PARAMETER AND SPEED ESTIMATION OF INDUCTION MOTORS FROM MANUFACTURERS DATA AND MEASUREMENTS

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Approval of the Graduate School of Natural and Applied Sciences

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Çağlar Hakkı ÖZYURT

ABSTRACT

PARAMETER AND SPEED ESTIMATION OF INDUCTION MOTORS FROM MANUFACTURERS DATA AND MEASUREMENTS

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In industrial drives market, requirements related to control quality and price of drives are important. In low cost drives, one of the aims is achieving speed estimation accuracy.

Since motor parameters are required to estimate speed and sometimes it is impractical to do no-load and locked rotor tests, it is necessary to estimate motor parameters from motor label or by simple measurements.

Throughout this study, some of parameter estimation and speed estimation methods found in literature are investigated and some new methods are proposed. These methods are applied to three induction motors and estimation results are compared with test results. Advantages and disadvantages of these methods are investigated.

As a result of this study, the most suitable parameter and speed estimation methods amongst these methods are obtained for low cost motor drives.

Keywords: induction motor, parameter estimation from manufacturer data, speed estimation, scalar control

ÖZ

ASENKRON MOTOR PARAMETRELERİNİN VE HIZININ KATALOG BİLGİLERİNDEN VE ÖLÇÜMLERDEN TAHMİNİ

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Endüstriyel sürücü pazarında, kontrol kalitesi ve sürücü fiyatları önemlidir. Düşük maliyetli sürücülerde amaçlardan biriside motor hızının doğru olarak tahmin edilmesidir.

Motor hızını tahmin edebilmek için motor parametrelerini bilmek gerektiğinden ve bazen kilitli rotor ve yüksüz motor deneylerini yapmak mümkün olmadığından, motor parametrelerinin etiket bilgilerinden veya basit ölçümlerden tahmin edilmesi gerekmektedir.

Bu çalışmada, literatürde bulunan parametre tahmin ve hız tahmin yöntemlerinden bazıları incelenmiş ve bazı yeni metodlar önerilmiştir. Bu metodlar üç tane asenkron motor üzerinde uygulanmış ve tahmin sonuçları deneylerle karşılaştırılmıştır. Bu metodların avantaj ve dezavantajları değerlendirilmiştir.

Sonuç olarak bu çalışmada, incelenen yöntemler arasında düşük maliyetli sürücülere en uygun olan parametre tahmin ve hız tahmin yöntemleri belirlenmiştir.

Anahtar Kelimeler: asenkron motor, üretici bilgilerinden parametre tahmini, hız tahmini, skalar kontrol

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INTRODUCTION

1.1. Introduction

Prior to 1950s nearly all industrial applications required the use of a DC motor drive since AC motors were not suitable for speed control with the technology available at the time [1]. Nowadays modern AC motor drive performance is comparable with DC motor drive. This goal has been achieved because development in power electronics and microprocessors led to introduction of sophisticated AC motor drives [2].

Number of AC motor drives using induction motor is still increasing in industrial applications. Majority are based on scalar control principle where the control algorithm can be implemented on simple microcontrollers. Sophisticated control methods require fast processors which increase the price of drives [2].

Cost saving aspects are important for applications at low power drives below 5 kW. At high power, the power components dominate the system cost. Therefore fast processor can be used at high power drives [7,8].

To reduce the initial cost of the low cost motor drives, it is necessary to use low performance microprocessors. Since price of the microprocessor is proportional to the performance of the microprocessor, in low cost drives it is necesary to control speed ad torque with minimum number of calculations and minimum measurements.

The aim of this study is achieving speed estimation accuracy and torque estimation accuracy with minimum number of calculations and measurements.

Any method for speed prediction is based on a model of the motor and the drive. The best accuracy of prediction for an induction motor may be expected when the exact model is used. However, this would bring too much computational burden and would require knowledge of all the motor parameters.

Motor parameters can be calculated from no-load and locked rotor tests or can be estimated. On-line estimation of parameters places an important burden of the microprocessor. Therefore, low cost drives avoid this approach and often estimate parameters from the user supplied motor label data. Some new methods are proposed in this study to estimate motor parameters off-line from manufacturer's data.

Since accurate knowledge of the motor parameters is required to predict speed from exact motor model, one of the aims of this study is achieving speed or torque estimation accuracy with minimum number of the motor parameters.

Various speed estimation techniques are described in literature. The most common method used in practice is linearization of torque-speed curve [5,10]. Base frequency, speed, output power, number of poles and stator resistance are used in this method. These data are obtained at base frequency and rated torque. This method has drawbacks at high loads and in the field weakening region.

Another speed estimation method, which does not require motor parameters except stator resistance, is based on a non-linear relationship between air-gap power and slip speed [6]. Base frequency, voltage, current, speed, power factor, output power, number of poles, efficiency, breakdown torque at base frequency and stator resistance are used in this method. These data are obtained at base frequency and rated torque. In this method, since the breakdown torque is assumed to be constant and stator resistance is neglected at calculation of slip speed, this approach is not suitable for high speeds and small motors, at which voltage drop on the stator resistance is comparable to input voltage at low frequencies. So there is room for improvement.

1.2 Contents of the thesis

Chapter 2 includes a brief explanation of proposed parameter estimation methods. In this chapter, results of parameter estimation methods are also investigated.

Chapter 3 is assigned to investigate the some of the speed estimation methods found in literature and proposed methods. A theoretical evaluation of these methods is also given in this chapter.

Chapter 4 is assigned for simulation and experimental work. In this chapter, hardware and modulation technique of the drive used for tests are briefly explained. Then calibration of voltage and current measurement modules are explained. Then measurement of torque, speed and rotational losses are explained. Then estimation of core loss, estimation of power factor, calculation of rms value of current and voltage are verified. Finally simulation software used in this thesis is based on exact induction motor model is explained.

Chapter 5 is assigned to verification of the exact induction motor model and evaluation of accuracy of speed estimation methods presented in the previous chapters.

Chapter 6 includes the conclusion of this study.

CHAPTER 2

PREDICTION OF INDUCTION MOTOR PARAMETERS FROM MANUFACTURER DATA

2.1 Introduction

The majority of variable speed drives are used in general purpose applications. In such applications, the most important factors are ease of initialization and low overall cost.

Motor parameters and motor ratings must be known to initialize the drive. Using these data, the drive often predicts the motor speed and some control is applied, if the user prefers to operate the drive in speed control mode or torque control mode. Classical method for parameter determination uses the no-load and locked rotor tests results. This classical parameter determination method is sometimes impractical for initializing a motor drive. To simplify the initialization process, motor parameters can be estimated from manufacturer data by the drive processor. When literature (Science Citation Index 1945-2004 and IEEE archieves) is investigated, only three research methods are found on this issue.

In one of these methods, motor parameters are estimated from manufacturer data with a numerical method [17]. This off-line parameter estimation method requires a computer and necessary software to make these calculations. In this method, initial values of motor parameters are calculated with some assumptions. Then, each parameter is changed from initial value to zero with small steps. This step size defines the accuracy. For each possible combination of parameters, exact equivalent circuit of induction machine is used and mechanical power, reactive power at full load and breakdown torque are calculated. Results of these calculations are compared with manufacturer supplied data and errors of these calculations are found. Then each error is weighted in accordance to the importance of these calculations by the user of this method. Total weight of the errors is calculated for each possible combination. This method is finalized by selecting the motor parameters by looking into minimum error weight. It is reported that this method is applied to 223 motors and error of this method is nearly 1%.

In [26], motor parameters are estimated from manufacturer data such as name-plate data and motor performance characteristics. This method is based on a non-linear optimization routine. Therefore this method is not suitable to be embedded on a low performance microprocessor.

In [27], parameter estimation method requires the name-plate data, ratio of starting to full load torque and the efficiency and power factor values at half and full load. Since motor data at half load are not accessible in manufacturer data, this method is not suitable for the aim of this study.

Since these methods are not suitable to be embedded on a low performance microprocessor, it is decided to propose a method which has good accuracy with lower computational burden.

In this chapter, several methods are proposed for prediction of motor parameters from manufacturer supplied data or motor label. These methods are examined on 1.1 kW, 2.2 kW and 4 kW induction motors. To verify the proposed methods, no-load and locked rotor tests are applied to these motors. Motor parameters are calculated from no-load and locked rotor tests results and compared with estimated motor parameters.

Predicted torque-speed characteristics of the test motors are also compared with measurements at 50Hz. Since the drive is normally operated in the portion of torque-speed curve between no-load speed and full-load speed, the predictions are done for this portion of the torque-speed curve.

It is seen in tests that some of the manufacturer supplied data may be different from test results. Parameter predictions are made using manufacturer's data and presented in Appendix A. However, all of the parameter predictions in this section are done on the basis of motor label data determined from tests on the three test motors.

The predicted performance for the proposed parameter identification method (torque, power factor, stator current) are compared with the predicted performance of the motors from no-load and locked rotor parameters and measured performance of the motors.

In the following sections, each of the proposed methods is described.

2.2 Method 1

In this method, approximate circuit model, which is seen in Fig.2.1, is used. Rated voltage, rated current, rated power factor, output power, frequency, rotor speed and measured stator resistance are used to estimate motor parameters. Flow chart of this method is seen in Fig.2.2. This method is summarized below.

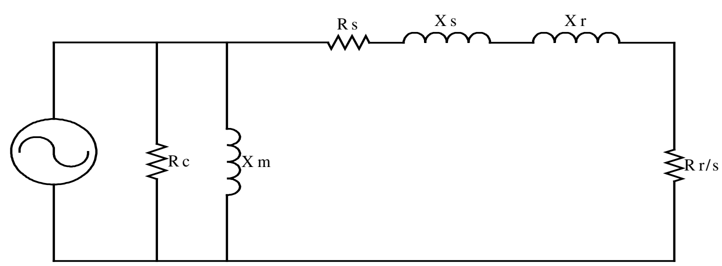

Fig.2.1. Approximate model of Induction Machine

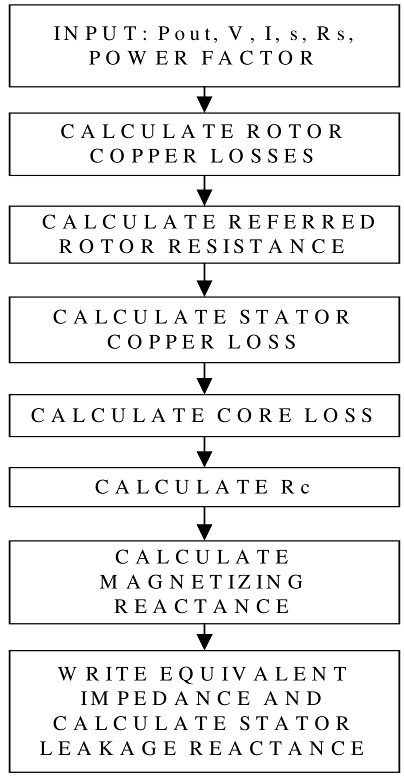

Fig.2.2 Flow chart of Method 1

It is assumed that friction and windage losses are equal to the 1% of output power. Another assumption is that stator leakage reactance is neglected for the calculation of magnetizing reactance. That imaginary part of stator current flows on the magnetizing reactance is assumed. Rotor copper losses can be calculated as in equation (2.5).

$$P_{out} = P_{AG} - P_{RCL} - P_{F\&W} \tag{2.1}$$

$$P_{F\&W} = 0.01 * P_{out} \tag{2.2}$$

$$(P_{OUT} + P_{F\&W}) = 3 * I_r^2 * \frac{R_r}{s} - 3 * I_r^2 * R_r \tag{2.3}$$

$$(P_{OUT} + P_{F\&W}) = 3 * I_r^2 * R_r * (\frac{1-s}{s}) \tag{2.4}$$

$$P_{RCL} = 3*I_r^2*R_r = (P_{OUT} + P_{F\&W})*(\frac{s}{1-s}) \qquad (2.5)$$

where P_{AG} denotes air-gap power, $P_{F\&W}$ denotes friction and windage losses, P_{RCL} denotes rotor copper loss, P_{out} denotes output power, s denotes slip, I_r denotes referred rotor current and R_r denotes referred rotor resistance.

2.2.1 Calculation of R_r

Referred rotor current can be written as

$$|I_r| = \frac{V_\phi}{\sqrt{(R_S + R_r/s)^2 + (X_s + X_r)^2}} \qquad (2.6)$$

where V_ϕ denotes phase voltage.

