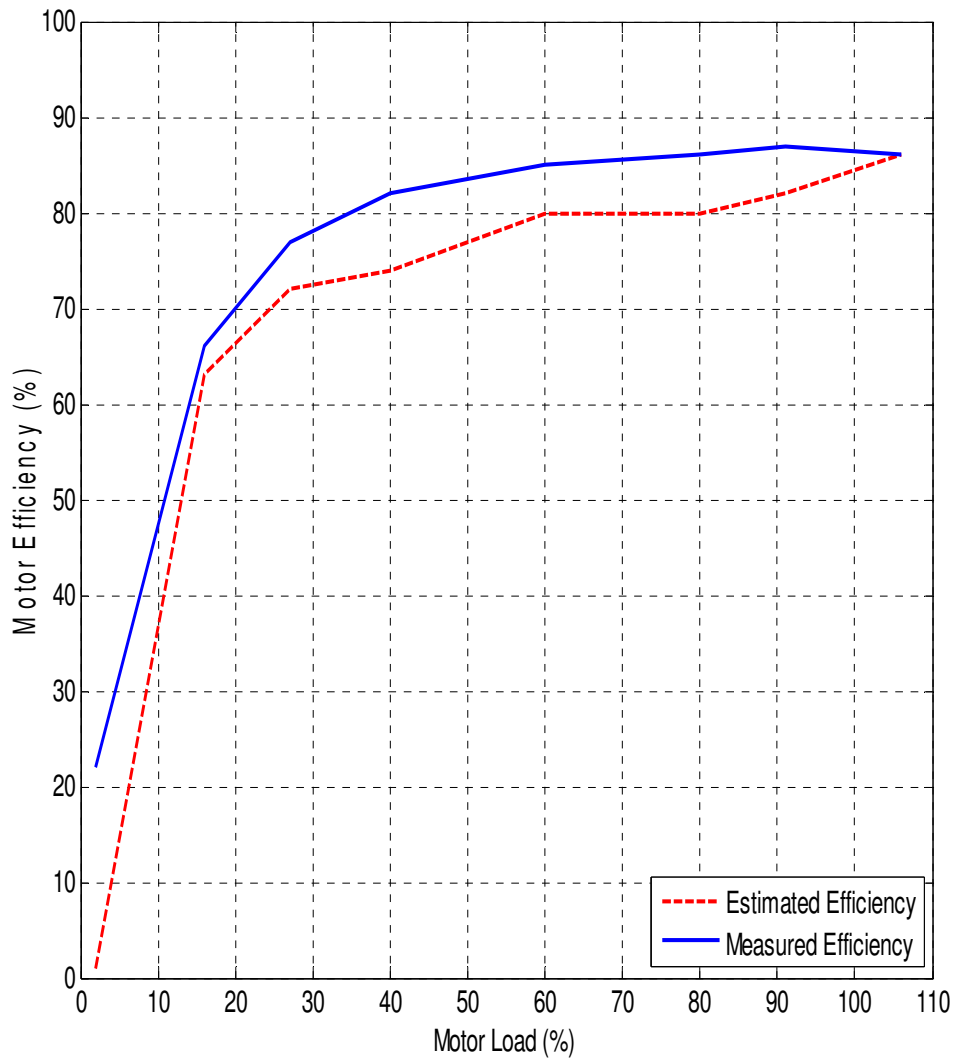


Figure 5.9. 11 kW motor efficiency curves.



**Figure 5.10.** 15 kW motor efficiency curves.

In Table 5.5 below a comparison of the efficiency estimation error is presented. The error is calculated using (5.7).

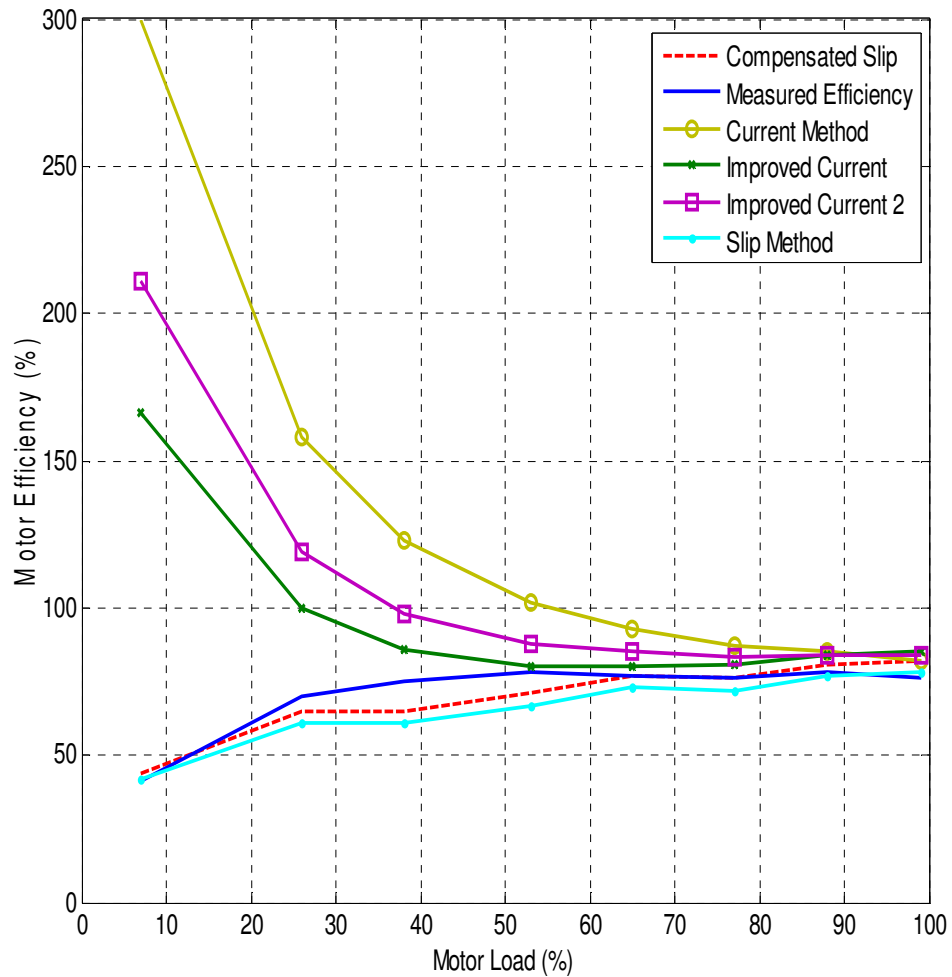
$$\varepsilon = \frac{\eta_{meas} - \eta_{est}}{\eta_{meas}} \times 100 \quad (5.7)$$

where  $\varepsilon$  is the percentage error,  $\eta_{meas}$  is the measured efficiency and  $\eta_{est}$  is the estimated efficiency obtained using the non-intrusive compensated slip technique.

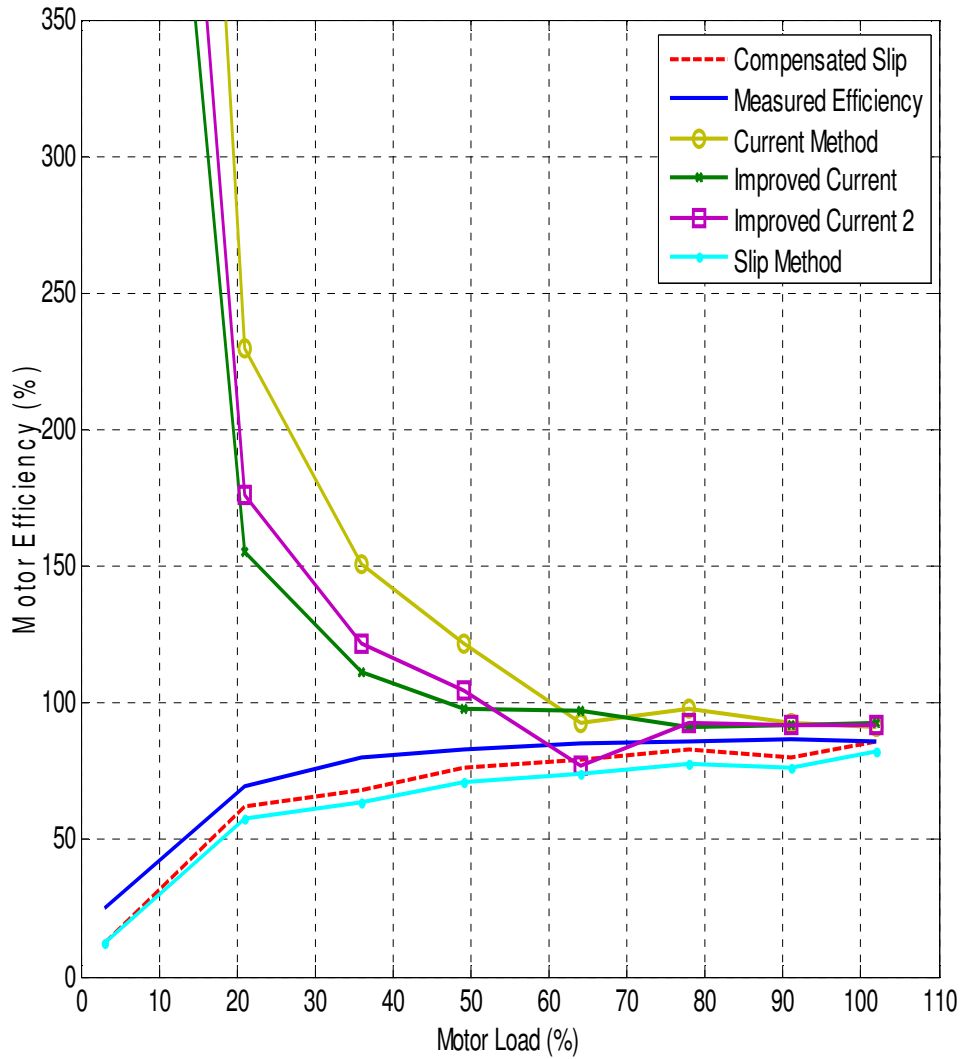
An average of the errors over the entire operating range of the motor is calculated for each test motor. The average error is also calculated for loading point above 50 and 75% of the rated motor output power for each test motor. This is done to analyse the performance of the method in each of the operating ranges.

**Table 5.5.** Percentage error in the non-intrusive compensated slip method.

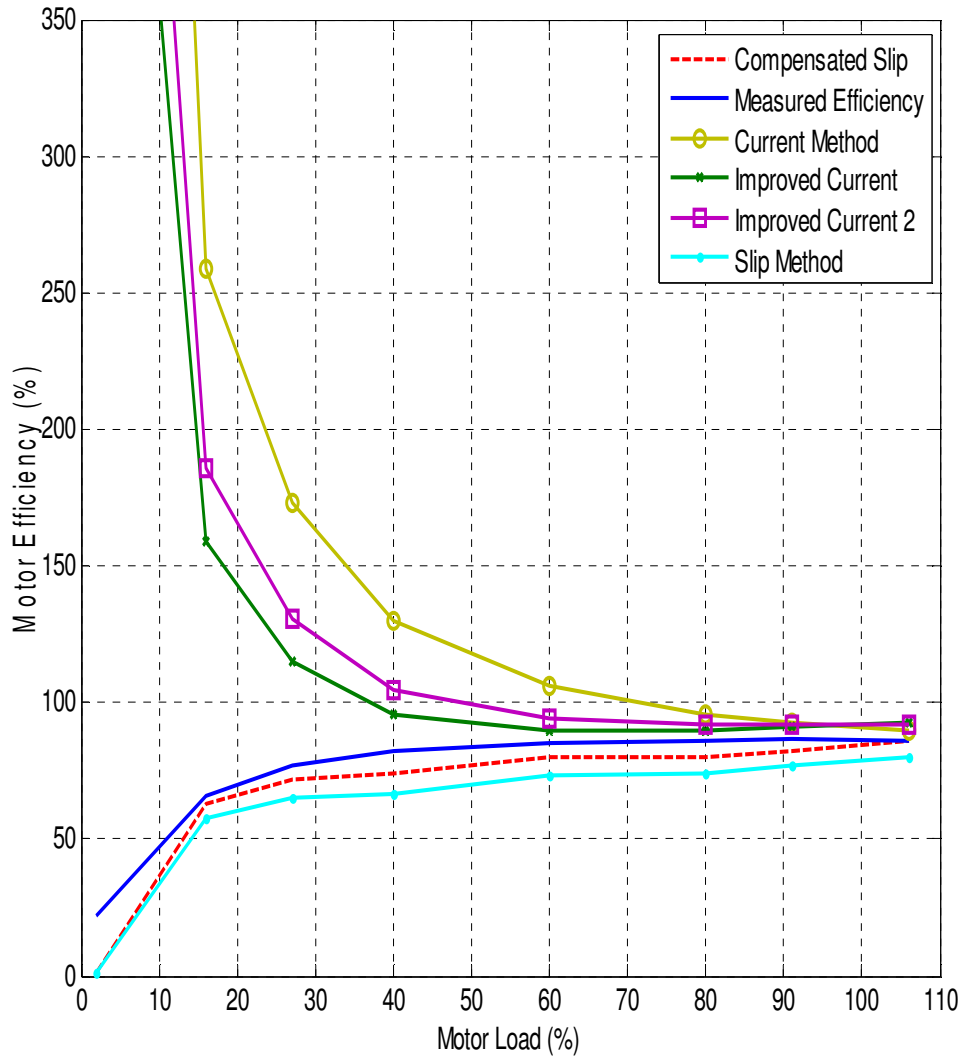
3 kW Motor		11 kW Motor		15 kW Motor	
Motor Load (%)	Error	Motor Load (%)	Error	Motor Load (%)	Error
7.3	-3.31	2.99	12.91	2.19	20.74
25.76	4.97	21	8.65	16.15	2.95
38.3	10.3	35.67	11.74	26.65	5.05
53.15	6.87	49.49	7.21	40.27	8.61
65.07	0.56	64.06	6.66	60.04	5.16
76.88	0.39	77.59	3.2	79.51	5.92
88.15	-3.34	91.44	6.35	91.05	4.2
99.32	-5.78	101.78	0.87	106	0.05
Average	1.33	-	7.2	-	6.59
Average > 50%	-0.26	-	4.86	-	4.79
Average > 75%	-2.91	-	3.47	-	3.39