Assume that

$$X_s = X_r \qquad \& \ (R_s + R_r/s)^2 >> (4*X_s^2) \qquad (2.7)$$

If the assumptions seen above are valid, rotor current and rotor copper losses formulas can be rearranged as below

$$|I_r^2| = \frac{V_\phi^2}{(R_s + R_r/s)^2} \qquad (2.8)$$

$$P_{RCL} = \frac{3*V_\phi^2*R_r}{(R_s + R_r/s)^2} \qquad (2.9)$$

from equation (2.9)

$$(\frac{P_{RCL}}{s^2})*R_r^2 + (\frac{2*R_s*P_{RCL}}{s} - 3*V_\phi^2)*R_r + R_s^2*P_{RCL} = 0 \qquad (2.10)$$

in equation (2.10), only referred rotor resistance is unknown, so rotor resistance is found by calculating the roots of equation (2.10).

2.2.2 Calculation of R_c

Core loss is calculated as in equation (2.14)

$$P_{in} = \sqrt{3} * V_{l-l} * I_{l-l} * \cos\varphi \qquad (2.11)$$

$$P_{loss} = P_{in} - P_{out} \qquad (2.12)$$

$$P_{SCL} = \frac{3 * V_{\phi}^{2} * R_s}{(R_s + R_r / s)^2} \qquad (2.13)$$

where P_{SCL} denotes stator copper loss.

$$P_{core} = P_{loss} - P_{SCL} - P_{RCL} - P_{F\&W} \qquad (2.14)$$

R_c is calculated as in equation (2.15).

$$R_c = \frac{3 * V_{\phi}^{2}}{P_{core}} \qquad (2.15)$$

2.2.3 Calculation of X_m

It is assumed that imaginary part of the stator current flows on magnetizing reactance.

$$X_m = \frac{V_{\phi}}{I * \sin\varphi} \qquad (2.16)$$

2.2.4 Calculation of X_s

Equivalent impedance of the model is written as in equation (2.17).

$$\frac{1}{Z_{eq}} = \frac{1}{R_c} + \frac{1}{jXm} + \frac{1}{(R_s + R_r / s) + j(X_s + X_r)} = A - jB \qquad (2.17)$$

If tangent of load angle is written as in equation (2.18) and substituting the equalities of A and B, equation (2.20) is achieved.

$$\tan(-\varphi) = \frac{-B}{A} \tag{2.18}$$

$$\frac{1}{X_m} - \frac{\tan\varphi}{R_c} = \frac{\tan\varphi * (R_s + R_r / s) - 2 * X_s}{(R_s + R_r / s)^2 + 4 * X_s^2} \tag{2.19}$$

$$4*\left(\frac{1}{X_m} - \frac{\tan\varphi}{R_c}\right)*X_s^2 + 2*X_s + \left(\frac{1}{X_m} - \frac{\tan\varphi}{R_c}\right)*(R_s + R_r / s)^2 - \tan\varphi*(R_s + R_r / s) = 0 \tag{2.20}$$

Only stator leakage reactance is unknown in equation (2.20), so stator leakage reactance can be calculated by solving the roots of equation (2.20).

2.3 Method 2

Approximate induction motor model is used in this method as in Method 1. Rated voltage, rated current, rated power factor, output power, frequency, rotor speed and measured stator resistance are used to estimate motor parameters. Flow chart of this method is shown in Fig.2.3. This method is summarized below.

Rotor copper losses and friction & windage losses are assumed to be equal to 1% of output power.

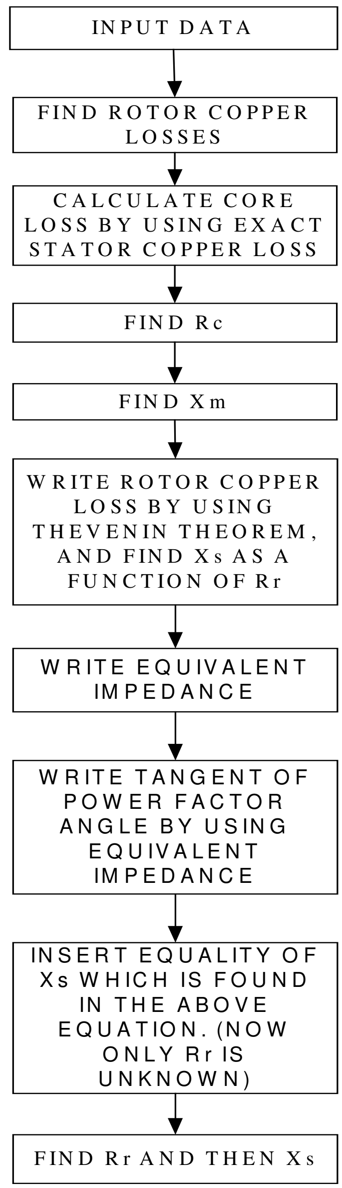

Fig.2.3. Flow chart of Method 2

2.3.1 Calculation of R_c & X_m

Only difference is that stator copper loss is calculated from exact circuit model.

$$P_{SCL} = 3 * I_s^2 * R_s \tag{2.21}$$

R_c is calculated by using equation (2.22)

$$R_c = \frac{3 * V_\phi^2}{P_{core}} \tag{2.22}$$

Calculation of magnetizing reactance is same with Model1.

$$X_m = \frac{V_\phi}{I * \sin\varphi} \tag{2.23}$$

2.3.2 Calculation of R_r & X_s

Rotor copper loss is written as in equation (2.25). One more important difference between Method 1 and Method 2 is for the calculation of rotor copper loss. In the calculation of rotor current, effect of the stator leakage reactance and referred rotor leakage reactance are not neglected in this method.

$$\left|I_r\right| = \frac{V_\phi}{\sqrt{(R_S + R_r / s)^2 + (X_s + X_r)^2}} \tag{2.24}$$

$$P_{RCL} = 3 * I_r^2 * R_r \tag{2.25}$$

Substitute the equality of referred rotor current into the equation (2.25), and calculate stator leakage reactance as a function of referred rotor resistance as shown in equation (2.26).

$$4 * X_s^2 = \frac{3 * V_\phi^2 * R_r}{P_{RCL}} - (R_s + R_r / s)^2 \tag{2.26}$$

If equivalent impedance and tan (φ) are written, stator leakage reactance is found as a function of referred rotor resistance.

$$\frac{1}{X_m}-\frac{\tan\varphi}{R_c}=\frac{\tan\varphi*(R_s+R_r/s)-2*X_s}{(R_s+R_r/s)^2+4*X_s^2} \tag{2.27}$$

$$2*X_s=\tan\varphi*(R_s+R_r/s)+\left(\frac{\tan\varphi}{R_c}-\frac{1}{X_m}\right)\left[(R_s+R_r/s)^2+4*X_s^2\right] \tag{2.28}$$

Substitute the equality of X_s^2 which is found equation (2.26) into the equation (2.28)

$$2*X_s=\tan\varphi*(R_s+R_r/s)+\left(\frac{\tan\varphi}{R_c}-\frac{1}{X_m}\right)\left(\frac{3*V_\phi^2*R_r}{P_{RCL}}\right) \tag{2.29}$$

If square of equation (2.29) is calculated and equality of $4X_s^2$ is substituted into equation (2.26), equation (2.30), which is independent from stator leakage reactance, is achieved.

$$\frac{3*V_\phi^2*R_r}{P_{RCL}}-(R_s+R_r/s)^2=\left[\tan\varphi*(R_s+R_r/s)+\left(\frac{\tan\varphi}{R_c}-\frac{1}{X_m}\right)\left(\frac{3*V_\phi^2*R_r}{P_{RCL}}\right)\right]^2 \tag{2.30}$$

In equation (2.30), only referred rotor resistance is unknown. Referred rotor resistance is found by calculating the roots of equation (2.30). Stator leakage reactance is calculated by substituting calculated referred rotor resistance into equation (2.29).

2.4 Method 3

In this method, steady state equivalent circuit model, which is seen in Fig2.4, is used. Only rated voltage, rated current, rated power factor, output power, frequency and motor speed values are used. To start with initial condition, stator leakage reactance is assumed to be equal to zero. Flow chart of this method is seen in Fig.2.5. This method is summarized below.

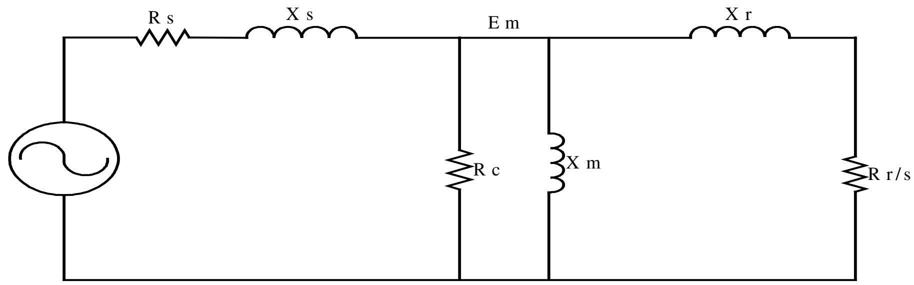

Fig.2.4 Equivalent circuit of induction machine

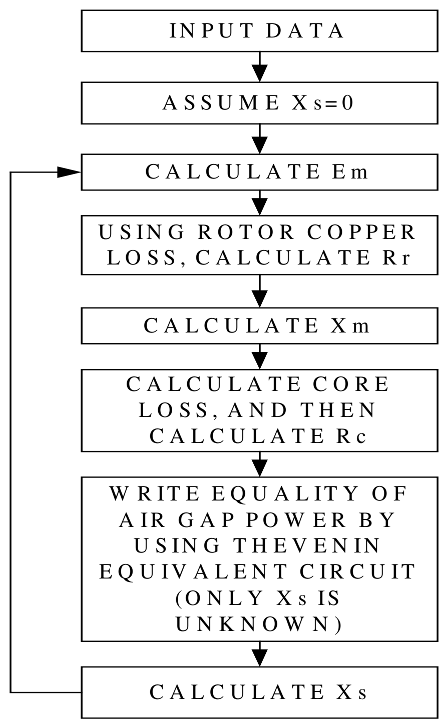

Fig.2.5. Flow chart of Method 3

2.4.1 Calculation of R_r

E_m and rotor copper loss are calculated by using equation (2.31) and (2.32) respectively.

$$\overrightarrow{E_m} = \overrightarrow{V_\phi} - (R_s + jX_s) * \overrightarrow{I_s} \tag{2.31}$$

$$P_{RCL} = \frac{3 * |E_m|^2 * R_r}{\left((R_r / s)^2 + X_r^2\right)} \tag{2.32}$$

If equation (2.32) is rearranged, equation (2.33) is achieved.

$$\frac{P_{RCL}}{s^2} * R_r^2 - 3 * \left|\overrightarrow{E}\right|^2 * R_r + P_{RCL} * X_r^2 = 0 \tag{2.33}$$

Rotor copper loss is calculated by using equation (2.5). Only referred rotor resistance is unknown in equation (2.33). Referred rotor resistance is calculated by solving equation (2.33).

2.4.2 Calculation of R_c & X_m

It is assumed that imaginary part of stator current flows on magnetizing reactance. Magnetizing reactance is calculated by using equation (2.34).

$$X_m = \frac{E_m}{I * \sin \varphi} \tag{2.34}$$

Core loss and R_c are calculated by using equation (2.36) and (2.37) respectively.

$$P_{SCL} = 3 * I_s^2 * R_s \tag{2.35}$$

$$P_{core} = P_{loss} - P_{SCL} - P_{RCL} - P_{F\&W} \tag{2.36}$$

$$R_c = \frac{3 * \left|\overrightarrow{E_m}\right|^2}{P_{core}} \tag{2.37}$$

2.4.3 Calculation of X_s

Thevenin theorem is applied to the motor model.

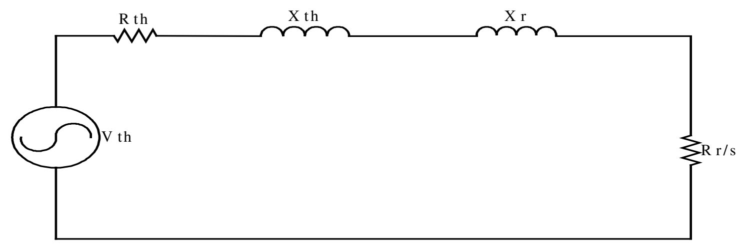

Fig.2.6. Thevenin theorem applied model of the induction machine

$$V_{TH} = V_{\phi} * \frac{X_m}{X_s + X_m} \tag{2.38}$$

$$X_{TH} = X_s \tag{2.39}$$

$$R_{TH} = R_s * \left(\frac{X_m}{X_s + X_m} \right)^2 \tag{2.40}$$

$$I_r = \frac{V_{TH}}{\sqrt{(R_{TH} + R_r / s)^2 + (X_{TH} + X_r)^2}} \tag{2.41}$$

Air gap power is calculated by using equation (2.42).

$$P_{AG} = P_{out} + P_{RCL} + P_{F\&W} \tag{2.42}$$

$$P_{AG} = \frac{3 * V_{\phi}^2 * X_m^2 * (R_r / s)}{(X_s + X_m)^2 \left[(R_s * \frac{X_m^2}{(X_s + X_m)^2} + R_r / s)^2 + (X_s + X_r)^2 \right]} \tag{2.43}$$

Only stator leakage reactance is unknown in equation (2.43). Stator leakage reactance is calculated by calculating the roots of equation (2.43). To finalize the parameter estimation, any stop criteria is not used. Process explained above is iterated 3 times with new values.

2.5 Method 4

In this method, all calculations are the same as with Method 3. The data used are same with Method 3. Flow chart of this method is seen in Fig.2.7. This method is summarized below.

Differences between Method 3 and Method 4 are that stop criteria of iterations is determined and some assumptions are changed. For instance, that $0,95 * I_S * \sin(\varphi)$ flows on X_m is assumed. In Method 3, results are three times iterated. However, in this method, power factor of the equivalent circuit is calculated and when it reaches the (nominal power factor ± 5%), iteration is stopped.

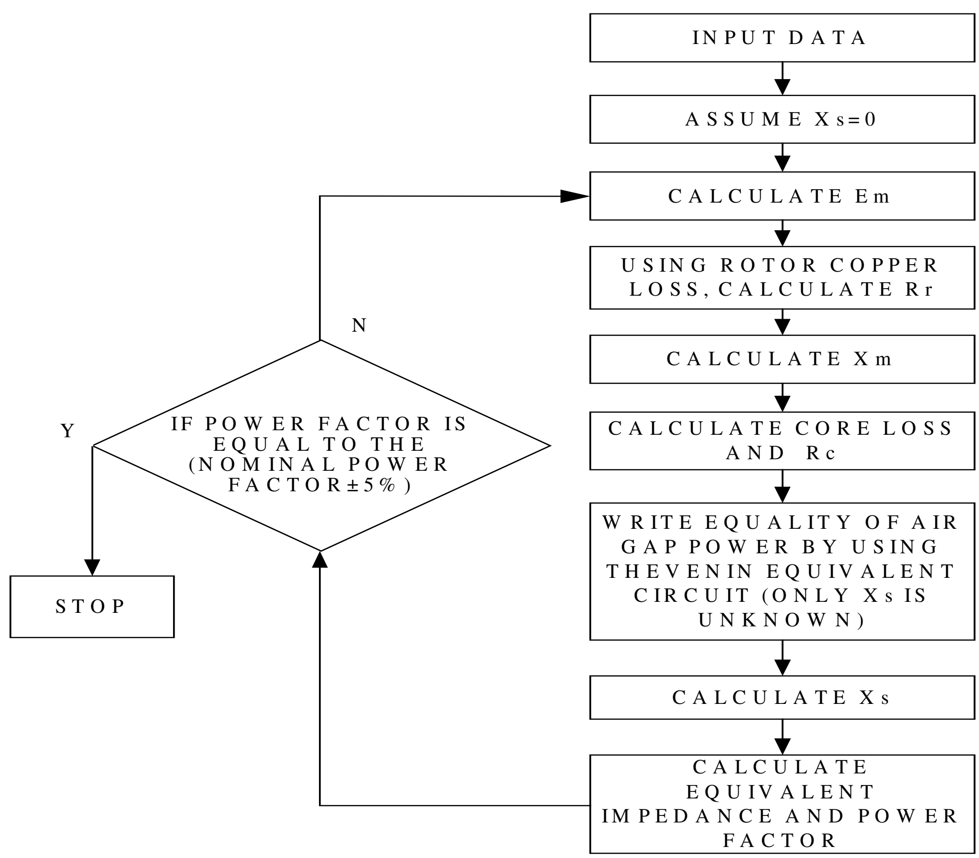

Fig.2.7 Flow chart of Method 4

2.6 Method 5

In this method, exact equivalent circuit shown in Fig.2.4 is used. Rated voltage, current, frequency, speed, power factor, output power and measured stator resistance is used in this method. Flow chart of this method is seen in Fig.2.8. This method is summarized below.

2.6.1 Calculation of X_m

It is assumed that 95% of imaginary part of stator current flows on magnetizing reactance. Stator leakage reactance is neglected and magnetizing reactance is calculated as in equation (2.44).

$$X_m = \frac{V_s - R_s.I_s}{0.95 * I_s * \sin(\varphi)} \tag{2.44}$$

2.6.2 Calculation of X_s

It is assumed that rotor side is purely resistive, stator leakage reactance is equal to rotor leakage reactance and 0.95 of imaginary part of stator current flows on magnetizing reactance.

$$I_r = \sqrt{I_s^2 - I_m^2} \tag{2.45}$$

Reactive power is calculated by using equation (2.46).

$$Q = \sqrt{3}.V_s.I_s.\sin(\varphi) \tag{2.46}$$

If equality of reactive power is written in terms of reactance and current, equation (2.47) is achieved. Only stator leakage reactance is unknown in equation (2.47). Hence, equation (2.47) is solved for stator leakage reactance.

$$Q = 3.X_s.I_s^2 + 3.X_r.I_r^2 + 3.X_m.I_m^2 \tag{2.47}$$

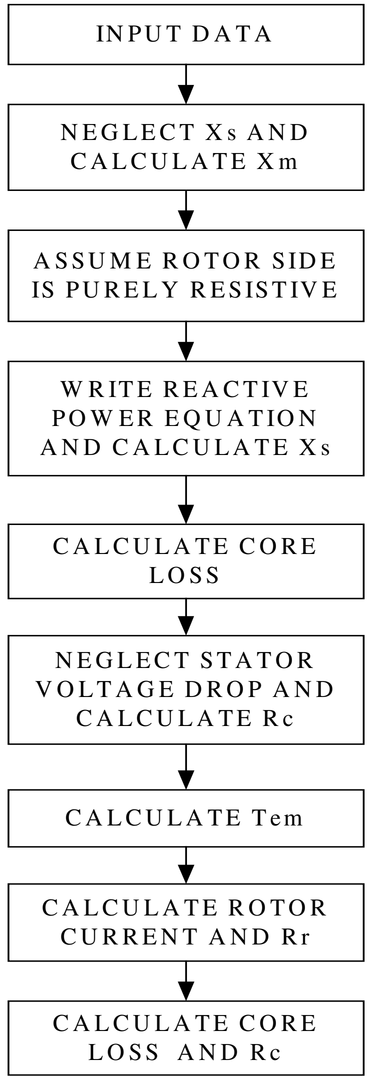

Fig.2.8 Flow chart of Method 5

2.6.3 Calculation of R_r

Initially core loss is calculated by using equation (2.49).

$$P_{core} = P_{loss} - P_{SCL} - P_{RCL} \tag{2.48}$$

$$P_{core} = P_{in}.(1 - \frac{\eta}{(1-s)}) - 3.I_s^2.R_s \tag{2.49}$$

Stator voltage drop is neglected and Rc is calculated.

$$R_c = \frac{3.V_s^2}{P_{core}} \tag{2.50}$$

It is assumed that there is nearly 90º phase shift between magnetizing current and referred rotor current. Then, referred rotor current is calculated from equation (2.51)

$$I_r = \sqrt{I_s^2 - I_m^2} - \frac{(V_s - R_s.I_s)}{R_c} \tag{2.51}$$

It is assumed that mechanical losses and stray losses are equal to the 0.01 of output power. Electromechanical torque is calculated by using equation (2.52).

$$T_{em} = \frac{P_{out} + P_{mec}}{(1-s).\omega_s} \tag{2.52}$$

If electromechanical torque is written as in equation (2.53), only referred rotor resistance is unknown. Referred rotor resistance is calculated from equation (2.53).

$$T_{em} = \frac{3.I_r^2.Rr / s}{\omega_s} \tag{2.53}$$

2.6.4 Calculation of R_c

In this part, R_c value is corrected. Firstly, core loss is calculated from equation (2.54).

$$P_{core} = P_{in} - P_{SCL} - P_{stray} - P_{conv.} \quad (2.54)$$

R_c is calculated by substituting equation (2.55) into equation (2.56).

$$E_m = V_s - (R_s + j.X_s).I_s\angle -\varphi \quad (2.55)$$

$$R_c = \frac{3.E_m^2}{P_{core}} \quad (2.56)$$

2.7 Results

To assess the parameter estimation methods, 1.1kW, 2.2kW and 4kW induction motors are selected in laboratory. Name plate values of these motors provided by the manufacturer and from the tests results by the author are given in Appendix A. Parameter calculation method from no-load and locked rotor tests results are also given in Appendix B.

As discussed before in the parameter predictions, label data for motors is determined from tests. In Table 2.1, Table2.2 and Table2.3, calculated parameters from no-load and locked rotor tests results and estimated motor parameters are given. By this way, effect of erroneous data of name-plate is prevented and parameter estimation methods can be verified.

In addition to these comparisons, it is wise to compare the torque-speed characteristics, which are calculated from estimated parameters and parameters calculated from no-load and locked rotor tests results. Torque-speed curves are prepared in accordance to the exact equivalent circuit shown in Fig.2.4. These torque-speed curves are shown in Fig.2.9, Fig.2.10 and Fig.2.11.

Table.2.1 Calculated parameters from no-load and locked rotor tests results and estimated motor parameters for 1.1kW induction motor

parameter	Calculated value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	6.8	6.8	-	6.8	-	6.8	-	6.8	-	6.8	-
Rr	6.6	9.2	-39.4	5.7	13.6	8.2	-24.2	7.3	-10.6	6.9	-4.5
Xs	9.4	0.0	100.0	9.2	2.1	5.6	40.4	11.0	-17.0	4.4	53.2
Xm	87.8	105.6	-20.3	105.6	-20.3	93.9	-6.9	88.9	-1.2	100.3	-14.2
Rc	1014.0	482.9	52.4	837.3	17.4	665.5	34.4	596.9	41.1	721.5	28.8

Table.2.2 Calculated parameters from no-load and locked rotor tests results and estimated motor parameters for 2.2kW induction motor

parameter	Calculated value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	3.3	3.3	-	3.3	-	3.3	-	3.3	-	3.3	-
Rr	3.5	3.4	2.9	3.5	0.0	3.2	8.6	3.0	14.3	3.0	14.3
Xs	5.1	0.0	100.0	1.0	80.4	2.4	52.9	4.7	7.8	1.8	64.7
Xm	98.4	86.1	12.5	86.1	12.5	78.4	20.3	76.3	22.5	83.2	15.4
Rc	1435.0	510.1	64.4	823.4	42.6	688.8	52.0	652.4	54.5	716.4	50.1

Table.2.3 Calculated parameters from no-load and locked rotor tests results and estimated motor parameters for 4kW induction motor

parameter	Calculated value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	3.9	3.9	-	3.9	-	3.9	-	3.9	-	3.9	-
Rr	4.2	4.0	5.0	4.1	2.4	3.9	7.1	3.6	14.3	3.6	14.3
Xs	6.6	0.0	100.0	1.5	77.3	2.5	62.1	7.3	-10.6	2.6	60.6
Xm	136.5	129.5	5.1	129.5	5.1	121.6	10.9	117.2	14.1	128.7	5.7
Rc	1382.0	800.9	42.0	1109.1	19.8	983.2	28.9	913.0	33.9	1010.7	26.9