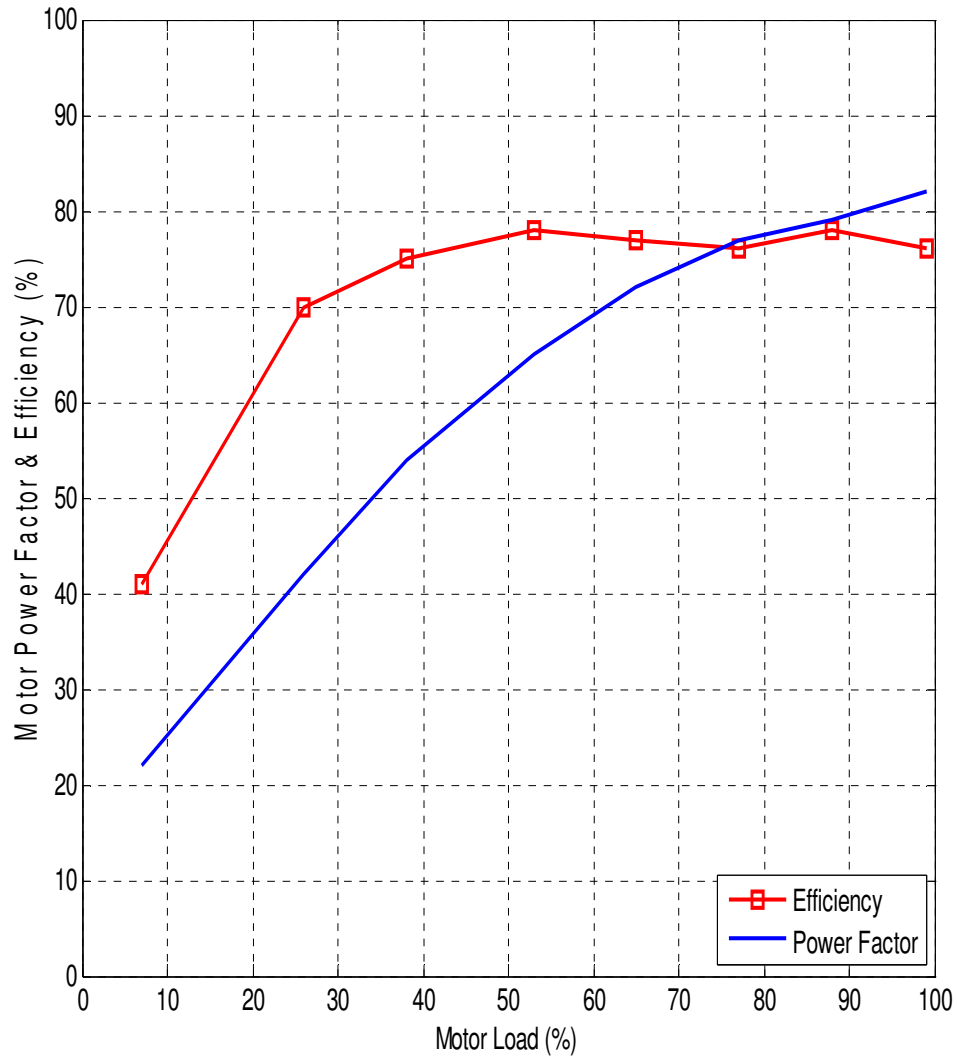
**Figure 5.11.** Comparison of efficiency estimation techniques - 3 kW motor.



**Figure 5.12.** Comparison of efficiency estimation techniques - 11 kW motor.



**Figure 5.13.** Comparison of efficiency estimation techniques -15 kW motor.



**Figure 5.14.** 3 kW motor power factor and efficiency curves.

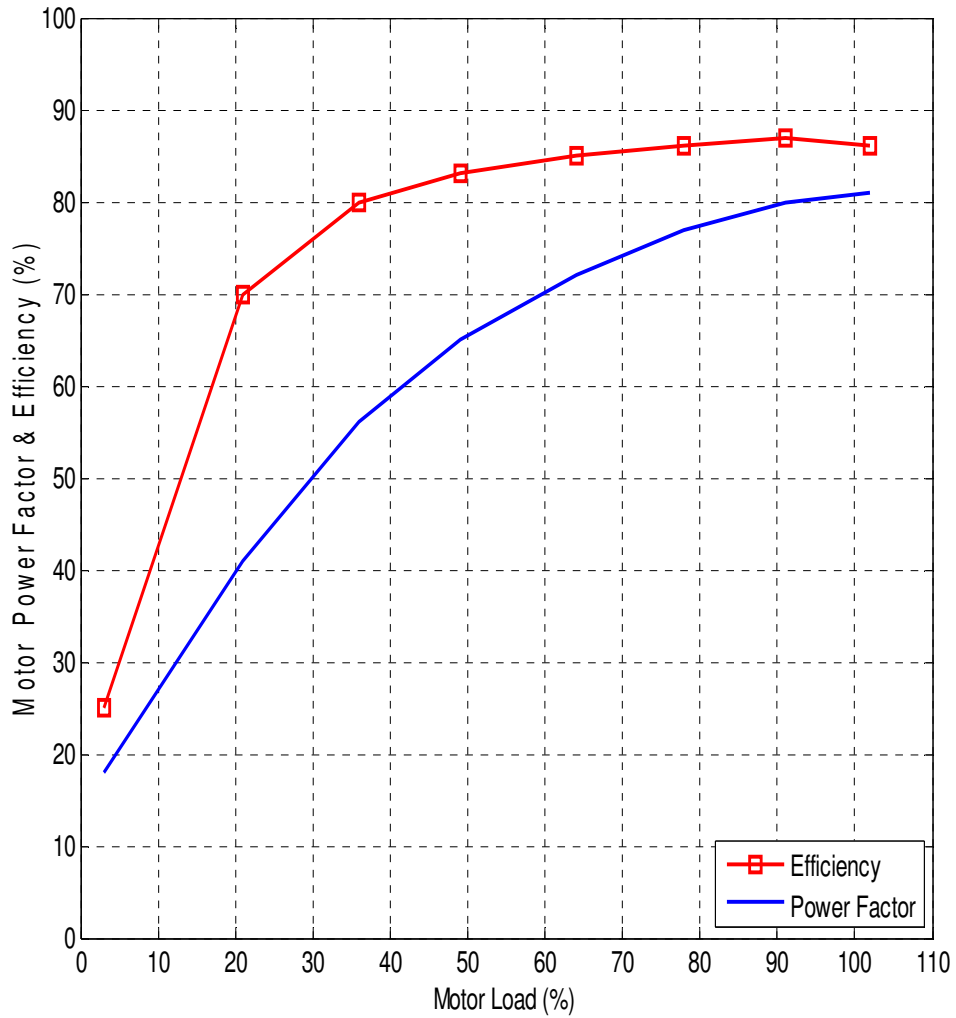


Figure 5.15. 11 kW motor power factor and efficiency curves.

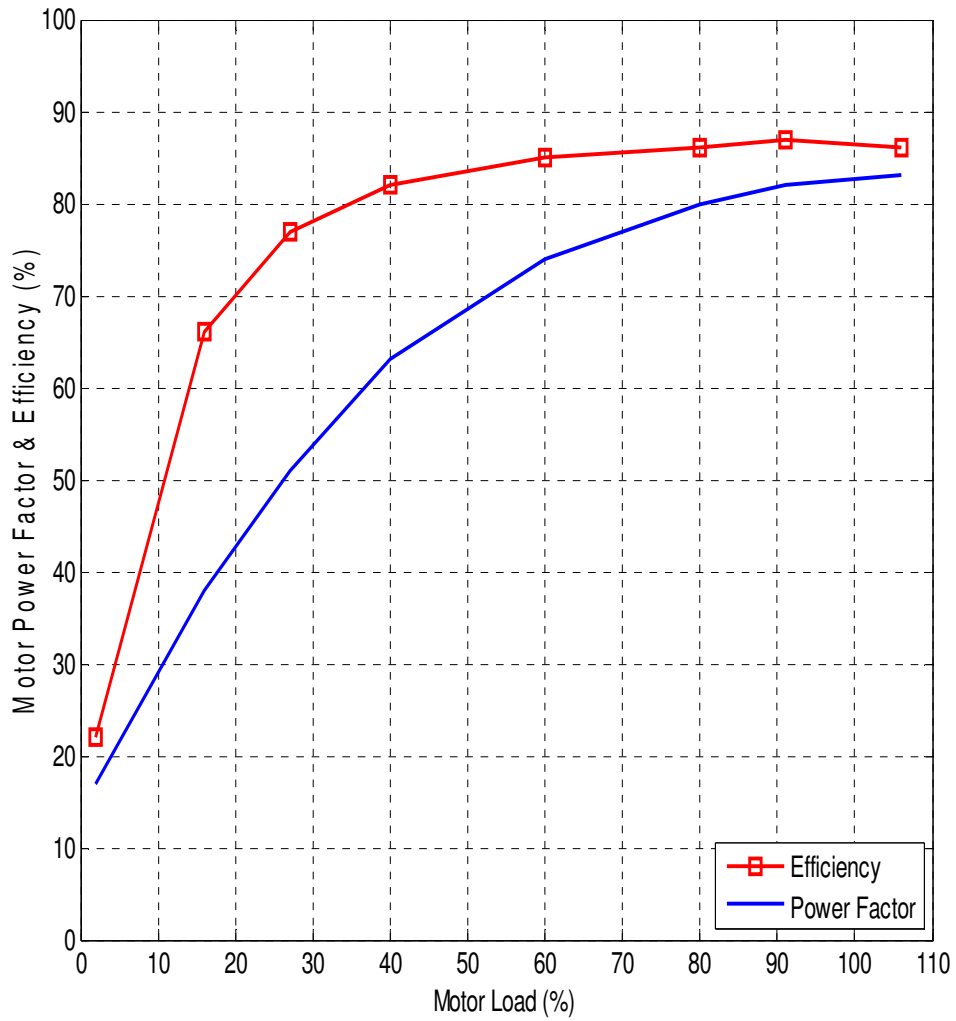


Figure 5.16. 15 kW motor power factor and efficiency curves.

### 5.3.5 Discussion

The results obtained from the implementation of the above-mentioned efficiency estimation techniques are presented in this section. Figure 5.8 shows that the estimated motor efficiency obtained from the non-intrusive compensated slip method closely follows the measured efficiency curve across the loading range of the 3 kW motor. The estimated output power is generally higher than the measured output power for load between 80 and 100% of the rated motor load. At loading points below 60% it was found to give estimates below the measured efficiency. In Figures 5.9 and 5.10 the non-intrusive compensated slip method results in efficiency estimates that closely follow the measured efficiency curve for the 11 and 15 kW motors. The estimated efficiency was found to be lower than the measured efficiency for all the loading points for the larger motors.

In Figures 5.11 to 5.13, the efficiency curves obtained from applying all the tested efficiency estimation techniques on the test motors show that both the standard slip method and the non-intrusive compensated slip method follow the measured efficiency curve across the full loading range of the motor. The efficiency curves of the three motors are typical efficiency curves for small motors. The efficiency of the motor drops significantly for loading points that are below 50% of the rated output power. The efficiency curves of all the motors tested show that the non-intrusive compensated slip method is the most accurate estimation technique. The current methods are the least accurate across all the loading points. They are especially poor at estimating the efficiency at the lower loading points.

In Figures 5.14 to 5.16, the power factor and efficiency of each of the test motors is plotted against the motor load. The figures show that the power factor of each motor decreases as the motor loading point is reduced. The efficiency of the motor follows a similar trend. Operating motors at an optimal power factor has several advantages: the apparent power required by the motor is reduced, which frees up capacity in the power system. Additional

equipment can then be installed [52]. Alternatively, it allows for the installation of lower rated equipment to achieve the same process requirements. An improved power factor results in a reduction in transmission losses. This is due to a smaller current that is required for the same amount of active power. All the test motors were at their most efficient when operating at loads above 75% of the rated output power. This is the same when power factor is considered. The optimal operating region for the motors is at above 75% of rated power. In this region, the average error for the three test motors is within 3.5%.

For the application of the non-intrusive compensated slip method presented, an accelerometer, voltage and current transducers was purchased. The proposed method can be implemented as a portable instrument or as a permanent field instrument for online monitoring of each motor in a plant. The latter will require a higher initial investment that depends on the number of motors in the plant. Methods that require more expensive equipment, such as variable voltage power supplies and variable loads are costly in comparison to the proposed method. A further cost component to be considered that of downtime that is incurred when applying a selected efficiency estimation technique. To conduct intrusive tests such as no-load tests and blocked-rotor tests, the motor-driven process has to be interrupted and the motor decoupled from the load. The cost of labour and lost production can be very high. Implementing a non-intrusive compensated slip method presented will not result in process interruption. The cost of downtime is avoided. Once the efficiency of an in-service motor is known, this can enable analysis and decisions to be taken which can result in significant savings in motor operating costs. The value of these benefits outweighs the initial investment.

For online monitoring of a plant, the proposed technique is implemented on each motor. The additional field sensors which are required will have a negative impact on the reliability of the plant. The transducers are likely to be less robust than the induction motors. Robust transducers can be installed at a higher initial cost. Implementing a plant-wide online monitoring system would be more maintenance-intensive and increases the plant maintenance costs. The benefits of the data obtained from having an online plant-

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monitoring solution justify the capital investment if the information is analysed and appropriate decisions are taken. The applications are discussed in Chapter 7.

When considering safety, installing the equipment and configuring the system will not introduce unique hazards to trained personnel. Special precautions need to be taken when working in the motor terminal box. An installation manual which details how the work should be performed can be used to improve the safety of personnel.

#### 5.4 CHAPTER SUMMARY

In this chapter a non-intrusive method of accurately estimating the motor efficiency using the motor vibration signature was presented. A speed estimation algorithm was used to implement the compensated slip motor efficiency estimation technique. The use of the speed estimation technique allows for a truly non-intrusive method of estimating the efficiency of an in-service motor. In the operating region above 75% of the rated output power, the average error for all three test motors with the efficiency estimation algorithm was within 3.5%.

The proposed method for estimating motor efficiency is easy to implement and it does not result in expensive plant downtime. It has useful practical applications for on-line motor management and condition monitoring. Data obtained from implementing the efficiency estimation technique can be used for motor replacement studies so that potential cost savings can be calculated. The new motor can be compared against the installed motor based on the estimated efficiency across the load profile.

## CHAPTER 6

# ERROR AND SENSITIVITY ANALYSIS

### 6.1 INTRODUCTION

It is important to understand the robustness of the method to a change in the conditions in which it is applied. This assists the user to understand limitations of the method. It ensures that it is applied in an environment where it will produce the desired results. This chapter explores the effects of a change in power system conditions on the performance of the non-intrusive compensated slip technique. An error analysis is done to quantify the errors when applying the proposed method.