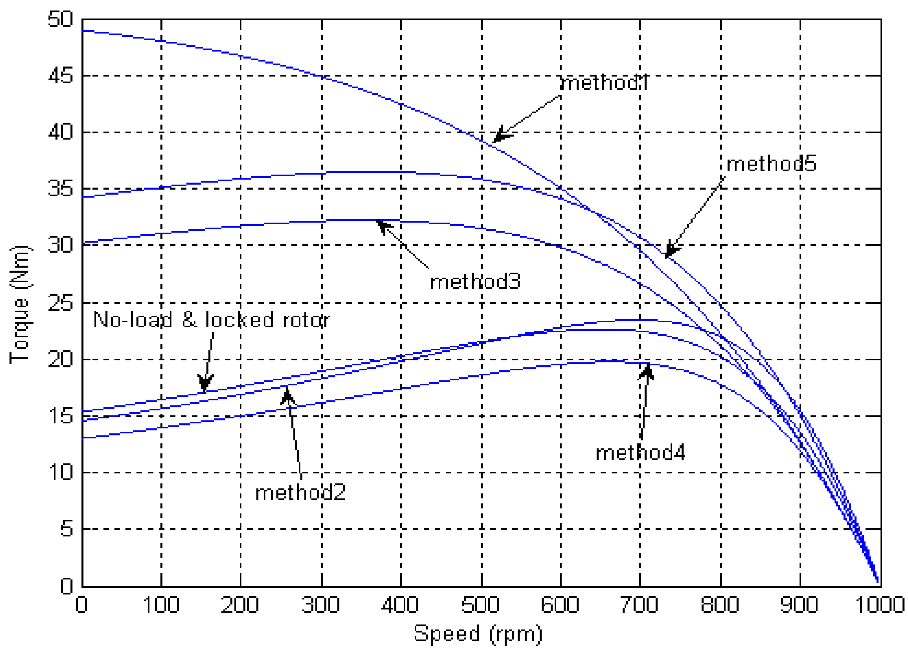

Fig.2.9 Torque-speed curves for 1.1kW induction motor

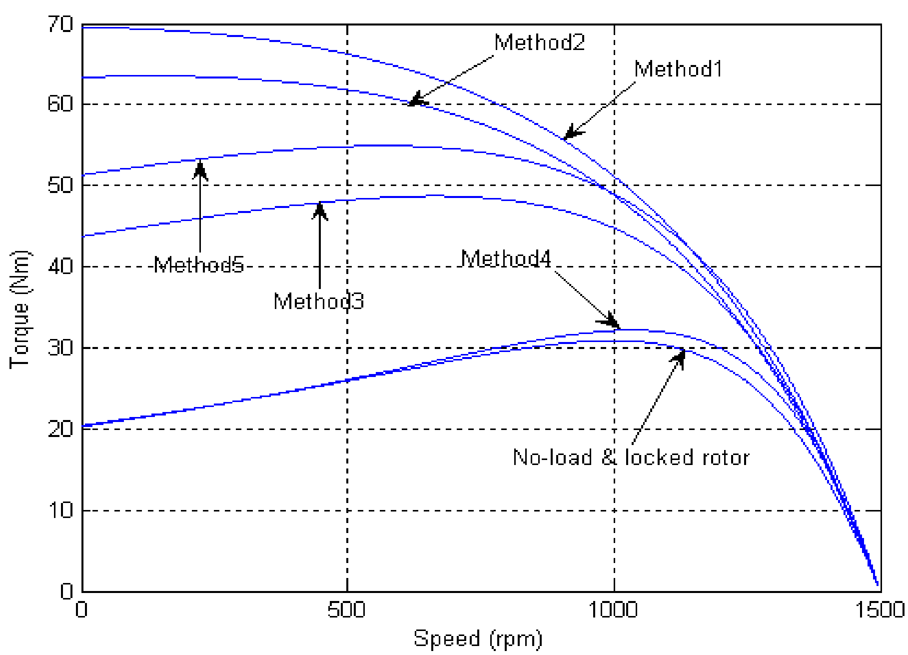

Fig.2.10 Torque-speed curves for 2.2kW induction motor

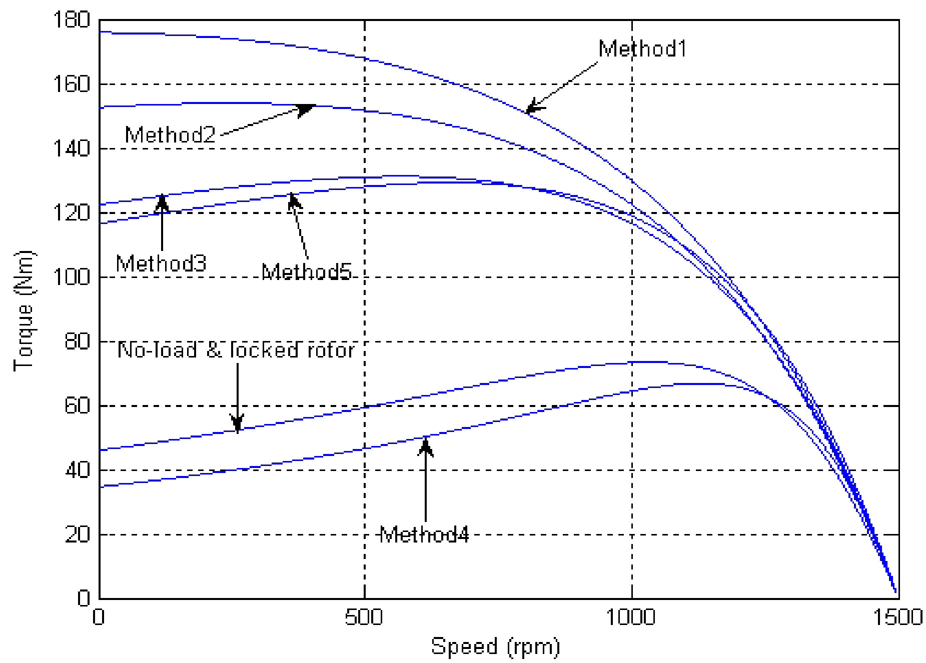

Fig.2.11 Torque-speed curves for 4kW induction motor

When the results are investigated, Method 4 can be identified as the best estimation method giving overall good prediction for the whole torque-speed curve of the three motors, when compared with the torque-speed curve estimation with no-load and locked rotor test parameters (reference characteristics) among the proposed methods.

Since the drive is normally operated in the portion of torque-speed curve between no-load speed and full-load speed, it is wise to compare the performances of these estimation methods in the linear region of torque-speed curve. Therefore, torque-speed curves are prepared for linear region as shown in Fig.2.12, Fig.2.13 and Fig.2.14.

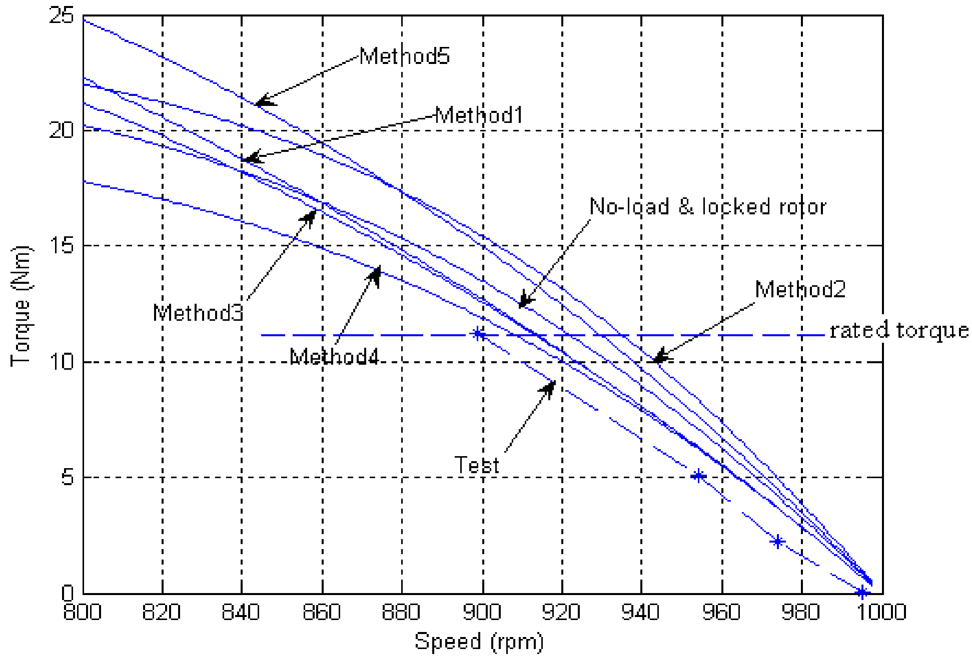

Fig.2.12 Torque-speed curves for 1.1kW induction motor

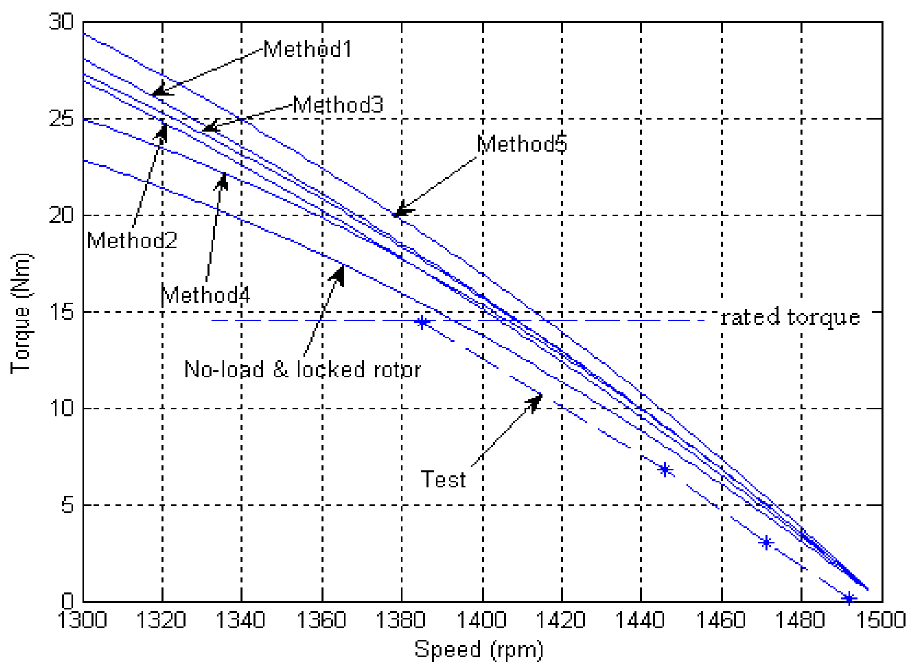

Fig.2.13 Torque-speed curves for 2.2kW induction motor

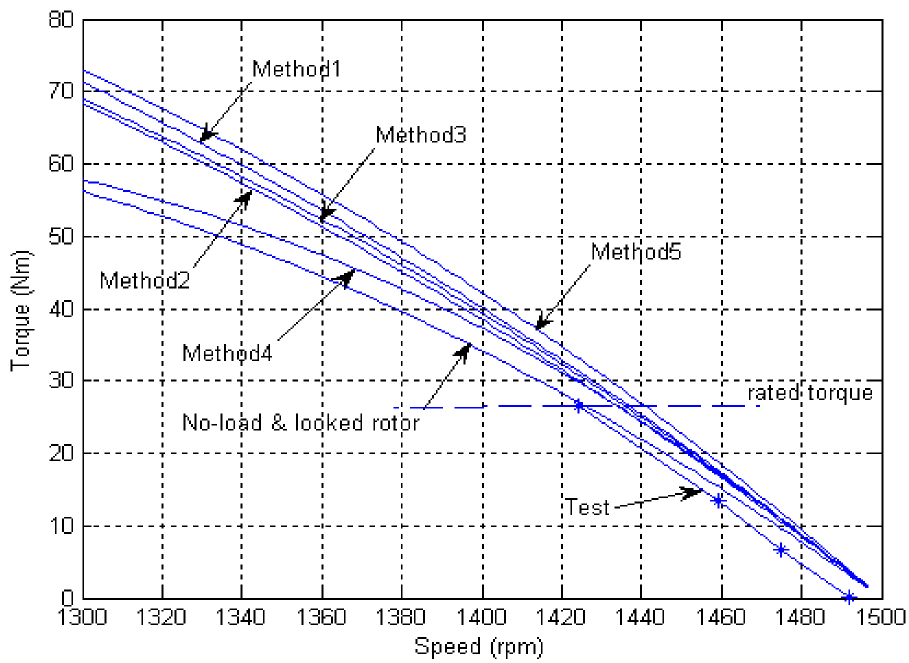

Fig.2.14 Torque-speed curves for 4kW induction motor

When the linear regions of the torque-speed curves are compared, it is seen that Method 4 has the nearest prediction to the reference torque-speed curve found with tests. As shown in Fig.2.12, Fig.2.13 and Fig.2.14, estimated torque values are larger than measured torques. When torque is taken as reference and estimated speeds are compared with reference, error is nearly 1%. However, when speed is taken as reference and predicted torques are compared with reference, error of Method 4 is nearly 10%.

The performance of the motors calculated from estimated parameters and calculated parameters from no-load and locked rotor tests results are compared also with measured motor performance at rated torque condition. The calculated performances in the tables are done at the slip value which is recorded at the rated torque load during laboratory tests. This comparison is shown in Table.2.4, Table.2.5 and Table.2.6.

Table.2.4 Comparison of performances for estimated parameters and calculated parameters from no-load and locked rotor tests results for 1.1kW motor

	Test results	Calculated parameters (% error)	Estimated parameters				
			Method1 (%error)	Method2 (%error)	Method3 (%error)	Method4 (%error)	Method5 (%error)
Torque	11.2 Nm	-6.2	1.8	-22.3	1.8	6.2	-17.0
Power factor	0.75	6.7	-6.7	-4	2.7	9.3	-6.7
Stator current	3.15 A	-8.2	4.4	-12.4	0.3	-3.27	-6.0

Table.2.5 Comparison of performances for estimated parameters and calculated parameters from no-load and locked rotor tests results for 2.2kW motor

	Test results	Calculated parameters (% error)	Estimated parameters				
			Method1 (%error)	Method2 (%error)	Method3 (%error)	Method4 (%error)	Method5 (%error)
Torque	14.6 Nm	4.1	-11.6	-6.8	-11.0	-8.2	-19.2
Power factor	0.84	1.2	-7.1	-4.8	-1.2	3.6	-4.8
Stator current	4.87 A	5.5	-4.7	-0.6	-9.6	-12.9	-12.9

Table.2.6 Comparison of performances for estimated parameters and calculated parameters from no-load and locked rotor tests results for 4kW motor

	Test results	Calculated parameters (% error)	Estimated parameters				
			Method1 (%error)	Method2 (%error)	Method3 (%error)	Method4 (%error)	Method5 (%error)
Torque	26.8 Nm	9.0	-5.2	-0.8	-3.7	-0.8	-11.6
Power factor	0.83	4.8	-4.8	-1.2	0.0	6.0	-2.4
Stator current	9.08 A	7.8	-1.5	2.3	-2.9	-7.1	-6.5

In Table.2.4, Table.2.5 and Table.2.6, error is defined as in equation (2.57).

$$\%error = \frac{test.result - estimated.value}{test.result} \tag{2.57}$$

In the evaluation of performances for estimated motor parameters, average of the error is considered. When Table.2.4 is investigated, it is shown that Method 3 and Method 1 are better than other methods for 1.1kW motor. It is shown in Table.2.5 that Method 2 is better than other methods for 2.2kW motor. For 4kW motor, Method 2 and Method 3 are more suitable than other methods. When all test motors are considered, Method 3 can be identified as the best estimation method amongst these methods.

Computational burden of parameter estimation methods is assessed in Table.2.7.

Table.2.7 Computational burden of parameter estimation methods

	Method1	Method2	Method3		Method4		Method5
			Initial	Comp. loop	Initial	Comp. loop	
Number of multiplications	33	25	9	48	10	66	66
Number of additions	6	3	3	5	3	10	4
Number of subtractions	12	9	7	7	8	8	18
Number of divisions	18	13	3	10	4	13	14
Number of square roots	3	1	1	4	2	4	4

To calculate the computation time of each method, DSPIC30F6010 (40 MHz) is taken as reference. Method 4 is assumed to be finalized in 6 iterations. It is seen that calculation time of Method 4 and Method 3 are nearly 10 ms and others are nearly 2 ms[1]. Computation times of Method 4 and Method 3 are larger than others. However,

[1] Multiplications, additions and subtractions are done in 1 instruction cycle. Division is assumed to be done in 20 instruction cycle and square root is assumed to be done in 500 µs.

parameter estimation is done at the initialization of motor drive and computation times of all methods are in the acceptable range.

To investigate the effect of erroneous data of name-plate for calculation of motor parameters and preparation of torque-speed curve, motor parameters are estimated from name-plate data and torque-speed curves are prepared in accordance to these parameters. Estimated parameters and prepared torque speed curves are shown in Appendices.

CHAPTER 3

PREDICTION OF MOTOR SPEED

3.1 Introduction

In industrial drives market, requirements related to control quality and price of drives are important. To reduce the initial cost of the low cost motor drives, it is necessary to use low performance microprocessors. Since price of the microprocessor is proportional to the performance of the microprocessor, in low cost drives one of the aims is achieving speed estimation accuracy with minimum number of calculations.

Speed estimation techniques depend on motor parameters. These motor parameters can be predicted from manufacturer data or measured. On-line measurement of parameters places an important burden on the microprocessor. For that reason, low cost drives avoid this approach and often estimate parameters from the user supplied motor label data.

The purpose of this section is to investigate methods of speed estimation in the literature and find out whether a more accurate and less computation intensive method can be developed. Various methods of speed estimation techniques are described in literature. The most common method used in practice is linearization of torque-speed curve [5][10]. This method is explained below as Method 3. Only base frequency, speed, output power, number of poles and stator resistance are used in this method. These data are obtained at base frequency and rated torque. Since the number of calculations is very low, this method can be applied with low performance microprocessors. This method has drawbacks at high loads and in the field weakening region as explained in Method 3. In [10], it is reported that when this method is applied to a 3.7 kW induction motor whose stator resistance is 0.114Ω, speed is estimated with 5% error at 20Hz under full load [10].

Another speed estimation method, which does not require motor parameters except stator resistance, is based on a non-linear relationship between air-gap power and slip speed [6]. This method is explained below as Method 1. Base frequency, voltage, current, speed, power factor, output power, number of poles, efficiency, breakdown torque at base frequency and stator resistance are used in Method 1. These data are obtained at base frequency and rated torque. When this method is applied to 3hp induction motor whose stator resistance is 0.89Ω, in [10] it is found that speed is estimated with 1% error at 10Hz under full load condition [6]. In this method, since the breakdown torque is assumed to be constant and stator resistance is neglected at calculation of slip speed, this method is not suitable for high speeds and small motors, at which voltage drop on the stator resistance is comparable to input voltage at low frequencies. For low hp motors, to obtain good speed prediction accuracy, methods must be developed taking into account the stator resistance.

When the methods in the literature are investigated, it is observed that each method has advantages and disadvantages. Therefore, it is decided to investigate the level of accuracy that may be expected from these approaches and possibly develop a more accurate approach with similar computation burden.

In this Chapter, both the existing speed estimation methods and proposed speed estimation methods are examined on 1.1 kW, 2.2 kW and 4kW induction motors.

First to verify the used circuit model, motor is driven with line voltage and calculated torque from model is compared with measured torque. That shows the best accuracy acceptable with this model.

Since the methods studied here are to be used in applications where the speed is controlled, it is essential to use an inverter. Many methods require measurement of voltage and current. Measurement of these variables affects the accuracy of predictions. For that reason, the current and voltage measurement circuits used are calibrated and measurement accuracy is investigated at different frequencies.

As the next step accuracy of the model is investigated while the three test motors are driven at 10Hz, 30Hz, 50Hz and 70Hz. Hence, idea of the accuracy of the model used is obtained for a frequency range of (10Hz-70Hz). This issue is investigated in Chapter5.

In this study, medium frequency is defined as between 20 Hz and 50 Hz. Frequencies over 50 Hz are named as high frequency. Low frequency is defined as below 20Hz in this study. Since 1.1kW, 2.2kW and 4 kW motors are available in laboratory and the capacity of the inverter is not suitable for larger motors, these motors are used in the experiments. In this study, 1.1 kW motor is named as small motor and 4kW motor is named as large motor.

Any method for speed prediction is based on the model investigated. The best accuracy of prediction may be expected when the exact model is used. However, this would bring too much computational burden and would require knowledge of all the parameters. For this reason, all the methods involve some degree of approximation. Therefore, it is wise to compare the speed estimation of a method with the speed estimation from the exact equivalent circuit.

To make realistic predictions, the simulations are made using the current and voltage values measured during tests. Therefore, any error that may be introduced due to the measurements of these variables is taken into account in these predictions. For the prediction Matlab environment is used. The Matlab model is described in Chapter 4.

In the following sections, each of the methods proposed in the literature and improvements proposed by the author are described.

3.2 Investigation of speed estimation methods

3.2.1 Method 1

In this method, exact steady-state circuit model is used. This method is based on a non-linear relationship between air-gap power and slip speed [6]. Base frequency, voltage, current, power factor, speed, number of poles, efficiency, output power, breakdown torque and stator resistance are used in this method. These data are obtained at the base frequency and rated torque. Instantaneous stator currents are measured in two phases. Output voltage of the inverter is assumed to be equal to the reference voltage. Method is summarized below.

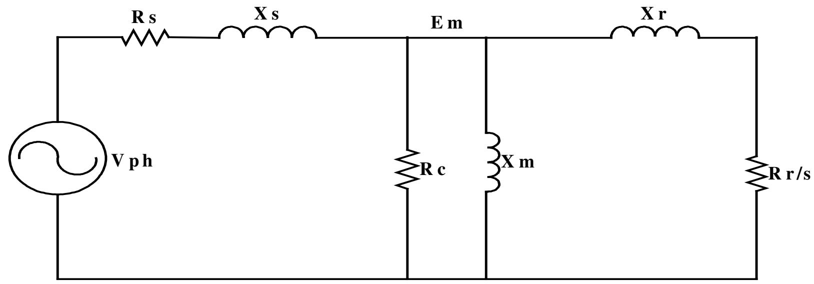

Figure.3.1: Exact steady-state model of induction machine

Thevenin theorem is applied to the stator side and torque equation is written as below.

$$T = \frac{3.V_{TH}^2.R_2/s}{\omega_s.\left[(R_{TH}+R_2/s)^2+(X_{TH}+X_2)^2\right]} \tag{3.1}$$

where ω_s is synchronous speed and V_{TH}, R_{TH} and X_{TH} are,

$$V_{TH} = \frac{V_{ph}.X_m}{X_1+X_m} \tag{3.2}$$

$$R_{TH} = R_1.\left(\frac{X_m}{X_1+X_m}\right)^2 \tag{3.3}$$

$$X_{TH} = X_1 \tag{3.4}$$

Breakdown torque can be written as

$$T_{bd} = \frac{3.V_{TH}^2}{2.\omega_s.\left[R_{TH}+\sqrt{R_{TH}^2+(X_{TH}+X_2)^2}\right]} \tag{3.5}$$

and slip at breakdown torque is,

$$s_{bd} = \frac{R_2}{\sqrt{R_{TH}^2+(X_{TH}+X_2)^2}} \tag{3.6}$$

If equation (3.1) is divided by equation (3.5), stator resistance is neglected and necessary transformations are carried out, the torque formula can be written as below.

$$T = \frac{2.T_{bd}}{\frac{s}{s_{bd}} + \frac{s_{bd}}{s}} \tag{3.7}$$

If this equation is solved, slip is,

$$s = \frac{K.K_o.T_R.s_R}{T_L}\left[1 - \sqrt{1 - \left(T_L \big/ K_o.T_R\right)^2}\right] \tag{3.8}$$

Where s_R is slip at rated torque condition and K_o, K and T_L are,

$$K_o = T_{bd} \big/ T_R \tag{3.9}$$

$$K = \frac{s_{bd}}{s_R} = K_o + \sqrt{K_o^2 - 1} \tag{3.10}$$

$$T_L = \frac{P_{gap}}{\omega_s} \tag{3.11}$$

In equation (3.11), air-gap power is calculated by subtracting the stator copper loss and core loss from input power. In the application of this method, equation (3.8) shows a non-linear relationship between air-gap power and slip. K_o, T_R and s_R values are found from motor catalogue data. K and T_L are calculated from equation (3.10) and (3.11) respectively. Finally slip is calculated from equation (3.8).

In this method, K_o is assumed to be constant. To satisfy this assumption, flux linkage must be kept constant at rated value. However, at high frequencies motor is in the field weakening region and flux linkage value is lower than rated value. Therefore, this method is not suitable for high frequencies.

Generally stator resistance of small motors is high and voltage drop on the stator resistance is comparable to input voltage at low frequencies. Since stator resistance is neglected in this method, this method is not suitable for small motors at low frequencies. However, stator resistance is generally small and voltage drop on the stator resistance can be neglected in large motors. Hence, this method can be used for large motors at low frequencies.

The validity of the assumptions at medium frequency is somewhere in between the low frequency and high frequency cases. Suitable types of motors and frequencies for this method are shown in Table.3.1.

Table.3.1 Suitable types of motors and frequencies for Method 1

	Frequency		
	Low	Medium	High
Small motors		**X**	
Large motors	**X**	**X**	

The computational burden of the method is assessed in Table.3.2.

Table.3.2 Calculation burden of Method 1

Number of multiplications	54
Number of divisions	19
Number of additions	9
Number of subtractions	9
Number of square roots	1

In view of Table.3.2 it can be concluded that, using of a high performance processor is obligatory in this approach. Since this method does not require any motor parameters except stator resistance, this method can be applied easily.

3.2.2 Method 2

To improve the performance of Method 1 in the field weakening region, this method is proposed. Philosophy of this method is same with Method 1. Base frequency, voltage, current, speed, power factor, output power, number of poles, efficiency, breakdown torque, stator resistance, magnetizing reactance and stator leakage reactance are used in this method. These data are obtained at base frequency and rated torque. Instantaneous stator currents are measured in two phases. Output voltage of the inverter is assumed to be equal to the reference voltage. This method is summarized below.

As explained in Method 1, K_o value is changing in the field weakening region. To improve the performance of Method 1 especially in the field weakening region, calculated breakdown torque from equation (3.13) is used instead of assuming K_o be constant. K_o is calculated as below.

$$K_o = \frac{T_{bd}}{T_r} \tag{3.12}$$

where T_r is rated torque and breakdown torque explained above is

$$T_{bd} = \frac{3.V_{TH}^2}{2.\omega_s.\left[R_{TH} + \sqrt{R_{TH}^2 + \left(X_{TH} + X_2\right)^2}\right]} \tag{3.13}$$

In the application of this method, breakdown torque is calculated from equation (3.13) where V_{TH}, R_{TH} and X_{TH} are calculated from equation (3.2), (3.3) and (3.4) respectively. By using calculated breakdown torque, Ko is calculated from equation (3.12) and rest of the calculations are same with Method 1.