In practical power systems there is always the possibility that conditions will vary from ideal. A change in the power system can occur due to faults, starting of large loads, etc. These changes lead to situations where motors do not operate under the operating conditions that they were designed for. In this chapter the effects of varying the supply voltage on the accuracy of the proposed efficiency estimation technique are determined through carefully designed experiments.

In conducting scientific research it is generally understood that all experiments produce results that contain a degree of errors and uncertainty. It is therefore important to identify all the sources of error and quantify their influence on the results. The results can then be presented with a basis that the errors introduced are bounded. An error analysis is performed on the non-intrusive efficiency estimation technique.

The chapter evaluates the influence of supply voltage conditions on the efficiency estimation technique. Voltage dips, swells and unbalance are defined and their effects are

then analysed. A practical evaluation of their effects is presented. An error analysis of the technique is then made. A worst case error estimate is calculated to determine the maximum error from the application of the method. The chapter is concluded by considering possible ways of reducing errors.

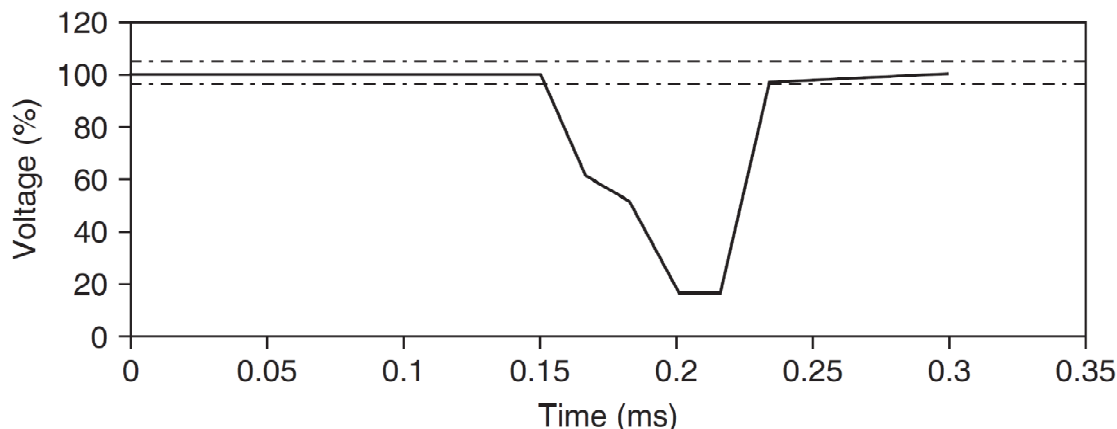
## 6.2 INFLUENCE OF SUPPLY VOLTAGE CONDITIONS

One of the main shortcomings of traditional motor efficiency estimation techniques is that they are based on the assumption an ideal supply [53]. The evaluation of the performance of these techniques is done under ideal supply conditions. A robust efficiency estimation technique is required that provides good accuracy under both ideal and non-ideal conditions. The probability of power quality events that affect the line voltage and current waveforms need to be considered. In this section the effects of voltage-related power quality events are evaluated. This includes the effects of voltage swells, dips and unbalance on the operation of induction motors. An experimental setup was developed to evaluate the performance of the proposed motor efficiency estimation technique.

### 6.2.1 Voltage Dips and Under-voltages

A voltage dip is defined as a short decrease in the RMS supply voltage. The reduction in the voltage can range from 5 to 95% of the nominal voltage [54]. The duration of the dip can vary from half a cycle up to one minute. Voltage dips are also commonly referred to as voltage sags. A reduction in the supply for longer than one minute is known as an under-voltage condition [55]. Figure 6.1 depicts a voltage dip in which the supply voltage drops to less than 20% of the nominal voltage. When a fault occurs in the power system it can result in a voltage dip. A common cause of voltage dips is the starting of large motors. When large motors are started directly on-line, a high inrush current is drawn. A voltage drop is experienced at the point of common coupling to other loads on the power system because of the impedance of the system. Energising transformers can also result in voltage

dips due to the inrush current drawn [56]. A weak power system can also result in equipment operating below nominal voltage. Supplying loads with long feeders may also lead to them operating in under-voltage conditions.



**Figure 6.1.** Supply voltage during a voltage dip [54].

The effects of voltage dips on induction motors depend on the severity of the dips. When a voltage dip occurs, an induction motor will start to lose speed and it can either stall or reaccelerate when the supply voltage recovers. The motor torque will reduce by a factor proportional to the square of the voltage at the motor terminals [57]. The motor slip will increase as the stator current increases. If the motor is supplying a constant torque load with low inertia, the motor will lose speed rapidly and this will result in the motor stalling. Motors driving high inertia variable torque loads are more robust to supply voltage variations. The ability of a motor to reaccelerate depends on the magnitude of the recovery voltage, the characteristics of the load and the initial speed loss that the motor experienced. The effects of a voltage dip vary according to the combined dynamic response of the motor-driven process. This includes the motor, gears, coupling and load [58].

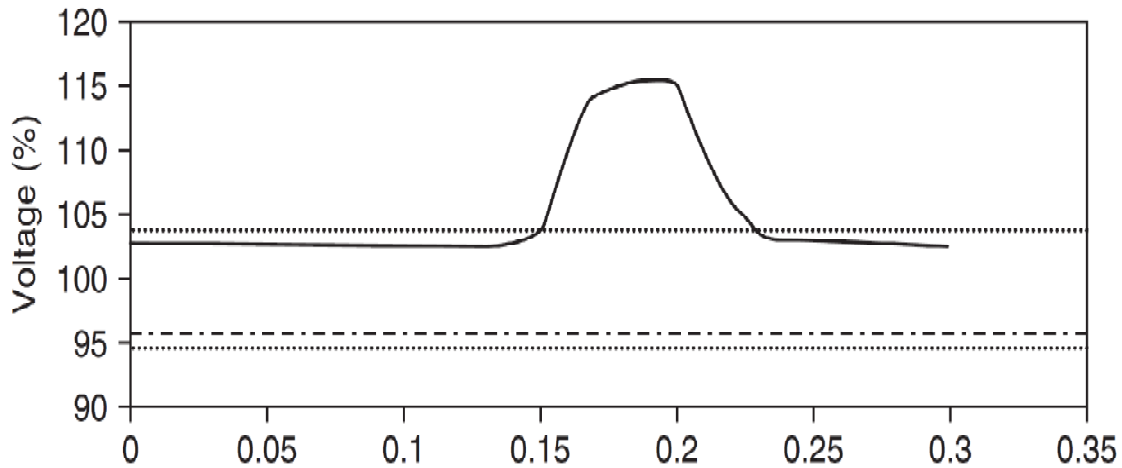
The effects of voltage dips and under-voltages on an induction motor are of interest. They change the motor's operating speed and slip from the rated values, which are only valid at

the rated terminal voltage. In slip-based techniques for estimating motor efficiency, it is assumed that the slip is proportional to the motor load. When the speed is reduced due to a voltage reduction, the motor load is over-estimated. The non-intrusive compensated slip method of Chapter 5 takes into account the supply voltage to correct for any supply voltage fluctuation. This is the last term in (6.1). The effectiveness of this compensation is tested in an experiment. Results from the under-voltage operation are presented in section 6.2.5.

$$\eta = \frac{Slip}{Slip_{rated}} \cdot \frac{P_{output,rated}}{P_{input}} \cdot \left(\frac{V}{V_{rated}}\right)^2 \quad (6.1)$$

### 6.2.2 Voltage swells and over-voltages

A voltage swell is a short increase in the RMS value of the supply voltage. The increase in the supply voltage can range from 110 to 180% of the nominal voltage [59]. An over-voltage can be defined as a voltage swell sustained over a period longer than one minute. Voltage swells are experienced as a result of faults in the power system. When a single-phase short-circuit occurs, the remaining phases will develop voltage swells [60]. Disconnecting large loads or switching in capacitor banks can also lead to voltage swells. In Figure 6.2 an example of a voltage swell is shown [54]. In the figure the supply voltage increases to 115% of the nominal supply voltage. A stiff power system can result in motors operating at over-voltage conditions.



**Figure 6.2.** Supply voltage during a voltage swell [54].

When a voltage swell occurs, an induction motor will begin to accelerate. The motor torque produced by the motor increases by a factor proportional to the square of the voltage at the motor terminals. The motor speed decreases if the synchronous frequency remains unchanged. Operating a motor at over-voltage conditions decreases the expected operating life. This is because of the higher core losses and additional stress on insulation [61].

The effects of voltage swells on the motor efficiency estimation technique are investigated since they change the motor's operating speed and slip from the rated values. The increase in the supply voltage results in a corresponding increase in the motor speed. When the speed is increased as a result of a voltage swell, the motor load estimated using the motor slip is smaller. The non-intrusive compensated slip method presented takes the supply voltage into account to correct for any supply voltage fluctuations. The effectiveness of the compensation is evaluated for over-voltage conditions.

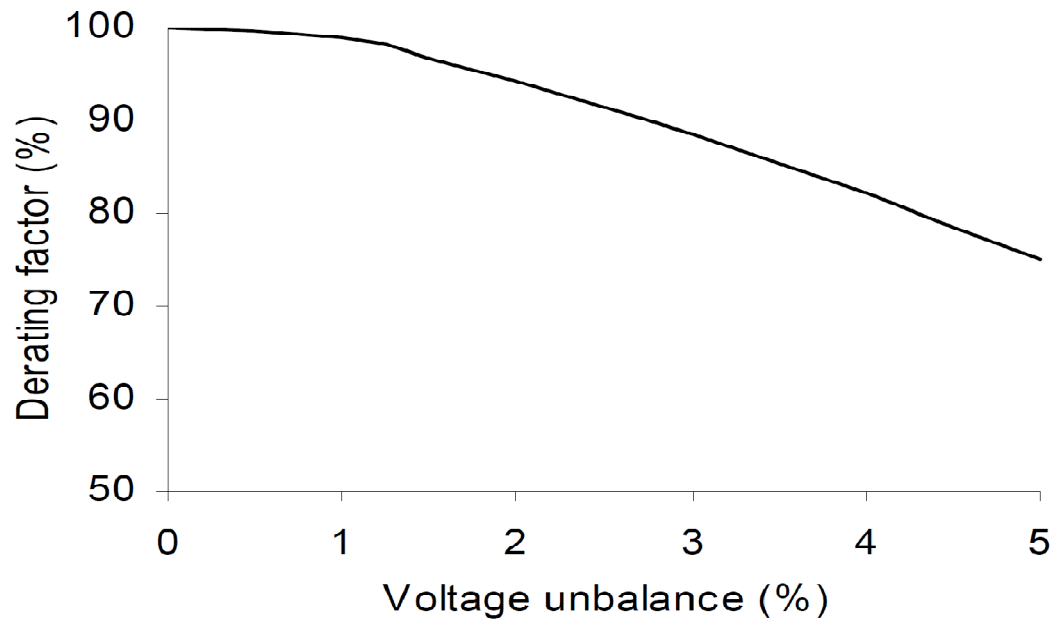
### 6.2.3 Voltage unbalance

Voltage unbalance is defined as a condition in a three-phase power system where the amplitudes of the supply voltages differ relative to one another. It can also be defined as the ratio of the magnitude of the negative sequence component to the positive sequence component of the voltage [55]. In literature it is commonly referred to as voltage imbalance. Voltage unbalance is caused by the presence of asymmetrical impedances in a power system [62]. The asymmetrical impedances may occur in the transmission and distribution network due to unbalanced impedances of transmission line, transformers and other loads with different impedances on each of the phases. Another common cause is the unbalanced distribution of single-phase loads in the power system.

Voltage unbalance has a detrimental effect on the performance of induction motors. The negative sequence component of the voltage that is present as a result of the unbalance generates a reverse rotating air-gap field. The reverse air-gap field acts in the opposite direction to the rotor rotation of the motor [63]. A negative torque is produced by the negative sequence currents produced [61]. The negative torque acts to subtract from the desired positive torque. The motor is then forced to draw more current and operate at a higher slip to produce an equivalent torque compared to operation in conditions of balanced supply voltage. This will result in an increase in rotor losses. It has been shown in [64] that the core losses in an induction motor will increase with an increase in voltage unbalance.

Voltage unbalance increases at motor terminals will cause a higher corresponding increase in stator losses in comparison to the increase in rotor losses. This is because the resistance of rotor bars is higher in the presence of an unbalanced supply voltage. The increase in losses in a motor due to unbalance introduces thermal stresses. These thermal stresses increase with an increase in the voltage unbalance. The thermal stresses lead to a reduction in the life of a motor due to deterioration in insulation. In squirrel cage motors the stator

winding insulation is the weakest point, since there is no rotor insulation [64]. NEMA has recommended the derating of motors as a function of the percentage voltage unbalance due to the adverse effects of unbalance [62]. The NEMA derating curve is shown in Figure 6.3. Sustained operation of a motor under conditions with voltage unbalance exceeding 5% is not recommended since it can lead to premature failure.



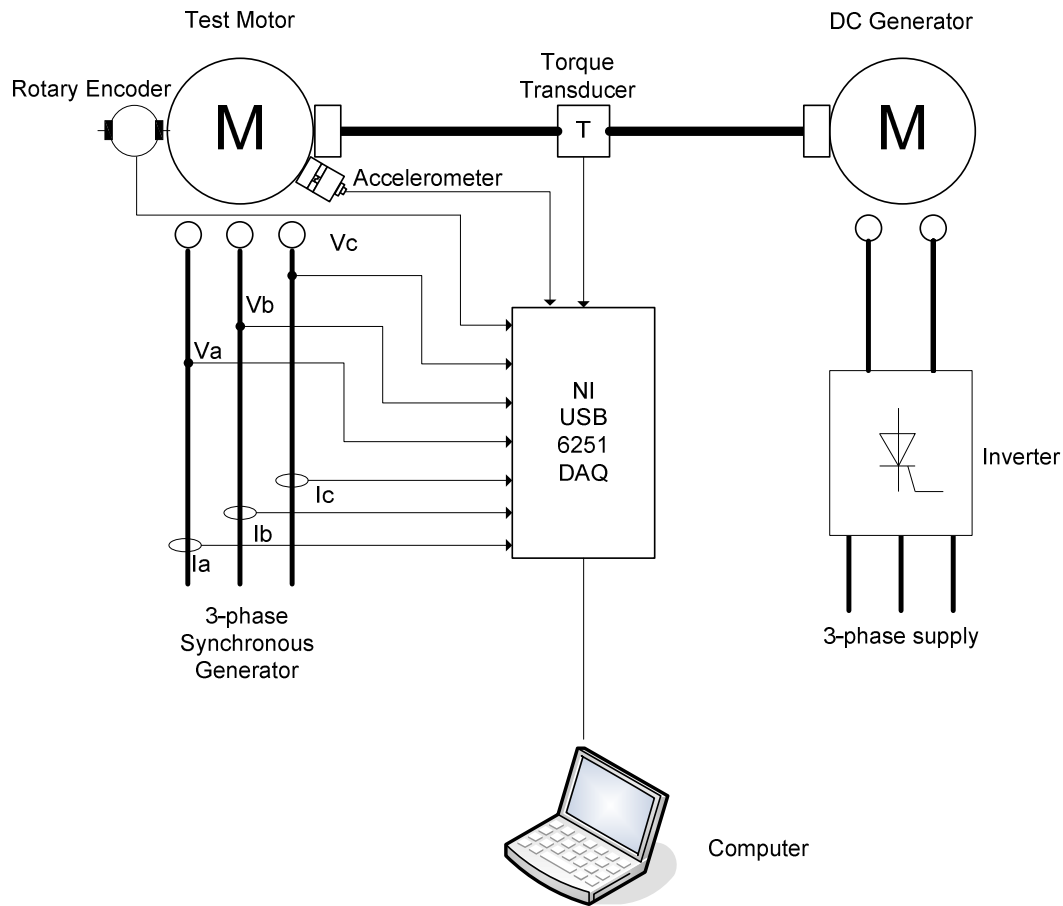
**Figure 6.3.** NEMA derating curve [62].