Correction of K_o value is expected to improve the performance of this speed estimation method. This method is suitable for large and small motors at high frequencies. Suitable types of motors and frequencies for this method are shown in Table.3.3.

Table.3.3 Suitable types of motors and frequencies for Method 2

	Frequency		
	Low	Medium	High
Small motors		**X**	**X**
Large motors	**X**	**X**	**X**

Table.3.4 Calculation burden of Method 2

Number of multiplications	63
Number of divisions	23
Number of additions	13
Number of subtractions	9
Number of square roots	2

In Table.3.4, calculation burden contains calculation of breakdown torque. However, breakdown torque is calculated only one time for each voltage and frequency. Therefore, calculation burden of Method 2 is assumed to be equal to the calculation burden of Method 1. However, Method 2 requires more motor parameters. For this reason, application of Method 2 is more difficult than Method 1.

3.2.3 Method 3

This method investigated here is one of the most commonly used methods in low cost application. In this method, torque-speed curve is assumed to be linear. This method uses only base speed, output power, frequency, number of poles and stator resistance. These data are obtained at base frequency and rated torque. Voltage and current are measured. This method is summarized below.
In [5], torque equation is written as in equation (3.14).

$$T = 3.\frac{p}{2}.\lambda_m^2.\frac{\left(\frac{R_r}{\omega_{sl}}\right)}{\left(\frac{R_r}{\omega_{sl}}\right)^2 + \left(L_{lr}\right)^2} \tag{3.14}$$

where λ_m denotes flux linkage, p denotes number of poles and L_{lr} denotes rotor leakage reactance. Equation (3.14) shows that torque is proportional to slip if flux linkage is kept constant at rated value where motor parameters are assumed to be constant. If these assumptions are existing, slopes of torque-speed curves are parallel and slip speed can be calculated from equation (3.15).

$$n_{sl} = \left(\frac{T_L}{T_R}\right).n_{slr} \tag{3.15}$$

where n_{slr} is slip speed at rated condition, T_R is rated torque and T_L is load torque. In the application of this method, T_L calculated from equation (3.11) is inserted to equation (3.15) and slip speed is calculated.

If this method is investigated, it is seen that this method has some drawbacks. One of these drawbacks occurs in the field weakening region. As explained in Method 1, flux linkage is reduced in the field weakening region. Therefore, slope of the torque-speed curve is changing as seen in equation (3.14). Therefore, it is expected that error ratio of this method is increasing in the field weakening region.

Another drawback of this method is that slope of torque-speed curve is dependent on change of motor parameters with temperature. Equation (3.14) shows that if rotor winding temperature is increased, slip speed is increased to reach the same torque.

Another drawback of this method is that erroneous data of the motor name-plate is reflected to estimation results. Although this drawback is valid for all speed estimation methods, effect of this drawback to the estimation result is weak in other methods. In other methods, motor name-plate data are used to calculate core-loss at base frequency and rated torque. Therefore, effect of erroneous data in name-plate is seen as weaker while calculating air-gap power. However, in this method, erroneous data of name-plate causes high errors at low frequencies.

If these drawbacks are taken into account, it is seen that this method may have large errors at low speeds and in the field weakening region. Suitable types of motors and frequencies for this method are shown in Table.3.5.

Table.3.5 Suitable types of motors and frequencies for Method 3

	Frequency		
	Low	Medium	High
Small motors		**X**	
Large motors		**X**	

Table.3.6 Calculation burden of Method 3

Number of multiplications	31
Number of divisions	15
Number of additions	4
Number of subtractions	9
Number of square roots	-

Although performance of this method is expected to be worse than Method 1 and Method 2, this method is one of the most commonly used methods in literature because of low computational burden and ease of application.

It is possible to improve the low speed and high speed performance of this method by using some of the motor parameters. However, no suggestions is made in this study to improve this method. Penalty of these improvements is increase of the computational burden and this reduces the attractiveness of this method.

3.2.4 Method 4

To improve the performance of Method 1, Method 2 and Method 3 in the field weakening region and at low frequencies, this method is proposed. This method is based on the relation between torque and slip. In Method 1, breakdown torque is assumed to be constant. However, in this method, breakdown torque is calculated for each voltage and frequency case. Torque equations are derived regarding to the stator resistance. For these reasons, this method is expected to perform better than Method 1, Method 2 and Method 3 in the field weakening region and at low frequencies.

In this method, base frequency, voltage, current, speed, power factor, output power, number of poles, efficiency and all motor parameters are used. These data are obtained at base frequency and rated torque. Voltage and two phase instantaneous currents are measured. This method is summarized below.

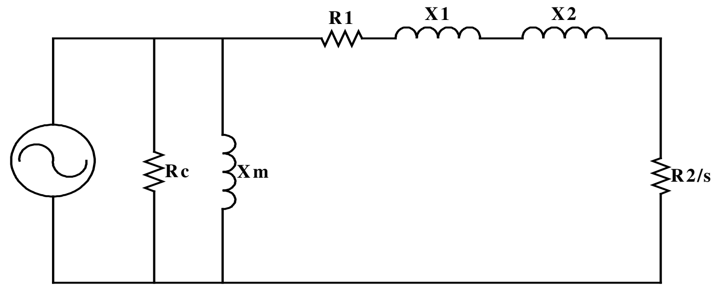

Figure.3.2. Approximate model of induction machine

Approximate model shown in Fig.3.2 is used in this model. Torque equation is written as below.

$$T = \frac{3.V_s^2.R_2 / s}{\omega_s.\left[(R_1 + R_2 / s)^2 + (X_1 + X_2)^2\right]} \tag{3.16}$$

Breakdown torque and slip at breakdown torque can be written as

$$T_{bd} = \frac{3.V_s^2}{2.\omega_s.\left[R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2}\right]} \tag{3.17}$$

$$s_{bd} = \frac{R_2}{\sqrt{R_1^2 + (X_1 + X_2)^2}} \tag{3.18}$$

If equation (3.16) is divided by equation (3.17) and necessary transformations are carried out, the torque formula can be written as

$$T = \frac{2.T_{bd}.(1 + a.s_{bd})}{\frac{s}{s_{bd}} + \frac{s_{bd}}{s} + 2.a.s_{bd}} \tag{3.19}$$

where

$$a = \frac{R_1}{R_2} \tag{3.20}$$

If equation (3.19) is solved, slip is found as

$$s = s_{bd}.\left[b - \sqrt{b^2 - 1}\right] \tag{3.21}$$

where

$$b = \frac{T_{bd}.(1 + a.s_{bd}) - a.s_{bd}.T_L}{T_L} \tag{3.22}$$

In the application of this method, T_{bd}, T_L and s_{bd} are calculated from equation (3.17), (3.11) and (3.18) respectively. Then a and b are calculated from equation (3.20) and (3.22) respectively. Slip is calculated from equation (3.21).

This method can be shown to lead to the same equation ((3.21) and (3.22)), if in the derivation, the exact equivalent circuit is considered and the stator leakage reactance is neglected. Therefore, it is possible to conclude at high frequencies, speed predictions are likely to be erroneous.

Since stator resistance is taken into account when torque equations are derived, this method is expected to give better results at low frequencies. Suitable types of motors and frequencies for this method are shown in Table.3.7.

Table.3.7 Suitable types of motors and frequencies for Method 4

	Frequency		
	Low	Medium	High
Small motors	**X**	**X**	
Large motors	**X**	**X**	

Table.3.8 Calculation burden of Method 4

Number of multiplications	56
Number of divisions	22
Number of additions	10
Number of subtractions	11
Number of square roots	3

If calculation burden of this method is investigated, it is seen that numbers of calculations are similar to Method 1 and Method 2.

Since all motor parameters are used in this method, application of this method is more difficult than Method 1 and Method 2.

3.2.5 Method 5

To improve the performance of Method 4 at high frequencies, this method is improved. In this method, exact circuit model is used. Philosophy of the method is same with Method 4. Since stator leakage reactance is taken into account in this method, this method is expected to give better results than Method 4. In this method, base frequency, voltage, current, speed, power factor, output power, number of poles and all motor parameters are used. These data are obtained at base frequency and rated torque. In this method, voltage and two phase instantaneous currents are measured. This method is summarized below.

Torque equation can be written as

$$T = \frac{3.V_{TH}^2 .R_2 / s}{\omega_s .\left[(R_{TH} + R_2 / s)^2 + (X_{TH} + X_2)^2\right]} \tag{3.23}$$

Breakdown torque and slip at breakdown torque can be written as

$$T_{bd} = \frac{3.V_{TH}^2}{2.\omega_s .\left[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2} \right]} \tag{3.24}$$

$$s_{bd} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \tag{3.25}$$

where V_{TH}, R_{TH} and X_{TH} are calculated from equation (3.2), (3.3) and (3.4) respectively.

If equation (3.23) is divided by equation (3.24) and necessary transformations are carried out, the torque formula can be written as

$$T = \frac{2.T_{bd} .(1 + a.s_{bd})}{\frac{s}{s_{bd}} + \frac{s_{bd}}{s} + 2.a.s_{bd}} \tag{3.26}$$

where

$$a = \frac{R_{TH}}{R_2} \qquad (3.27)$$

If equation (3.26) is solved, slip is found as

$$s = s_{bd}.\left[b - \sqrt{b^2 - 1}\right] \qquad (3.28)$$

where

$$b = \frac{T_{bd}.(1 + a.s_{bd}) - a.s_{bd}.T_L}{T_L} \qquad (3.29)$$

In the application of this method, V_{TH}, R_{TH} and X_{TH} are calculated from equation (3.2), (3.3) and (3.4) respectively. Then T_{bd}, T_L and s_{bd} are calculated from equation (3.24), (3.11) and (3.25) respectively. Then a and b are calculated from equation (3.27) and (3.29). Finally, slip is calculated from equation (3.28).

Since load torque and breakdown torque equations are derived in accordance to the exact steady-state equivalent circuit, this method is expected to be suitable for all frequencies and motor types. This method is expected to give the same results with simulation of the motor model. Suitable types of motors and frequencies for this method are shown in Table.3.9.

Table.3.9 Suitable types of motors and frequencies for Method 5

	Frequency		
	Low	Medium	High
Small motors	**X**	**X**	**X**
Large motors	**X**	**X**	**X**

Table.3.10 Calculation burden of Method 5

Number of multiplication	56
Number of division	22
Number of addition	10
Number of subtraction	11
Number of square roots	3

If calculation burden of this method is investigated, it is seen that number of calculations is similar to Method 4. That all parameters are used in this method is shown as disadvantage of this method.

3.2.6 Method 6

To improve the performance of Method 1 and Method 3 at low frequencies, this method is proposed. To minimize the effect of stator resistance, equivalent circuit is modified. This method is based on the relation between slip and torque equations. Torque equations are derived in accordance to the modified equivalent circuit. Philosophy of this method is similar to Method 4.

Base frequency, voltage, current, speed, power factor, output power, efficiency, number of poles, breakdown torque and all motor parameters are used in this method. These data are obtained at base frequency and rated torque. Voltage and two phase instantaneous currents are measured. This method is summarized below.

Modified equivalent circuit shown in Fig.3.3 does not contain stator resistance. Input voltage (e_s) value is changing in accordance to the slip and phase current. e_s is calculated by subtracting the voltage drop on the stator resistance from input voltage.

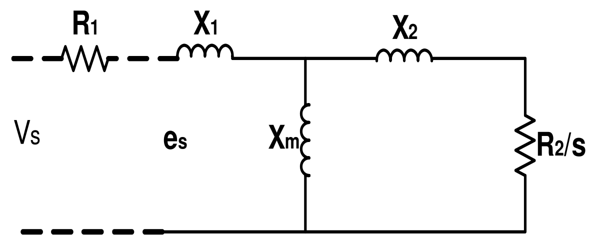

Figure.3.3. Modified equivalent circuit of induction machine

If thevenin theorem is applied to stator side, equivalent circuit can be modified as shown in Fig.3.4.

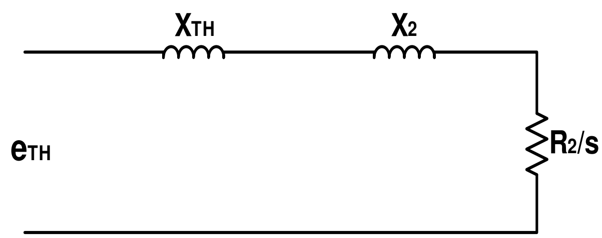

Fig.3.4. Thevenin theorem applied form of the equivalent circuit

where e_{TH}, R_{TH} and X_{TH} are

$$e_{TH} = e_s \cdot \frac{X_m}{X_1 + X_m} \tag{3.30}$$

$$R_{TH} \cong 0 \quad \& \quad X_{TH} = \frac{X_1 . X_m}{X_1 + X_m} \tag{3.31}$$

Torque equation is written as

$$T = \frac{3 . e_{TH}^2 . R_2 / s}{\omega_s . \left[(R_2 / s)^2 + (X_{TH} + X_2)^2 \right]} \tag{3.32}$$

Criteria for occurrence of breakdown torque is,

$$\frac{R_2}{s_{bd}} = (X_{TH} + X_2) \tag{3.33}$$

Equivalent circuit when breakdown torque occurs is shown in Fig.3.5.

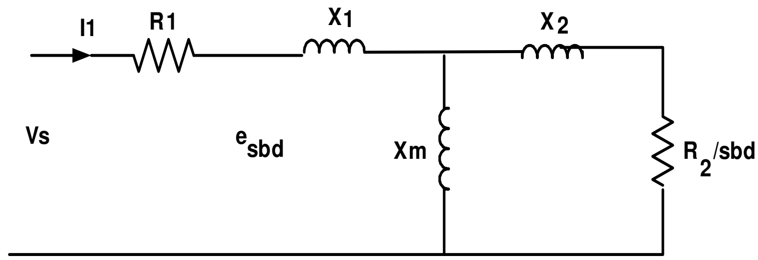

Fig.3.5.Equivalent circuit of induction machine at breakdown torque

Breakdown torque equation is written as

$$T_{bd} = \frac{3.e_{THbd}^2}{2.\omega_s.(X_{THbd} + X_2)} \tag{3.34}$$

where

$$e_{THbd} = e_{sbd} \cdot \frac{X_m}{X_1 + X_m} \tag{3.35}$$

$$R_{THbd} = 0 \qquad \& X_{THbd} = \frac{X_1.X_m}{X_1 + X_m} \tag{3.36}$$

If X_m is assumed to be much larger than X_1,

$$X_{TH} = X_1 \tag{3.37}$$

If equation (3.32) is divided by equation (3.34) and necessary transformations are carried out, the torque formula can be written as below

$$T = \left(\frac{e_s}{e_{sbd}}\right)^2 \cdot \frac{2.T_{bd}}{\frac{s}{s_{bd}} + \frac{s_{bd}}{s}} \tag{3.38}$$

If equation (3.38) is solved, slip is found as

$$s = s_{bd}.\left[b - \sqrt{b^2 - 1}\right]$$

(3.39)

where

$$b = \frac{(e_s / e_{sbd})^2 . T_{bd}}{T_L} \quad (3.40)$$

The most critical point in this method is the estimation of e_{sbd} value at breakdown torque condition. e_{sbd} is calculated from equation (3.41).

$$e_{sbd} = V_s - R_1 . I_1 \quad \text{Eq.3.41}$$

where I_1 denotes stator current and can be calculated by dividing the equivalent impedance of circuit shown in Fig.3.5 to the input voltage.

In the application of this method, e_s and e_{sbd} are calculated from equation (3.41). s_{bd} and T_{bd} are calculated from equation (3.6) and (3.5) respectively. T_L is calculated from equation (3.11). Finally slip is calculated from equation (3.39).

In the calculation of e_s and e_{sbd}, stator current is assumed to be in phase with input voltage. Therefore, this method is expected to calculate e_s and e_{sbd} lower than actual values of e_s and e_{sbd}. For this reason, it is expected that the error of this method is increasing at low speeds. At high frequencies, reactance of the equivalent circuit is dominant. Therefore, this approximation increases the error ratio of this method at high frequencies. Despite of erroneous assumptions, this method can be used for all frequencies, since effect of stator resistance and reducing flux linkage in the field weakening region are taken into account. Suitable types of motors and frequencies for this method are shown in Table.3.11.

Table.3.11 Suitable types of motors and frequencies for Method 6

	Frequency		
	Low	Medium	High
Small motors	**X**	**X**	**X**
Large motors	**X**	**X**	**X**

Table.3.12 Calculation burden of Method 6

Number of multiplications	54
Number of divisions	22
Number of additions	10
Number of subtractions	12
Number of square roots	3

If calculation burden of this method is investigated, it is shown that number of calculations is similar to Method 4. Since all motor parameters are used as in Method 4, application of this method is more difficult than Method 1 and Method 3.

3.2.7 Method 7

To improve the performance of Method 6, it is necessary to estimate e_{sbd} accurately. Therefore, a different approach for calculation of e_{sbd} is proposed in this method. Philosophy of the method is same with Method 6. Only the estimation of e_{sbd} is different from Method 6. Base frequency, voltage, current, speed, power factor, output power, efficiency, number of poles, breakdown torque and all motor parameters are used in this method. These data are obtained at the base frequency and rated torque. Voltage and two phases instantaneous currents are measured. This method is summarized below.

To find e_{sbd}, referred rotor current is estimated. Torque equation can be written as below

$$T = \frac{P_{gap}}{\omega_s} \tag{3.42}$$

where air-gap power is,

$$P_{gap} = 3 * I_2^2 * R_2 / s_{bd} \tag{3.43}$$

From equation (3.42) and (3.43), referred rotor current at breakdown torque condition can be written as below.

$$I_2 = \sqrt{\frac{T_{bd} * s_{bd} * \omega_s}{3 * R_2}} \tag{3.44}$$

Neglecting voltage drop on the stator leakage reactance, e_{sbd} can be calculated from equation (3.45).

$$e_{sbd} = \sqrt{\left(\frac{R_2}{s_{bd}}\right)^2 + (X_s)^2} * \sqrt{\frac{T_{bd} * s_{bd} * \omega_s}{3 * R_2}} \tag{3.45}$$

In the application of this method, s_{bd} and T_{bd} are calculated from equation (3.6) and (3.5) respectively. e_s and e_{sbd} are calculated from equation (3.41) and (3.45) respectively. T_L is calculated from equation (3.11). Finally, slip is calculated from equation (3.39).

Since stator resistance is taken into account, this method is expected to give better results than Method 1. In the calculation of e_s, stator current is assumed to be in phase with input voltage. Therefore, this method is expected to calculate e_s lower than actual value of e_s. For this reason, it is expected that error of this method is increasing at low speeds. At high frequencies, neglecting voltage drop on the stator leakage reactance while calculating e_{sbd} increases the error ratio of this method. Even if the error ratio of this method is increasing at high frequencies, speed estimation results of this method are also acceptable. Suitable types of motors and frequencies for this method are shown in Table.3.13.

Table.3.13 Suitable types of motors and frequencies for Method 7

	Frequency		
	Low	Medium	High
Small motors		**X**	**X**
Large motors		**X**	**X**

Table.3.14 Calculation burden of Method 7

Number of multiplications	54
Number of divisions	22
Number of additions	7
Number of subtractions	13
Number of square roots	5

If calculation burden of this method is investigated, it is seen that the number of calculations except number of square roots is similar to Method 4. Since all motor parameters are used, application of this method is more difficult than Method 1 and Method 3.

3.3 Evaluation of speed estimation methods

Results of speed estimation methods are given briefly in this section. Speed estimation methods are compared in Table.3.15.

Table.3.15 Evaluation of speed estimation methods

Methods	Small motors		Large motors	
	Low speed	High speed	Low speed	High speed
	Full load	Full load	Full load	Full load
M1			**X**	
M2		**X**	**X**	**X**
M3				
M4	**X**		**X**	
M5	**X**	**X**	**X**	**X**
M6	**X**	**X**	**X**	**X**
M7		**X**		**X**

Only Method 3 has a linear relationship between torque and slip, the other methods have a non-linear relationship between torque and slip. In Method 1 and 2, stator resistance is neglected. Hence, these methods are likely to lead errors at low hp motors and high loads. In Method 3, slope of torque-speed curve is assumed to be constant and this is expected to result in poor predictions in the field weakening region. In Method 4 and Method 5, the exact model is used. Estimation of power factor and rms values of current and voltage are critical at low speeds and high loads for these methods. In Method 6 and Method 7, estimation of e_{sbd} and e_s is the critical point. While estimating e_{sbd} in Method 7, referred rotor resistance is used. Error of this assumption becomes more important at low speeds and for this reason, high errors at low speeds may be expected. While estimating e_s in Method 6, current is assumed to be in phase with input voltage. However, this assumption increases the error at low frequencies. Since only stator resistance and motor name-plate data are used and number of calculations is low, Method 3 is the easiest method to be applied on a motor drive. Table.3.39 and Table.3.40 show that if dc shift on current is prevented, error ratios of all methods are reducing. Although dc shift on stator current worsens the estimation of rms value of current and power factor, results of Method 4, Method 5 and Method 6 are not worsened as much as the results of other methods.

CHAPTER 4

SIMULATION AND EXPERIMENTAL WORK

4.1 Introduction

Initially hardware and software, which are used in the experiments, are briefly explained in this chapter. Then, calibration of voltage measurement module, current measurement module and calibration of torquemeter are explained shortly. Then, measurement of rotational loss is explained. In speed estimation algorithms, core loss, rms value of current, rms value of voltage and power factor are estimated. In this chapter, these estimations are verified. Finally, simulation of motor model in Matlab is explained.

4.2 Hardware

Hardware used in experiments consists of DSP board, lock-out module, isolation module, IPM, current and voltage measurement modules and power stage. The block diagram of hardware is shown in Figure.4.1.

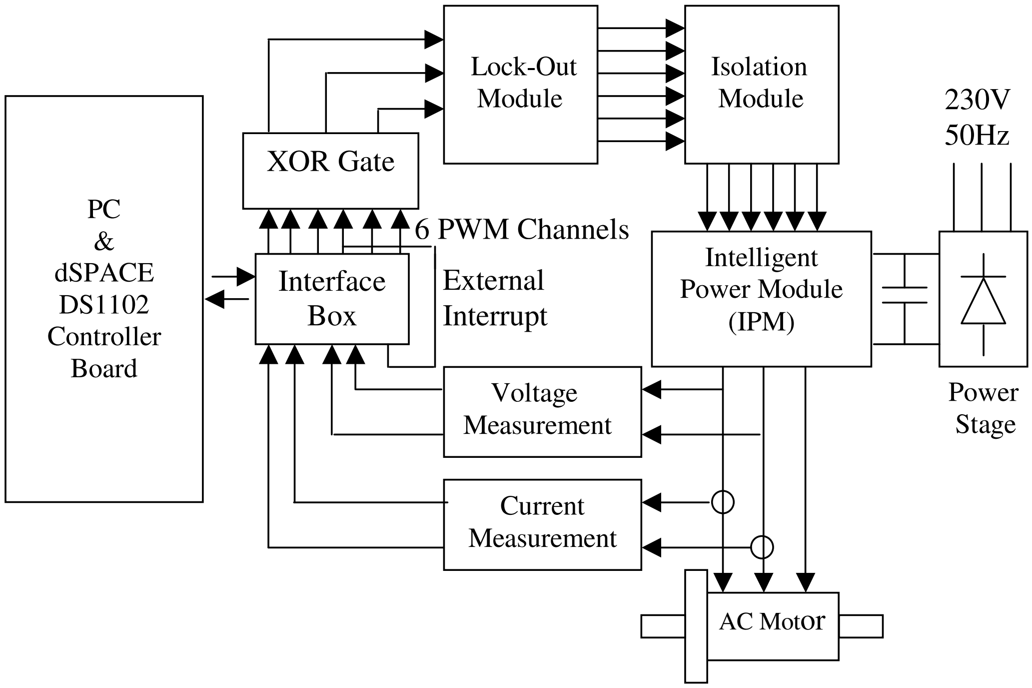

Figure.4.1 Block diagram of hardware

Power stage consists of three phase uncontrolled rectifier, dc link capacitors and snubber capacitor. Two 500 μF 450V capacitors are serially connected. However, these capacitors are not sufficient to make dc link voltage be constant when motor is driven with inverter. For this reason, currents and voltages produced by the inverter are oscillating. This issue is investigated in Appendices. Isolation module provides the isolation between intelligent power module (IPM) and lock-out module. Lock-out module provides 3 μs dead-time between the turn-on and turn-off signals of upper and lower switches of IPM. XOR gate module is used to produce symmetric PWM. Voltage and current measurement modules consist of sensors, low-pass filters and amplifiers. Details of the hardware are explained in [13] and [14].

4.3 Modulation technique

Space vector PWM technique is used as modulation technique. SVPWM technique generates less harmonic distortion in the output voltage and current with a smaller number of switchings.