The accuracy of the efficiency estimation technique developed from the previous chapter is expected to be adversely affected when motors operate under voltage unbalance conditions. The voltage compensation offered in the technique is designed to counter the effects of under- and over-voltage conditions. The RMS voltage used is the combined average of all three phases. This does not make provision for the effects of voltage unbalance. Unbalance causes a motor to operate under higher slip for a particular loading point than under a balanced supply voltage. A study of (6.1) shows that the compensated slip method will overstate the output power and result in an efficiency estimate that is higher than the actual efficiency.

### 6.2.4 Experimental setup

An experimental setup was developed for evaluating the performance of the non-intrusive motor efficiency estimation technique under supply voltage conditions. A schematic diagram of the experimental setup is shown in Figure 6.4. In the experimental setup a synchronous generator is used to supply power to a motor under test. In order to simulate an under-voltage condition, the generator set point is varied to generate a voltage at 10% below nominal. The set point is also adjusted to generate a voltage of 10% above the nominal. This is to simulate an over-voltage. A shaft-mounted torque transducer and rotary encoder were used to measure the shaft torque and rotational speed. The input current and voltage in each phase are measured using current and voltage probes. A magnetically mounted accelerometer is used to measure the vibration of the motor under test. The signals are sampled using an NI USB 6251 DAQ device connected to a laptop computer.

The test motors are loaded using a DC generator. A three-phase controlled inverter is used to convert the generated power to AC and feed it back into the supply grid. The load torque for the induction motor under test is varied by using a current controller to adjust the armature current set point of the DC generator. The controller also synchronises the DC generator's output power to the supply grid frequency and phase.



**Figure 6.4.** Experimental setup for evaluating the effects of voltage variation.

Software was developed in LabVIEW for the experiment. A flowchart of the test software is shown in Figure 6.5. In these experiments, the generator output is first set to the desired voltage. The test motor is then loaded at each loading point and allowed to settle. Once the motor has settled, measurements are obtained from the transducers. The different efficiency estimation algorithms are applied to the same data set. This allows for accurate comparison of the different techniques under the same conditions. The results are saved to file and then displayed on the user interface. The loading point is varied from no load to full load.

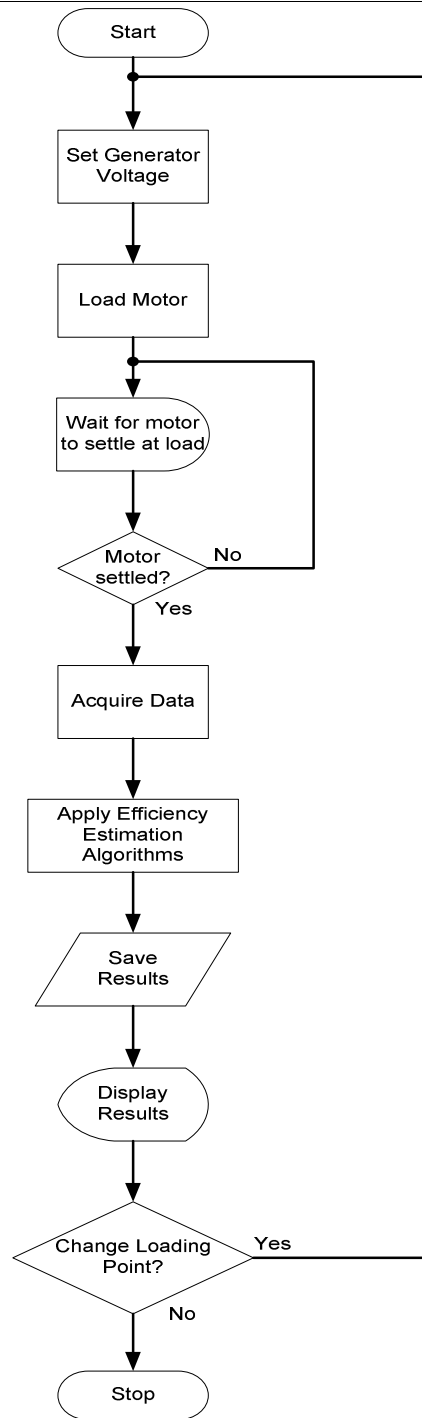


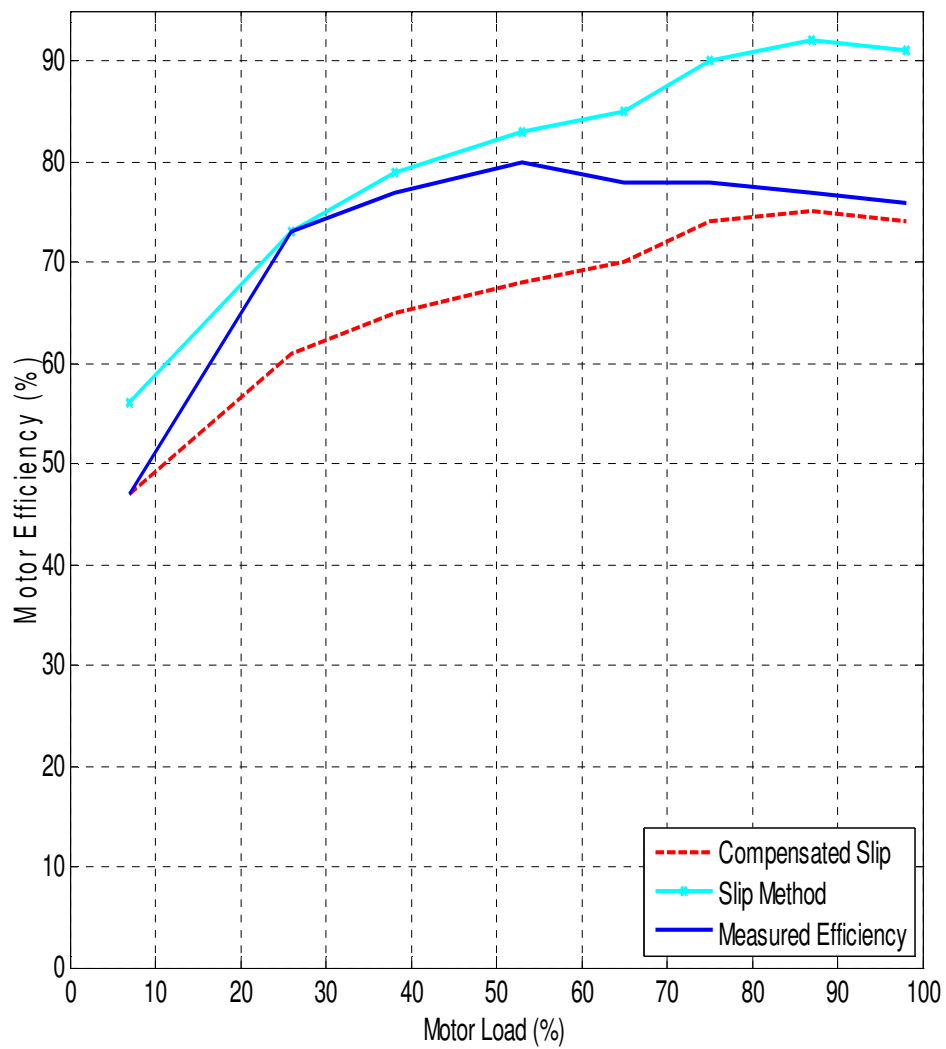
Figure 6.5. Flowchart of the test software.

### 6.2.5 Experimental results

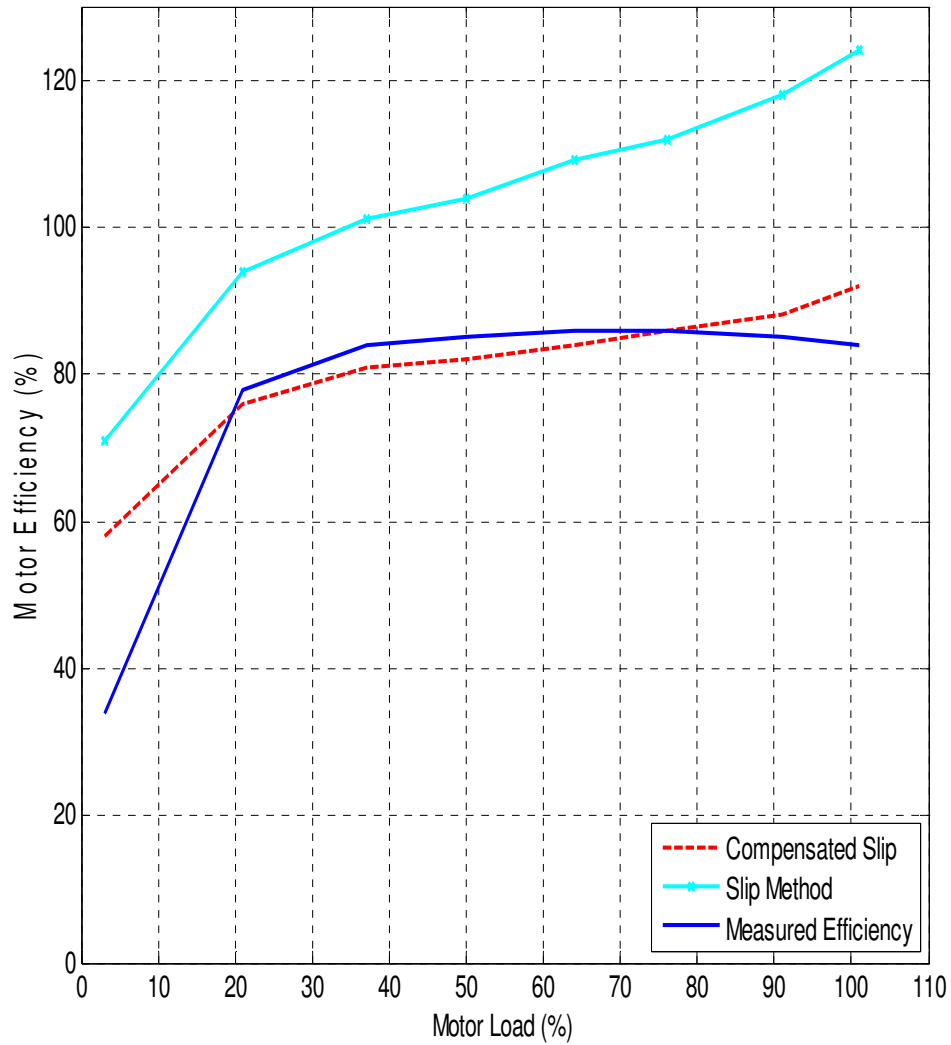
The results that were obtained from the experiments evaluate the effects of the supply voltage on the performance of the non-intrusive efficiency estimation techniques. Table 6.1 shows the percentage error obtained from the efficiency estimation technique during voltage dips. Figure 6.6 shows the efficiency curves that were obtained from the 3 kW test motor when operated at 10% below the nominal rated voltage. The results from the 11 kW test motor under the similar conditions are shown in Figure 6.7. Figure 6.8 shows the efficiency curves that were obtained from the 3 kW test motor when operated at 10% above the nominal rated voltage. The results from the 11 kW test motor under similar conditions are shown in Figure 6.9. Table 6.2 depicts the percentage error obtained from the efficiency estimation technique during voltage swells.

**Table 6.1.** Percentage error in efficiency estimation technique during voltage dips.

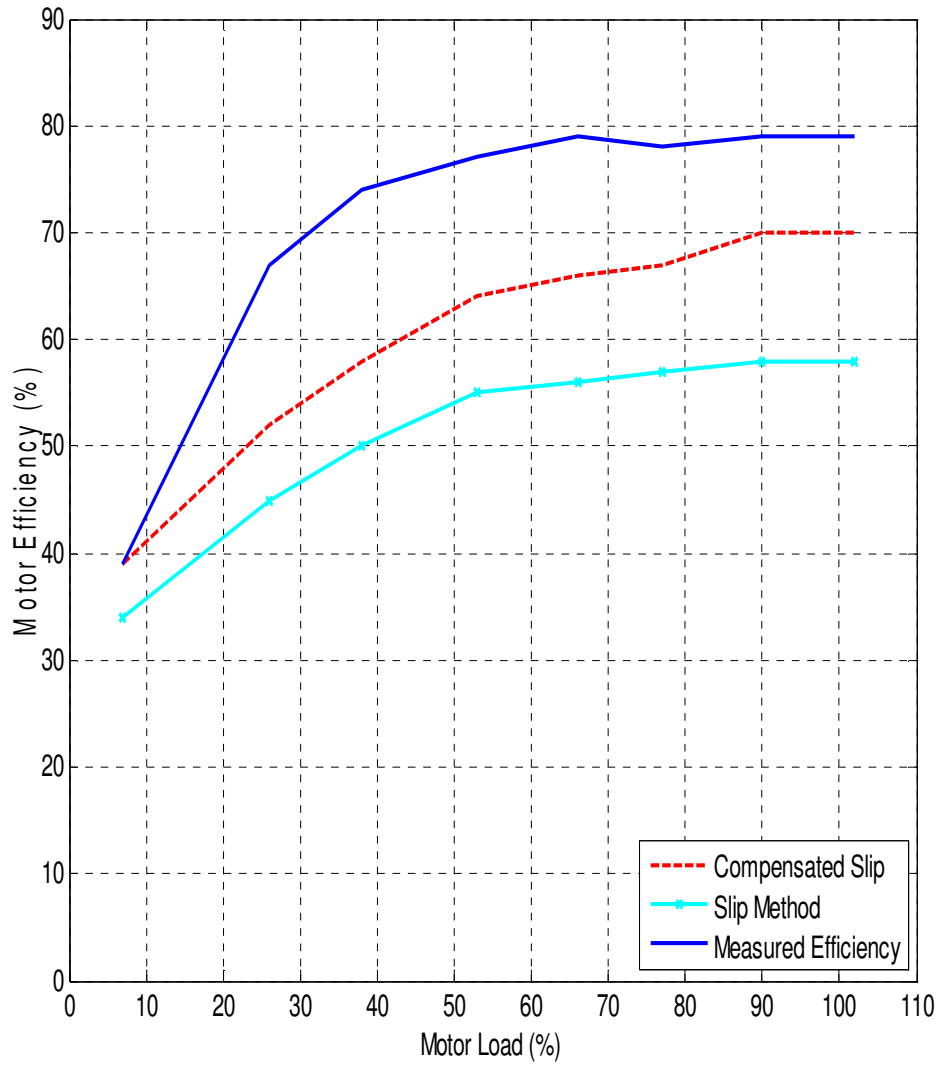
<b>10 % Below Rated Nominal Voltage</b>			
<b>3 kW Motor</b>		<b>11 kW Motor</b>	
<b>Motor Load</b>	<b>Error</b>	<b>Motor Load</b>	<b>Error</b>
7	0.65	3	-70.59
26	16.44	21	2.56
38	15.58	37	3.57
53	15.00	50	3.53
65	10.26	64	2.33
75	5.13	76	1.24
87	2.60	91	-3.53
98	2.63	101	-9.52
Average	8.54	-	8.80
Average > 50%	7.12	-	1.19
Average > 75%	3.45	-	3.94



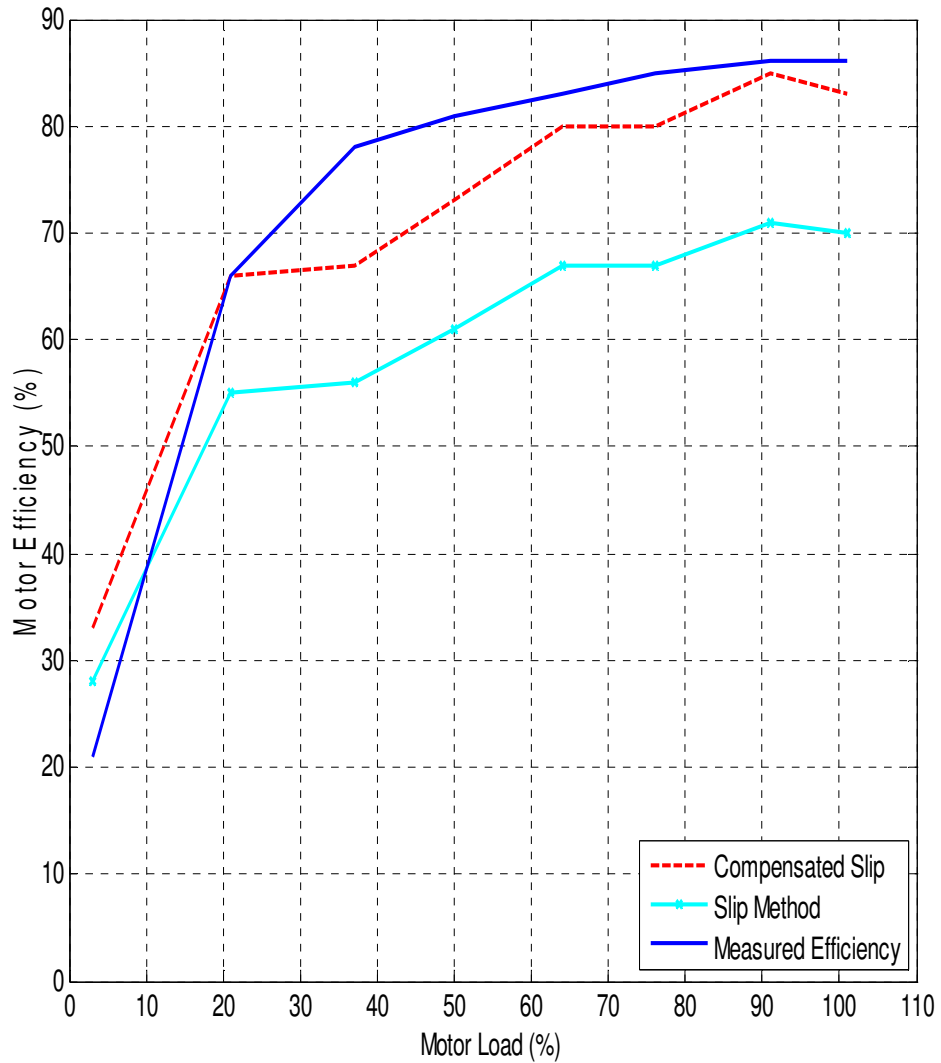
**Figure 6.6.** The efficiency curves of the 3 kW motor in under-voltage conditions.



**Figure 6.7.** The efficiency curves of the 11 kW motor in under-voltage conditions.



**Figure 6.8.** The efficiency curves of the 3 kW motor in over-voltage conditions.



**Figure 6.9.** The efficiency curves of the 11 kW motor in over-voltage conditions.

**Table 6.2.** Percentage error in efficiency estimation technique during voltage swells.

<b>10 % Over Rated Nominal Voltage</b>			
<b>3 kW Motor</b>		<b>11 kW Motor</b>	
<b>Motor Load</b>	<b>Error</b>	<b>Motor Load</b>	<b>Error</b>
7	0.35	3	-57.14
26	22.39	21	0.89
38	21.62	37	14.10
53	16.88	50	9.88
66	16.46	64	3.61
77	14.10	76	5.88
90	11.39	91	1.16
102	11.39	101	3.49
Average	14.32	-	2.27
Average > 50%	14.05	-	4.80
Average > 75%	12.30	-	3.51

### 6.2.6 Discussion

From the literature review of efficiency estimation techniques, it was noted that the compensated slip method corrects the effects of the voltage variation by factoring in the supply voltage. Figures 6.6 and 6.7 show that the standard slip method overstates the efficiency of both test motors across all loading points. This result is expected as the reduction in the supply voltage leads to a decrease in the motor speed. A decrease in the motor speed results in an increase in the slip. This is because the synchronous speed is unchanged. This results in an estimated efficiency that is higher than the measured efficiency. The compensated slip method produces a more accurate efficiency estimate since it compensates for the reduced supply voltage. In Table 6.1 the percentage error obtained from the efficiency estimation technique during voltage dips is comparable to the accuracy that is obtained under normal supply conditions.

A study of Figures 6.8 and 6.9 shows that the standard slip method under estimates the efficiency of both test motors across all loading points. From the discussion of section 6.2.2, the results are to be expected. The increase in the supply voltage leads to a corresponding increase in the motor speed. An increase in the motor speed results in a reduction in the slip when the synchronous speed is unchanged. This results in the estimated efficiency that is lower than the measured efficiency. The results obtained from the compensated slip method are more accurate. Compensation is made for the change in the supply voltage. In Table 6.2 the percentage error obtained from the efficiency estimation technique during voltage swells is comparable to the accuracy that is obtained under normal supply conditions. The accuracy obtained from the 3 kW motor in over-voltage conditions is worse than that obtained under rated supply voltage. The results of the experiments conducted show that the non-intrusive compensated slip technique is robust to variations in the supply voltage.

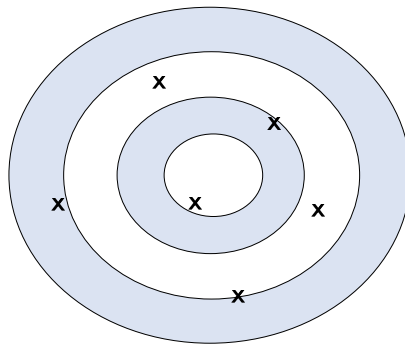
### 6.3 MEASUREMENT ERROR ANALYSIS

In this section the sources of error in the non-intrusive speed estimation technique are investigated. An analytical study of experimental uncertainties in determining the performance of the non-intrusive speed estimation techniques is developed. In all scientific experiments a certain level of uncertainty exists. The error associated with a scientific experiment can be defined by (6.2), [65].

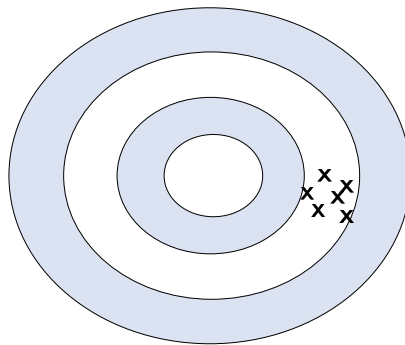
$$\xi = \xi_m + \xi_h + \xi_i \quad (6.2)$$

where  $\xi$  is the overall measurement error,  $\xi_m$  is the methodical error,  $\xi_h$  is the human error and  $\xi_i$  is the instrumental error. The different error components will be expanded on in subsequent sections.

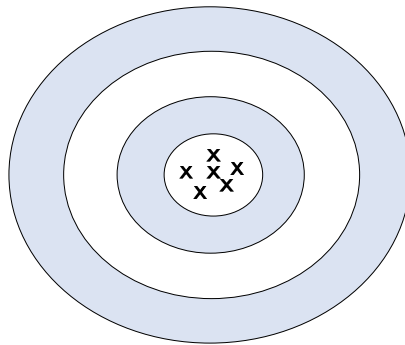
A discussion of the validity of measurement results should also take into account the concepts of accuracy and precision. The accuracy of a measurement is defined as the closeness of the measurement to the true value of the parameter that is being measured. Precision is the closeness of repeated measurements of the same parameter value [66]. Figure 6.10 illustrates the concepts of accuracy and precision using a bull's eye target. In bull's eye A the precision is poor because the measurement values are spaced far apart. The accuracy is high because the mean of the measurements is close to the true value or target. Bull's eye B illustrates a case where there is good precision, as shown by close grouping of the measurements, while the accuracy is poor. The ideal situation for measurements is where both the accuracy and the precision of the measurements are good. In general, good precision yields accurate results unless there is a bias in the measurement instrument used.



A. Poor precision, good accuracy



B. Good precision, poor accuracy



C. Good precision, good accuracy

**Figure 6.10.** The concept of accuracy and precision on a bull's eye target.

### 6.3.1 Methodical error

Methodical error is the error that is inherent in the motor efficiency estimation method that is applied. In methods that are defined in standards such as the IEEE or IEC, the methodical error is introduced by the adopted induction motor model and assumptions made about the physical environment in which the measurements are taken. Test standards introduce errors in the specification of the minimum accuracy for measurement instruments.

The non-intrusive compensated slip method is based on the relationship that is expressed in (6.1). One of the main drawbacks of slip-based methods is that the NEMA and IEC standards allow motor manufacturers a tolerance of up to 20% on the rated slip of a motor [14]. This introduces a significant error in the efficiency calculation. However, it was found that all the IEC motors used in the experiments conducted in this research had accurate datasheets. In order to successfully implement the non-intrusive compensated slip method and maintain an acceptable level of accuracy, the specifications of new motors purchased have to include more stringent testing from the supplier to determine accurate speed and slip ratings at the rated voltage. This is achieved by requesting a manufacturer to perform a type test on each motor design. The design can then be verified to a desired level of accuracy. Any subsequent variation in motor parameters would be due to tolerances in the manufacturing process and the condition of the motor. The tolerance on the name plate ratings or datasheets will be manufacturer-dependent.

### 6.3.2 Human error

The experiments that were conducted were automated to reduce the influence of human error. Custom software was written in LabVIEW for the DAQ and the implementation of the motor efficiency estimation techniques. The changing of the load for the motors under test was done manually. The generator used for varying the supply voltage is described in

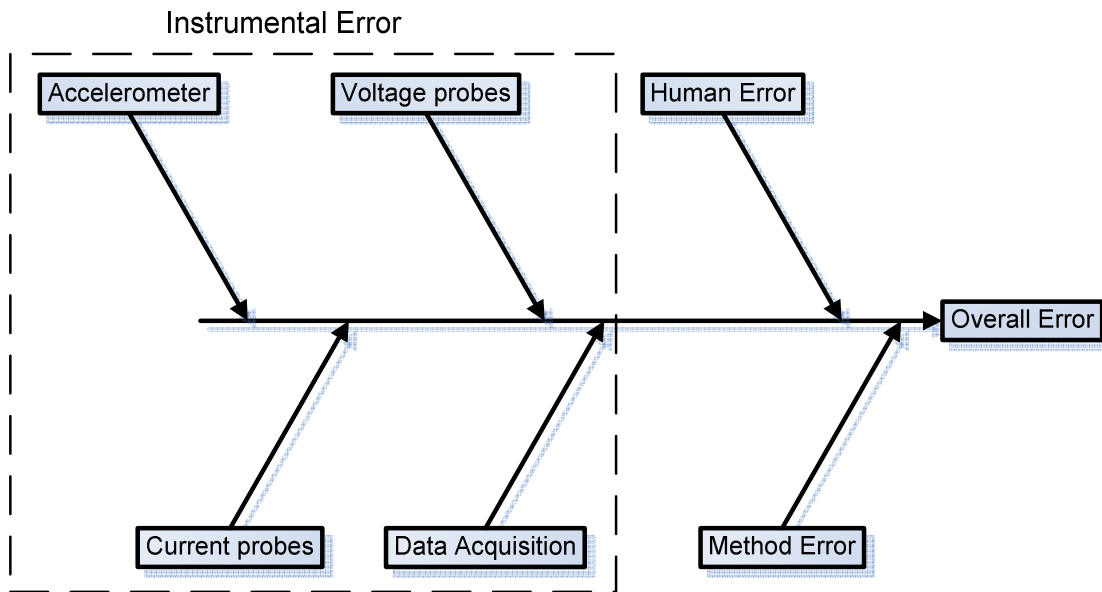
section 5.2.4. This aspect of the experiments is susceptible to human error. Human error can also play a role in the time taken between tests. Changes in environmental conditions, such as the ambient temperature, and their influence on motor parameters can influence the results. The effects of the human error introduced can be considered insignificant.

### 6.3.3 Instrumental error

The instruments that are used to take measurements also introduce errors in accuracy. In the non-intrusive compensated slip method, instruments are used to measure voltage, current and vibration. A DAQ device is also used to sample the measured signals. Each of the instruments used contributes to the overall measurement error. In order to minimise the instrumental error, the measurement instruments were calibrated prior to conducting the experiments.

A further source of instrumental errors can be the improper use of instruments. Clamp-on current and voltage transducers were used. Improper jaw closure and alignment of clamp-on instruments can produce inaccurate measurements. If the conductor is not centred in the Hall-effect probes, errors will be introduced in the amplitude and phase of measured signals. This can exceed 1%. Errors due to improper jaw closure can be as high as 1% in the amplitude measurements and 5% in phase measurements [14].

In Figure 6.11, the sources of errors for the non-intrusive efficiency estimation technique are shown.



**Figure 6.11.** The sources of errors in the non-intrusive motor efficiency estimation technique.

The accuracy of the instruments used in the experiment is summarised in Table 6.3. The speed estimation accuracy is the mean of the results obtained from the speed estimation technique presented in Chapter 4.

**Table 6.3.** Percentage error in transducers and estimated parameters.

Instrument/ Parameter	Error (%)
Voltage probes	$\pm 2$
Current probes	$\pm 3$
Estimated speed	$\pm 0.2$

### 6.3.4 Statistical analysis

Measurements of physical phenomena will always contain some degree of inconsistency. This is due to imprecision in a combination of methodical, human and instrumental errors. The random errors associated with motor losses and efficiency are assumed to be normally

distributed [19]. An effective way of reducing random errors in a normal distribution is by taking the mean value of multiple measurements. This approach was employed in the experiments that were conducted. The measurement sample mean is given by (6.3), [67].

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n} \quad (6.3)$$

where  $\bar{X}$  is the arithmetic mean,  $X_i$  is the  $i^{\text{th}}$  measurement and  $n$  is the number of samples. Standard deviation can be used as a measure of the dispersion of measurements from the average value. The standard deviation of a data sample is given by (6.4).

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} \quad (6.4)$$

where  $\sigma$  is the standard deviation. The mean values and standard deviation of the efficiency estimates for each of the test motors were calculated and are shown in Table 6.4. In a normal distribution 68.2% of all the estimates will lie with the standard deviation.

**Table 6.4.** Percentage error in the efficiency estimation technique.

3 kW Motor		11 kW Motor		15 kW Motor	
Motor Load	Error	Motor Load	Error	Motor Load	Error
7.3	-3.31	2.99	12.91	2.19	20.74
25.76	4.97	21	8.65	16.15	2.95
38.3	10.3	35.67	11.74	26.65	5.05
53.15	6.87	49.49	7.21	40.27	8.61
65.07	0.56	64.06	6.66	60.04	5.16
76.88	0.39	77.59	3.2	79.51	5.92
88.15	-3.34	91.44	6.35	91.05	4.2
99.32	-5.78	101.78	0.87	106	0.05
Mean	1.33	-	7.2	-	6.59
Mean > 50%	-0.26	-	4.86	-	4.79
Mean > 75%	-2.91	-	3.47	-	3.39
Standard deviation	5.60		4.01		6.22

### 6.3.5 Error estimation

Several error estimation methods exist for quantifying the error boundary. The worst case error method was used to calculate the worst case error that can be obtained from implementing the non-intrusive compensated slip method. The worst case error assumes that all the instrumental errors are at a maximum [65]. For the non-intrusive compensated slip method the error derived from (6.1) is given by:

$$\eta \pm \xi_{\eta} = \frac{Slip \pm \zeta_{slip}}{Slip_{rated}} \cdot \frac{P_{output,rated}}{(V \pm \xi_v)(I \pm \xi_i)} \cdot \left( \frac{V \pm \xi_v}{V_{rated}} \right)^2 \quad (6.5)$$

$$1 \pm \varepsilon_{\eta} = \frac{1 \pm \varepsilon_{slip}}{1} \cdot \frac{1}{(1 \pm \varepsilon_v)(1 \pm \varepsilon_i)} \cdot \left( \frac{1 \pm \varepsilon_v}{1} \right)^2 \quad (6.6)$$

$$1 \pm \varepsilon_{\eta} = \frac{(1 \pm 0.002)(1 \pm 0.02)^2}{(1 \pm 0.02)(1 \pm 0.03)} \quad (6.7)$$

$$1 \pm \varepsilon_{\eta} = 1 \pm 0.097 \quad (6.8)$$

The worst case error that can be obtained from the efficiency estimation method is 9.7%. This calculation only takes into account the instrumental error. This result is used with (6.2) to factor in the effect of the methodical error.

$$\xi_{\eta} = 0.2 + 0 + 0.097 \quad (6.9)$$

$$\xi_{\eta} = 0.297 \quad (6.10)$$

The worst case overall error that can be obtained from the technique is therefore 29.7%. The influence of human error is assumed to be negligible, since most of the experiments are automated.

The tolerance of the slip was found to be within 1% of the rated slip. The accuracy of the method employed can be improved by using higher accuracy instruments. The minimum instrument accuracies as stipulated by the IEEE standard 112 are shown in Table 6.5 [15].

**Table 6.5.** Minimum transducer accuracy for IEEE 112 standard.

Instrument/Parameter	Error (%)
Voltage probes	±0.5
Current probes	±0.5
Speed	±0.067

This can be used to improve the worst case error estimate:

$$1 \pm \varepsilon_{\eta} = \frac{(1 \pm 0.00067)(1 \pm 0.005)^2}{(1 \pm 0.005)(1 \pm 0.005)} \quad (6.11)$$

$$1 \pm \varepsilon_{\eta} = 1 \pm 0.021 \quad (6.12)$$

$$\xi_{\eta} = 0.01 + 0 + 0.021 \quad (6.13)$$

$$\xi_{\eta} = 0.031 \quad (6.14)$$

The worst case error estimate that will be obtained from implementing the non-intrusive compensated slip method under the conditions described above is 3.1%. It should however be noted that the worst case error estimate overstates the actual error. This is because the

probability of all the transducers operating at their worst is at a minimum and their influence on the final estimate is not equally weighted. This method only produces a maximum error boundary for the techniques. Other methods, such as the realistic error estimation and the realistic perturbation-based estimation methods, take into consideration the influence of each parameter to provide a more realistic error estimate [19], [65].

#### 6.4 CHAPTER SUMMARY

A detailed analysis of the sensitivity of the non-intrusive compensated slip efficiency estimation technique to variations in the supply voltage was presented. The analysis was supported by experimental performance data. This shows that the technique is robust to under-voltage and over-voltage power system conditions. The accuracy of the method in the conditions is comparable to the performance at the rated supply voltage. In voltage unbalance conditions, the accuracy of the techniques is expected to decline. This is because of the effects of unbalance on the efficiency of induction motors are not factored into the technique.

A thorough measurement error analysis was presented. The contribution made by methodical, human and instrumental error was discussed. The methodical error due to inherent assumptions in the method may have an adverse effect on the overall accuracy of the efficiency estimation technique. The non-intrusive compensated slip method was found to have a worst case error estimate of 3.1%.

## CHAPTER 7

# APPLICATIONS TO MOTOR MANAGEMENT

### 7.1 INTRODUCTION

Electric motors are a key part of industry. They are used in a wide variety of equipment and processes. This includes fans, pumps, compressors, conveyor drives and machine tools. Motors are a leading power consumer due to their widespread use in industry. Motors account for more than two thirds of the electrical power consumption in some countries. As the cost of electricity continues to increase, motors provide a great opportunity to reduce energy consumption.

Energy conservation technologies can reduce the energy consumption by an estimated 11 to 18% [68]. The reduced energy consumption results in a reduction in operating costs for businesses. This means less power has to be generated. This in turn reduces the harmful greenhouse gases emitted into the atmosphere.

Motor management can be described as strategies that focus on reducing the total cost of ownership of motors in a plant. The cost of ownership of motors includes the energy cost of running a motor, the cost of purchasing motors, the cost of maintaining motors, and the business cost incurred as a result of motor-related process interruptions [69]. A comprehensive motor-management strategy incorporates the benefits of the latest technology and the application of best practices to the repair of motors in a plant. The ultimate aim of a motor-management strategy is to ensure a reliable plant at the lowest possible motor-related costs [70].

In this chapter the applications of the motor efficiency and speed estimation techniques are presented with a focus on motor management. The benefits that can be obtained from using energy-efficiency motors are discussed. Energy management and the cost savings that can be obtained through developing a structured approach to motor energy consumption are investigated. An economic model for determining the optimal time a motor should be replaced with a higher efficiency motor is presented. Further, a motor maintenance strategy is proposed.

## 7.2 ENERGY MANAGEMENT

An energy management strategy in an organisation must aim to reduce the energy cost component in order to maximise profit. This is primarily achieved through ensuring that the business uses energy as efficiently as possible. An energy management programme must seek to minimise the adverse impact on the environment. This can be achieved by understanding how the business uses energy and creating an awareness of energy saving. Efficient maintenance structures must be put in place [71].

Motor energy-management strategies focus on load management, efficiency management and power factor correction [72]. A starting point for energy management is to perform an energy audit. This determines how power is consumed by the plant. Once an audit has been conducted, energy-saving opportunities can be identified. Plans for implementing them can be put in place. The energy audit identifies the following areas for potential improvements [73].

- The efficiency of the operations.

- The efficiency of the billing systems.
- The efficiency of the maintenance activity.

The *efficiency of operations* entails assessing the design and operation of the different processes in the plant to determine if they use energy efficiently. A motor energy audit must focus on the motor sizes and determine how well they are matched to the load requirements. Incorrect motor sizing has a negative impact on the efficiency of the motor. A motor that is sized larger than required results in operation at a lower efficiency. This translates to energy loss. Motors usually operate at their highest efficiency at between 75 to 80% of their rated load. The efficiency and power factor both decline as the load reduces. Motors are often oversized to allow for higher future loads or to make provision for short-term load requirements [70].

The *billing system* must be analysed to ensure that the economic tariff structure is optimal while considering the plant's operational requirements. It is also important to determine the contribution made by motors to the overall energy consumption a plant. This allows for the quantification of potential savings through motor management strategies. The maintenance activity within the plant has to be assessed to determine the standard. Poor maintenance results in a reduction in efficiency.

A portable instrument for measuring and logging of motor load profiles and estimating efficiency is a valuable tool to conduct an energy audit. It could further be used to determine the power factor of the motor.

Once the data from an audit has been collected, it must be analysed and opportunities for energy savings should be identified. Action plans must then be put in place. The following alternatives can be implemented:

- a. The motor can be kept intact.
- b. The motor can be replaced with a new standard motor.

- c. The motor can be replaced immediately with a higher efficiency motor.
- d. Control systems such as flux optimisation or variable speed drives can be implemented to improve the efficiency of the motor [72].

The action taken depends on the load or process requirements. After analysing the plant processes there, opportunities for optimising the process efficiency through implementing a control strategy can be identified. A thorough economic comparison of the available options is necessary to maximise savings.

### **7.3 MOTOR REPLACEMENT**

In this section the development of a motor replacement strategy is discussed. Tools for economic analysis of the potential benefits of replacing motors with energy-efficient motors are presented.

#### **7.3.1 Motor replacement strategy**

The benefits of replacing a standard-efficiency motor with an energy-efficient motor have been presented. A motor replacement strategy has to be developed. This ensures that clear guidelines exist on how to ensure that motors are operated with the desired reliability and at optimal life cycle costs. An installed motor can be replaced with an energy-efficient motor under the following conditions [74]:

- a. When a motor has failed;
- b. When a new motor is required for an application; and

- c. When a motor currently in operation is to be replaced.

In each of the cases an economic evaluation of the available options has to be performed to quantify the benefits. A repair/replacement strategy has to consider the following:

- The impact on energy usage
- The cost of the capital to be spent
- The motor size
- The motor repair cost
- The motor operating and repair history
- The replacement motor cost
- The availability of a replacement [75].

The energy usage and efficiency of the installed motor must be compared to an energy-efficient replacement motor. An energy-efficient motor provides an opportunity to reduce the cost of energy for operating the plant. There is an opportunity to assess if the motor is properly sized for the load. An oversized motor operates at a lower efficiency level. This results in energy wastage. The repair cost can be used to make the repair/replace decision. If the motor repair cost exceeds a certain percentage of the replacement cost, the motor must be replaced with an energy-efficient motor. The motor operating and repair history is an important factor when making the decision. A strategy for repairing/replacing a motor must consider the reliability of the motor and the probability of future failures. If a motor has been repaired for a predetermined number of times, it should be scrapped. The availability of an energy-efficient replacement motor needs to be investigated. If there is a long lead time for the replacement motor, then the production losses incurred until replacement might be excessive. The lead time for the motor repair had adverse consequences if there are no spares and it runs critical process equipment. The above-mentioned factors need to be taken into account when doing an economic evaluation.

New installations present a good opportunity to introduce energy-efficient motors on a plant. The plant will yield benefits of using energy-efficient motors. The motor strategy for

a plant must specify that all new motor installations use energy-efficient motors. A detailed analysis can be done to determine the feasibility of introducing an energy efficient motor as a replacement for a standard-efficiency motor that is still operational.

### 7.3.2 Economic analysis

In order to replace a standard efficiency motor with an energy-efficient motor, a capital investment is required. Before a capital investment is made, an economic analysis has to be performed to determine the return on investment. The return on investment is used to determine the economical feasibility of purchasing a new motor. A challenge in implementing a motor replacement or repair strategy is that the financial benefits of the investment may only be realised a few years later. The justification for the capital investment has to be made at the time the motor is replaced. Methods for performing the required economic analysis are presented in this section.

When comparing different economic investment options, it is necessary to convert them to a common base. Numerous techniques can be used to enable such a comparison. The most widely used methods for enabling economic comparison are the payback, net present value, internal rate of return, project balance and annual equivalent methods. Although all of the tools mentioned can be used, the preferred methods are the net present value and payback methods. These two methods and their application to motor comparison are investigated in detail [76].

To evaluate as to whether replacing a motor with an energy-efficient motor is feasible, information on the process and motors is required. The electricity tariff structure, annual motor load profile and motor efficiency curve are required to determine the annual power consumption of the motors to be compared. In a plant where there is an established energy-management structure, motor load profiles for each motor may exist. Where such

information is not readily available, a power-logging instrument can be used to determine the motor load profile.

The efficiency estimation technique presented in this research can be used to determine the motor efficiency curve at each point of the motor load cycle. The efficiency curve of the energy-efficiency replacement motor can be requested from the motor manufacturer. The effective interest, energy cost inflation rate, cost of motor replacement and its expected operating life are additional information required to determine the net present value of the investment.

The annual savings that will be realised by replacing a motor with an energy-efficient motor are given by (7.1), [77].

$$A_{saving} = P_{out} L h_r C \left( \frac{1}{E_c} - \frac{1}{E_r} \right) \quad (7.1)$$

where  $P_{out}$  is the motor rated power in kW,  $L$  is the percentage of full load divided by 100,  $h_r$  is the annual motor operating hours,  $C$  is the average energy cost per kWh,  $E_c$  is the efficiency of the motor currently installed and  $E_r$  is the efficiency of the energy-efficient replacement motor. In (7.1) it is assumed that the motor will operate at the same load when it is in service. In order to be able to compare the total savings that will be achieved, the net present value of the savings need to be calculated over the motor's expected operating life.

Once the annual savings have been determined, the net present value of the savings that will accrue over the motor's operating life can be determined. The net present value is a method that is used to bring the savings that will be realised over an extended period to their present equivalent. It takes the time value of money [76] into account. This calculation must include the cost of the capital required to purchase the new motor and a projection of the expected inflation rate for the cost of energy over the operating life of the

motor. To determine the present value of the savings, it is necessary to calculate the effective interest rate using (7.2).

$$i = \frac{100+r_2}{100+r_1} - 1 \quad (7.2)$$

where  $i$  is the effective interest rate,  $r_1$  is the expected annual energy cost inflation rate and  $r_2$  is the required internal rate of return on investments. The inflation rate and internal rate of return are assumed to be constant over the calculation period. After the effective interest rate has been calculated, the present value of the savings to be obtained can be determined from (7.3).

$$NPV_{saving} = A_{saving} \frac{(1+i)^n - 1}{i(1+i)^n} \quad (7.3)$$

where  $A_{saving}$  is the annual savings,  $i$  is the effective interest rate and  $n$  is the expected operating life of the new motor. The present value of the savings obtained can then be compared to the expense that will be incurred in purchasing the new motor. If the cost of the new motor is less than the net present value of the savings that will be achieved, a business case can be presented.

In providing economic justification for motor replacement, the payback period can be used as an alternative method for making the decision. The payback period for a motor replacement study is the time it will take for the benefits of replacing the current motor to exceed the capital invested in purchasing the new motor. The payback period can be calculated using (7.4), [77].

$$n_{PB} = \frac{\ln\left(\frac{A_{saving}}{iC_{motor} - A_{saving}}\right)}{\ln(1+i)} \quad (7.4)$$

where  $n_{PB}$  is the payback period in years,  $A_{saving}$  is the annual savings,  $i$  is the effective interest rate and  $C_{motor}$  is the cost of the replacement motor. The cost of the new motor must include labour and downtime for the installation and uninstalling. When using the payback period for deciding the feasibility of replacing a motor, a project with a shorter payback period is most feasible.

In determining the annual savings it should be noted that equation (7.1) is only applicable to motors that operate under constant load. This is because the efficiency of both motors under consideration will vary with different loading points. The annual savings do not take into account the demand charge for electricity. In cases where the motor is considered to make an appreciable contribution to the maximum demand, the annual energy savings calculation has to be modified to take this into account [78]. The power saved in kW can be calculated using (7.5).

$$P_{saving} = P_{out} L \left( \frac{1}{E_c} - \frac{1}{E_r} \right) \quad (7.5)$$

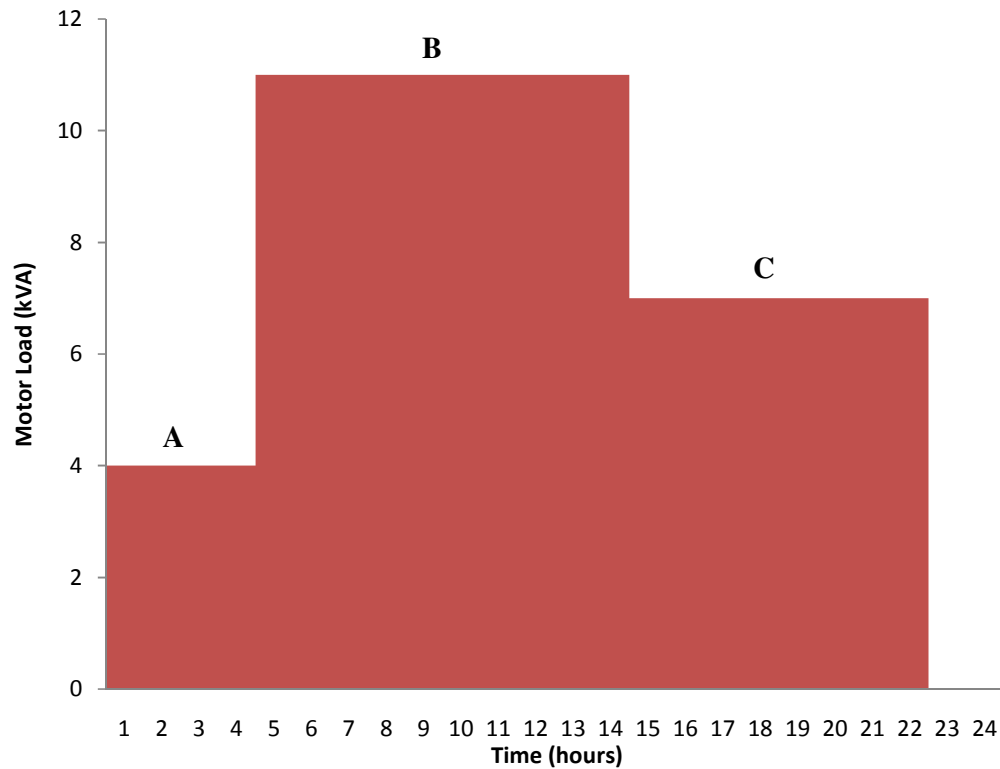
The annual savings that will be achieved by reducing the maximum demand are determined using (7.6).

$$D_{savings} = 12 \times P_{saving} \times D_c \quad (7.6)$$

where  $P_{saving}$  is the power saving in kW and  $D_c$  is the demand charge. The total annual saving,  $T_{saving}$  is given by (7.7). The total annual saving can be substituted for the annual savings in the expression for calculating the net present value and the payback period:

$$T_{saving} = A_{saving} + D_{savings} \quad (7.7)$$

If the motor load profile is not constant the equations presented need to be applied to each relatively constant portion of the motor load cycle that is relatively constant. An example of such a load profile is shown in Figure 7.1.



**Figure 7.1.** Motor load daily load profile.

The annual savings are determined as follows:

1. The calculation would be done for each of the three loading points, A, B and C. The annual operating hours would be determined by multiplying the daily hours at each loading point by the number of days the motor operates per year.

2. The output power for each of the loading points would be determined.
3. The annual saving would be calculated using the efficiency at each loading point.
4. The total annual saving would be determined using (7.8) as the sum of the savings for each loading point:

$$A_{saving} = \sum_A^C P_{out} L h_r C \left( \frac{1}{E_c} - \frac{1}{E_r} \right). \quad (7.8)$$

In developing a motor replacement policy the tools that have been presented can be applied. It is recommended that minimum economic requirements be determined and adopted for a company. This guides decision making on motor replacement based on either the net present value or the payback period. A decision should not be based on motor replacement only. It must factor in the expected future repair costs of the older motor installed in the plant. A comprehensive economic analysis must also explore the benefits obtained from power factor correction and the impact of available rebate programmes for energy-efficient motors. This will form an integral part of a motor-management strategy.

#### 7.4 MOTOR MAINTENANCE

The importance of a good maintenance strategy in an organisation is often understated. Table 7.1 shows the contribution made by maintenance-related to the total operating costs [79]. This varies across different industry sectors. The maintenance cost is made up of the following components.

- a. The direct cost of repairs
- b. The cost of any pro-active work (labour, materials, contractor, etc)
- c. The cost of lost revenue and reputation due to downtime
- d. The cost of any penalties that are incurred as a result of damaged products or operating systems.

**Table 7.1.** The contribution of maintenance to operating costs [79].

Industry	Contribution (%)
Mining	20 – 50
Primary metals	15 – 25
Electric utilities	15 – 25
Manufacturing	5 – 15
Processing	3 – 15
Fabrication and assembly	3 – 5

It is clear that the cost of maintenance can be too significant to ignore in any plant. A good motor maintenance programme extends the life of motors and improve system availability. This will result in a reduction in maintenance costs and downtime-related losses [70]. A motor-maintenance strategy must have guidelines for motor storage, installation, operation and repair.

Motors that are kept in storage for have a higher probability of failure if they are not stored according to best practices. The way in which a motor is installed has a significant impact on its reliability and operating life. When a motor is installed it is essential to ensure that is has the proper foundation and alignment procedures in place to minimise additional stresses to the motor. This can exceed the design limits [70]. Motors should be operated according the manufacturers’ guidelines to ensure that they achieve the design life.

The repair of motors presents an opportunity to implement policies that will result in long-term savings. The repair of motors must be governed by guidelines such that repairs are only carried out when it is financially feasible. Managing motor repairs starts with establishing repair specifications and identifying suitable suppliers that can provide high-quality repairs [75]. Agreements must be put in place with supplies to ensure that the repair of motors is done according to industry best practices. The motor repair decision flowchart in Figure 7.2 illustrates how decisions can be made when a motor fails in order to minimise the life cycle costs. Keeping a detailed motor repair history is important. Analysing the



trends can allow for estimating the life of the motor based on its reliability and age. This can prevent the repair of a motor that is near the end of its life and allows for the introduction of an energy-efficient motor in its place. The proposed decision-making process focuses on using all available data to make decisions that will realise cost savings over the operating life of the motor and plant. It guides a motor manager to take a holistic approach that takes into account energy efficiency and long-term benefits.

A reliability-centred maintenance (RCM) approach has been found to be effective for motors [80]. RCM is a proactive maintenance strategy that has processes for anticipating which failure modes will occur [79]. Once the failure modes have been determined the consequences of each failure mode are analysed. Plans are developed to eliminate or minimise the consequences of each of the failure modes.

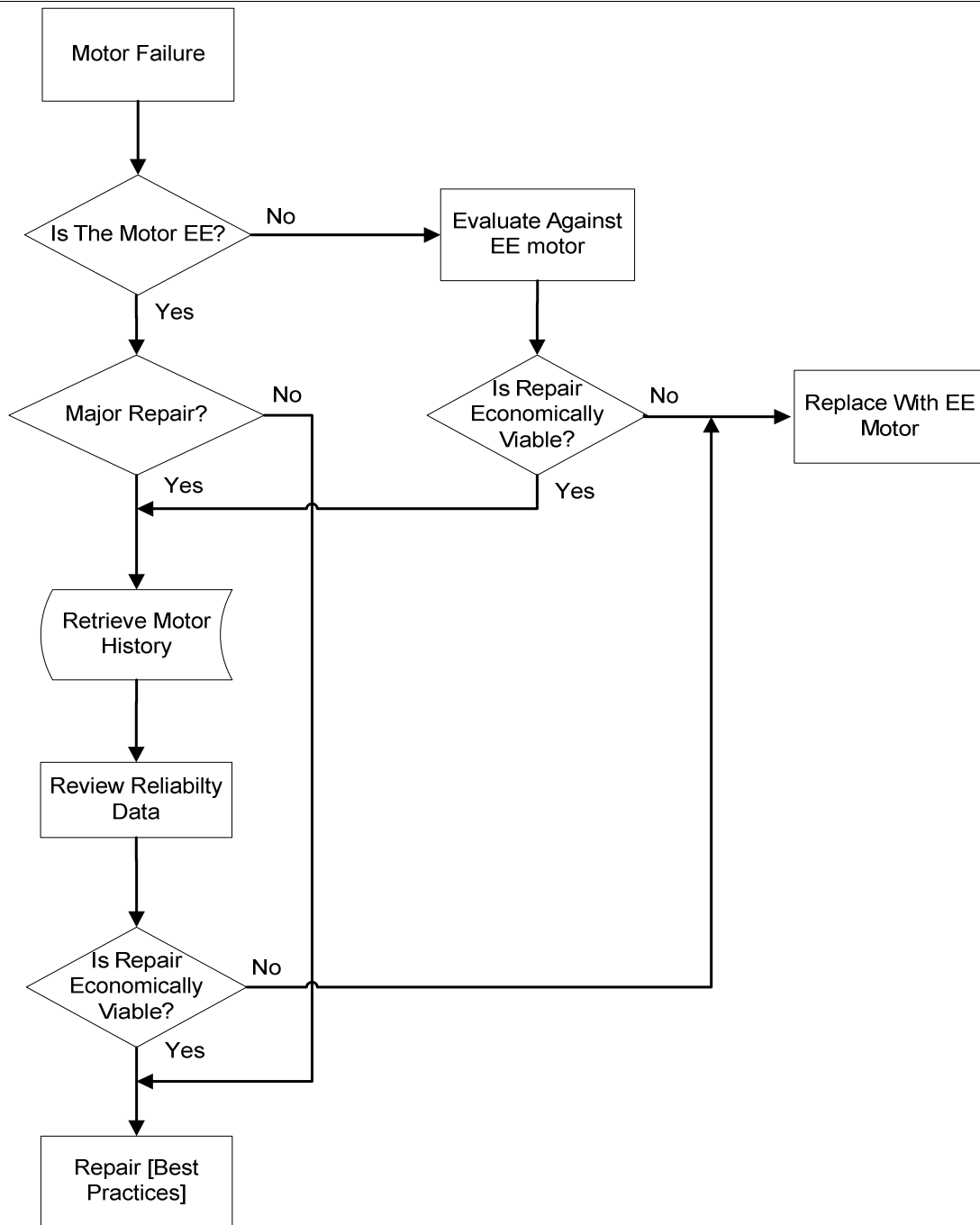


Figure 7.2. Motor repair decision flowchart.

## 7.5 MOTOR CONDITION MONITORING

Condition monitoring is the best solution for equipment failures that do not occur frequently, but cause costly repair or downtime. The vibration-based speed estimation technique presented in this research has direct applications to vibration-based condition monitoring. Vibration monitoring techniques for identifying faults in rotating equipment have been widely published [81]. It has been found to be a reliable way of detecting mechanical and electrical faults in electric motors. The early detection of conditions that will lead to motor failure will allow preventative maintenance to be done in a planned way to prevent the consequences of a breakdown.

In vibration-based condition monitoring techniques the amplitude and frequency of the motor vibration signal are used to identify different faults that occur in a motor. The following types of electrical faults can be detected in the vibration signature [49]:

- Unbalanced supply voltage;
- Single phasing of the supply or loose connections;
- Unbalanced stator resistance. Inter-turn insulation faults. Phase-to-earth insulation faults. Phase-to-phase insulation faults;
- Stator shorted laminations;
- Stator loose iron;
- Broken rotor bars;
- Broken rotor shorting rings;
- Bad joints between rotors bar and shorting rings;
- Shorted rotor laminations; and
- Cracked rotor bars.

Mechanical faults that can be identified from the vibration signature are listed below:

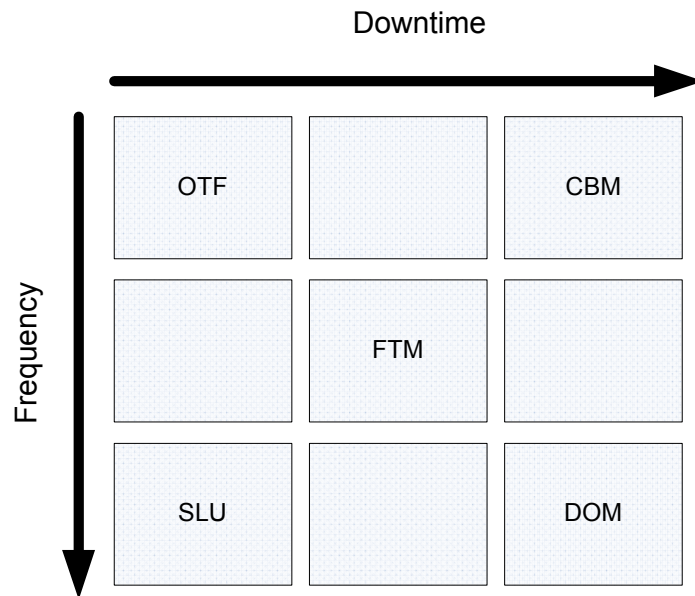
- Stator eccentricity,

- Stator loose iron,
- Eccentric rotor (variable air gap),
- Loose rotors bars,
- Roll bearing defect (early stage),
- Roll bearing defect (advanced stage),
- Misalignment (angular, parallel and bearing),
- Unbalance (force, couple, and overhung rotor),
- Eccentric rotor,
- Bent shaft,
- Mechanical looseness (depends on the type of looseness), and
- Rotor rub.

Condition monitoring will form a part of the motor maintenance strategy. The RCM strategy for the motors will determine the steps to be taken when a fault is identified. Depending on the nature and cost to repair a fault, the RCM analysis can recommend running a motor to failure.

Figure 7.3 shows a model that can be used to select which maintenance policy to adopt for equipment, based on the frequency of failure and the duration of the downtime as a result of the failure [82]. For failures that do not occur frequently and do not result in a lot of downtime, it is proposed that the equipment be operated to failure without any maintenance intervention. Failures that occur very frequently but do not result in a lengthy downtime can be addressed by upgrading the skills of the operator or maintenance technicians to allow them to repair the equipment quickly to reduce the downtime. When failures on equipment occur at a moderate frequency and the downtime as a result of the failure is also moderate, scheduling time-based maintenance intervals could be the most economic approach.

Condition-based maintenance is a good strategy for equipment failures that occur infrequently but lead to excessive downtime when they do occur. This strategy must be employed on critical plant equipment where downtime will result in a situation where personnel safety is threatened and/or huge financial losses will be incurred. The worst case scenario for plant equipment is a situation where equipment fails very frequently and each failure results in a lot of downtime. In such a case, it is recommended that a design change be made to improve the equipment.



OTF= Operate to Failure  
 CBM = Condition-based Maintenance  
 FTM = Fixed Time Maintenance  
 SLU = Skills Level Upgrade  
 DOM = Design Out Maintenance

**Figure 7.3.** A selection model for maintenance policies.

## **7.6 MOTOR MANAGEMENT**

The discussion of the previous section culminates in the development of a total motor-management strategy. This ensures that motors on a plan have the lowest possible operating cost and very high reliability. A total motor-management approach with real time efficiency and vibration-based condition monitoring is proposed.

### **7.6.1 Strategy**

A comprehensive strategy for motor management must be developed for an organisation. This strategy should provide a clear guideline on new motor specifications, motor operation, motor repair/replacement, energy management to maintenance etc. The development of the strategy must include all stakeholders. It must be supported by senior management to ensure success.

### **7.6.2 People**

The people working in the team must have the required level of skill and motivation to implement the required tasks in the motor-management strategy autonomously.

### **7.6.3 Work management**

A structured work management process, which includes long-term planning and efficient work scheduling and execution, must be established. Key components of work management start with having a process in place for identify and assigning the work that needs to be done.

### **7.6.4 Material management**

A process for material management must be put in place to ensure that the required materials to maintain motors are available on time. This also entails that an efficient procurement process be in place for repairs and the purchasing of new motors.

### **7.6.5 Basic motor maintenance**

Basic motor maintenance refers to routine preventative maintenance tasks such as condition monitoring. These tasks should be determined through the RCM process for maintaining the motors in a plant.

### **7.6.6 Performance management**

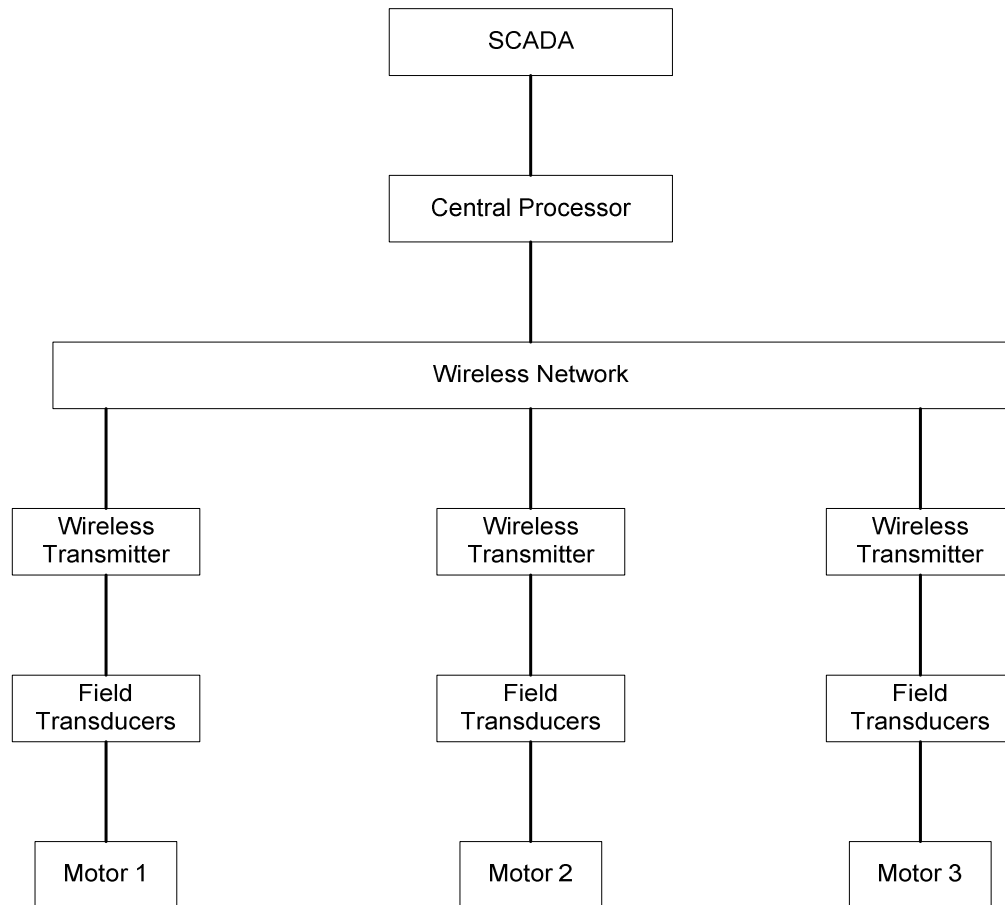
Performance targets for the motor-management programme have to be developed and defined clearly. The periodic measurement of performance against the set targets is important to determine how effective the strategy is. It also provides an opportunity to identify performance gaps and action plans to close the gaps.

### **7.6.7 Technical support systems**

Technical support systems that make implementing the motor-management strategy easier and more efficient should be used. Such systems should include the condition-monitoring tool described in the previous section and systems for data collection and storage. In Figure 7.4 a motor-management system is presented. This system consists of local field instruments at each motor for measuring its voltage, current and vibration. The data are then sent via a wireless network to a central processor. At the central processor the speed and efficiency estimation technique presented in Chapter 5 is implemented. Energy usage and reliability indicators for each motor can also be calculated at the central server. The vibration signal may also be used for condition monitoring. The data are sent to a Supervisory Control and Data Acquisition (SCADA) system for storage so that historic data can be accessed for use in motor replacement and energy-management studies. Alarms can be sent to the SCADA system to inform control room operators of developing motor faults so that corrective action can be planned and scheduled. This will result in cost saving because unplanned downtime will be reduced.

### 7.6.8 Motor reliability

The RCM process should provide a comprehensive preventative maintenance programme that will ensure that motors operate at high reliability. Once a well-established motor-management process is in place, the organisation can provide valuable input to motor manufacturers that can result in design improvements.



**Figure 7.4.** Motor management support system.

## 7.7 CHAPTER SUMMARY

An overview of motor energy management has been presented. Tools for performing an economic comparison of motors were discussed. The tools can be used to determine the annual savings that can be realised by using an energy-efficiency motor, as well as the payback period on the initial capital investment. The non-intrusive compensated slip method can be used to estimate the efficiency of an installed motor. This enables the above-mentioned calculations to be made.

The motor speed estimation technique based on vibration signature analysis can be used for detecting numerous fault conditions. An outline of the different motor faults that can be detected from vibration signature analysis was given. A method of deciding how to handle motor failures has been proposed. This method takes into account the economic aspects of repairing the motor, whilst considering the reliability history of the motor.

A comprehensive motor-management strategy is presented. This motor management strategy centres on finding the correct balance through:

- assembling the correct team of people;
- implementing good work management structure;
- applying effective performance management systems;
- putting in place an effective materials management structure; and
- using support systems that add value.

A motor-management system built around a network of field sensors to provide real-time data on the condition of motors in a plant. This allows proactive decisions to be made to minimise breakdowns and optimise energy usage.

# CHAPTER 8

## CONCLUSION

### 8.1 INTRODUCTION

In this chapter a summary of the work that has been done in this dissertation is presented. The contributions of this work are highlighted. Recommendations for future work are presented.

### 8.2 DISSERTATION SUMMARY

A review of motor efficiency estimation techniques has been presented in Chapter 2. Although several authors have presented various different methods for estimating the efficiency of an in-service motor, many of the methods still present a high level of intrusion. There is a trade-off between the level of invasiveness of the method and the accuracy of the efficiency estimate obtained. The few truly non-intrusive methods that are reasonably accurate still need further development and testing to simplify and verify their practicality and accuracy.

A comprehensive survey of speed estimation techniques is presented in Chapter 3. The strengths and weaknesses of the available estimation techniques were discussed. A new technique for estimating motor speed based on vibration signature analysis is presented in Chapter 4. The performance of this method is evaluated experimentally. It is found that this method can provide accurate speed estimates within 0.55% of the measured motor speed.

In Chapter 5, a practically implementation of six of the motor efficiency estimation techniques that were discussed in Chapter 2 is presented. The performance of these

methods is evaluated against the accurate measured efficiency of the motor under test. The new method for estimating motor efficiency is practically implemented. This method is based on a non-intrusive compensated slip method. The motor speed is obtained using the speed estimation technique introduced in Chapter 4. An experimental setup was developed to test the proposed motor efficiency estimation technique. Three test motors were used in the evaluation of the techniques. The proposed method of estimating motor efficiency is easy to implement and does not result in expensive plant downtime.

In Chapter 6, the effects of a change in power system conditions on the performance of the non-intrusive compensated slip technique are investigated. An error analysis is done to quantify the errors that one can expect when using the proposed technique. The efficiency estimation technique can provide efficiency estimates that are within  $\pm 3.1\%$  of the actual motor efficiency.

Chapter 7 presents the applications of the motor efficiency and speed estimation techniques to motor management. The benefits that can be obtained from using energy-efficient motors are discussed. Energy management and the cost savings that can be obtained through developing a structured approach to motor energy consumption are investigated. An economic model for determining as to whether a motor should be replaced with a higher efficiency motor is presented. A comprehensive motor maintenance strategy is also proposed in this chapter.

### 8.3 CONTRIBUTION

The contributions that have been made by this work are outlined below.

- A comprehensive literature review was conducted on motor efficiency estimation techniques. Gaps in the body of knowledge were identified.
- A survey of motor speed estimation techniques was presented. A new motor speed estimation technique was developed. Its performance was verified through results experimental results.

- Six efficiency estimation techniques were implemented. Their practical performance was compared to the non-intrusive compensated slip technique.
- A non-intrusive compensated slip method for estimating the efficiency of induction motors was developed. The performance of this method was verified through experimental data.
- The robustness of the non-intrusive compensated slip method to variations in the supply voltage was evaluated.
- An error analysis was done to determine the expected error that can be introduced from the application of the proposed efficiency estimation technique.
- An integrated approach to apply the speed and efficiency estimation technique as part of a motor-management strategy to reduce motor life cycle costs while increasing reliability was presented.
- An experimental setup that can be developed into an instrument was developed. Custom software was written in LabVIEW for controlling the experiments and implementing the efficiency and speed estimation techniques.

The research performed in this work has also produced the following research papers:

- A paper titled “A Practical Evaluation of Motor Efficiency Estimation Techniques” was presented at the *Industrial and Commercial use of Energy Conference* in Cape Town in August 2010. This paper was based on the work done in Chapter 5.
- A paper titled “A Non-intrusive Compensated Slip Method for Motor Efficiency Estimation using Vibration Signature Analysis” was presented at the *IEEE Industrial Electronics Society AFRICON11 Conference* in Livingstone in September 2011. This paper was based on the work done in Chapters 4 and 5.
- A journal article titled “A Non-intrusive Method for Motor Efficiency Estimation using Vibration Signature Analysis” has been submitted to the *Elsevier International Journal of Electrical Power and Energy Systems* for publication. This paper was based on the work done in Chapters 2, 4 and 5.



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## 8.4 RECOMMENDATIONS FOR FUTURE WORK

The following are recommendations for future work:

- The effects of power quality on slip-based motor efficiency estimation techniques can be investigated.
- A study on the applications to motor condition monitoring of the speed estimation technique can be developed further. A comparison between current and vibration signature analysis techniques for condition monitoring can be made.
- The effects of motor defects or developing faults on the efficiency of motors can be investigated.
- The development of an accurate non-intrusive motor output torque estimation technique can be researched to provide an alternative motor efficiency estimation technique.

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