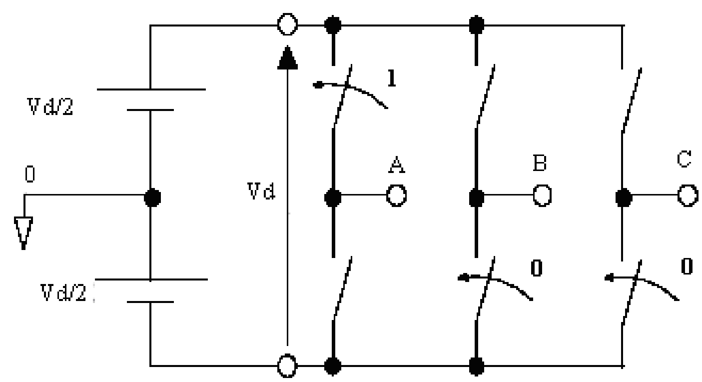

Figure.4.2 Used inverter topology

When an upper transistor is switched on (i.e., when A, B or C is 1), the corresponding lower transistor is switched off. There are eight possible combinations of on and off states.

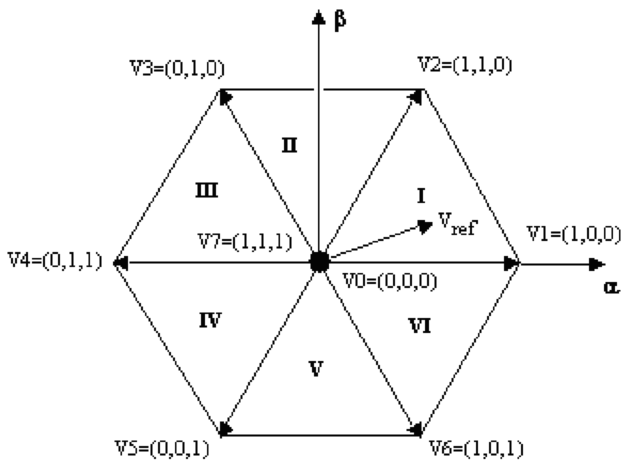

Figure.4.3 Basic space vectors and switching states

A mean space vector $\vec{V}_{ref}$ over a switching period TS can be defined. Assuming that TS period is sufficiently small, $\vec{V}_{ref}$ can be considered approximately constant during this switching period. The SVPWM technique is based on the fact that every reference vector is expressed as average of the two adjacent active space vectors and the zero-state vectors. Switching sequence is arranged such that the transition from one state to the next is performed by switching only one inverter leg. Active and zero state times are calculated by equating the applied average voltage to the desired voltage. Modulation frequency is selected as 10 kHz. Details of this modulation technique are explained in [15] and [16]. In this study, only this modulation technique is used on the inverter.

4.4 Calibration of voltage measurement module

To calibrate the voltage measurement module, motor is driven with inverter and output of voltage measurement module, which is obtained by Trace program, is compared with measured signal by oscilloscope. Schematic of voltage measurement module is shown in Figure.4.4.

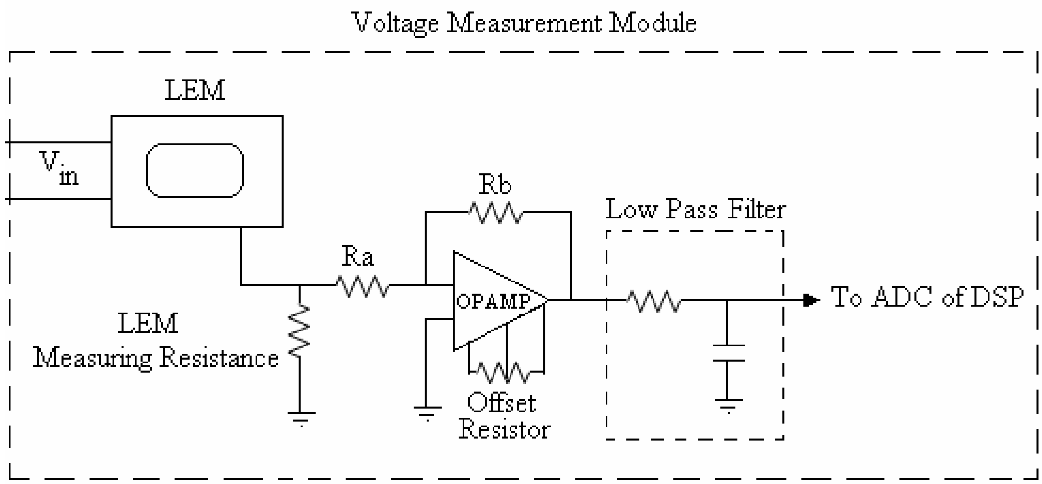

Figure.4.4 Schematic of voltage measurement module

Calibration of the module is performed for different voltage levels and frequencies. Output of the LEM is filtered by low-pass filters, whose cut-off frequency is set to nearly 2 kHz. Filter components are 100nF capacitor and 810 Ω resistor. Cut-off frequency of the filter, gain and phase shift of filter are calculated from equation (4.1), (4.2) and (4.3) respectively.

$$f = \frac{1}{2\pi RC} \tag{4.1}$$

$$Gain = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\sqrt{1+(wRC)^2}} \tag{4.2}$$

$$PhaseShift = \angle(-\tan^{-1} wRC) \tag{4.3}$$

Phase difference and gain of the filter are calculated from 10Hz to 200Hz.

Table.4.1 Phase difference and gain of used low-pass filters

Frequency (Hz)	Gain	Phase shift (degrees)
10	1	-0.2916
30	0.9999	-0.8747
50	0.9997	-1.4577
70	0.9994	-2.0403
100	0.9987	-2.9135
150	0.9971	-4.3655
200	0.9949	-5.8120

Low-pass filters are designed as if motor is driven up to 200Hz. Since the gain of the filter is nearly unity and phase shift is very low in the working region, this voltage measurement module is reliable. Measured voltage from oscilloscope and Trace program are shown in Figure.4.5 to Figure.4.12. To measure the voltage from oscilloscope, a low-pass filter is connected between star point and phase of the motor. Differential probe is used to sense the filtered voltage signal. Sensitivity and accuracy of the LEM voltage transducer is shown in Appendices.

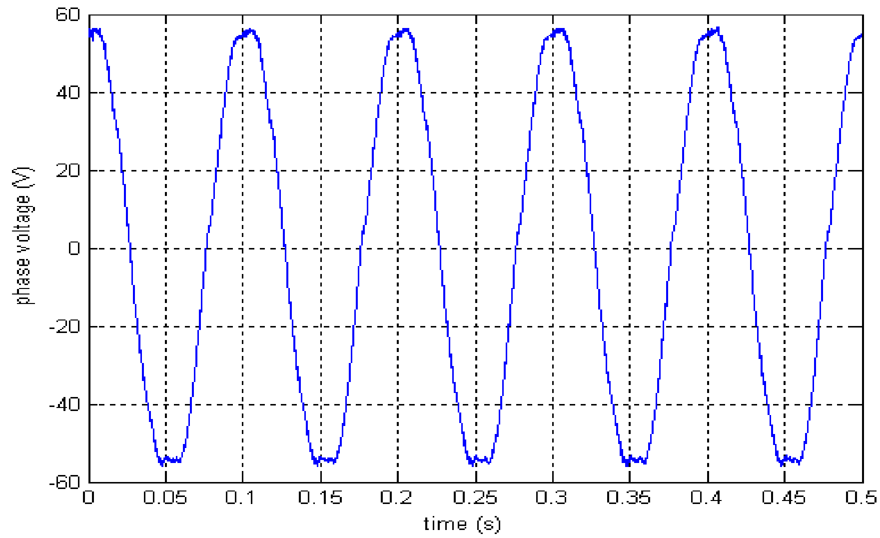

Fig.4.5 Stator phase voltage obtained from Trace program at 10Hz

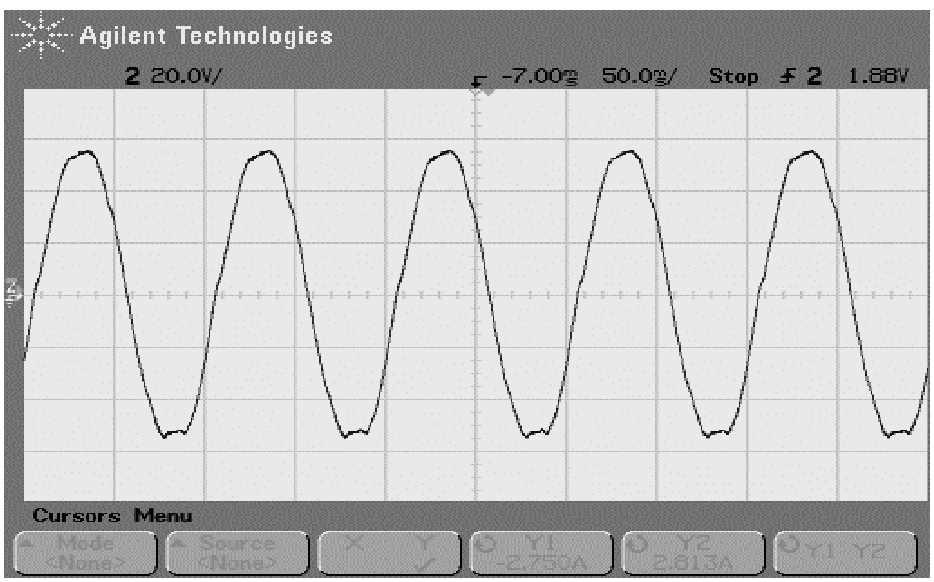

Fig.4.6 Stator phase voltage obtained from oscilloscope at 10Hz

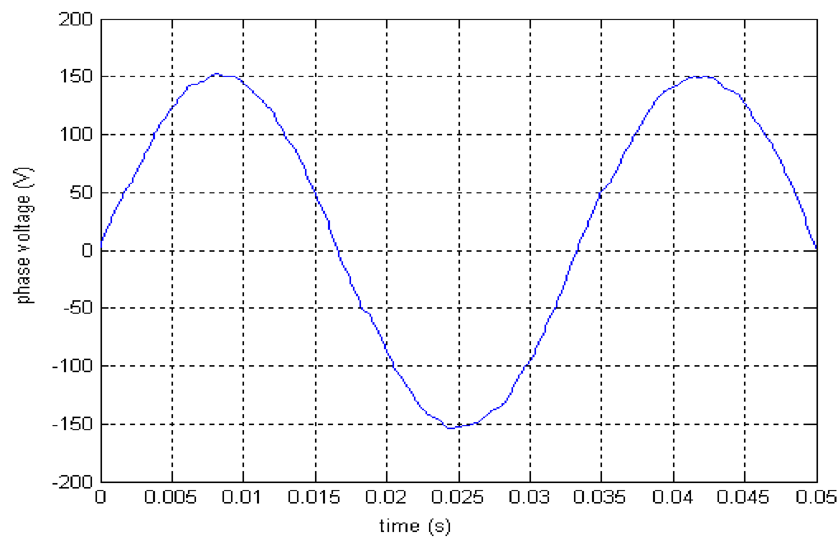

Fig.4.7 Stator phase voltage obtained from Trace program at 30Hz

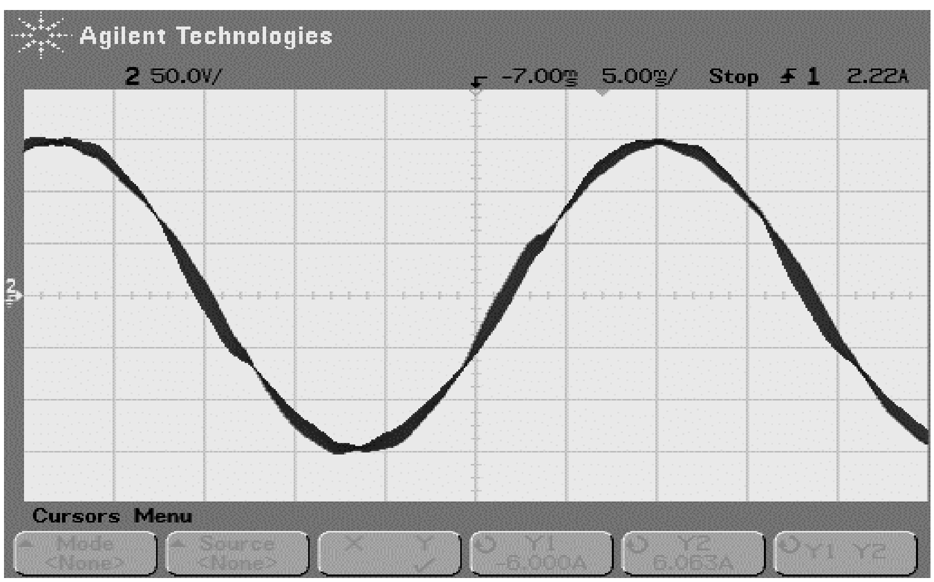

Fig.4.8 Stator phase voltage obtained from oscilloscope at 30Hz

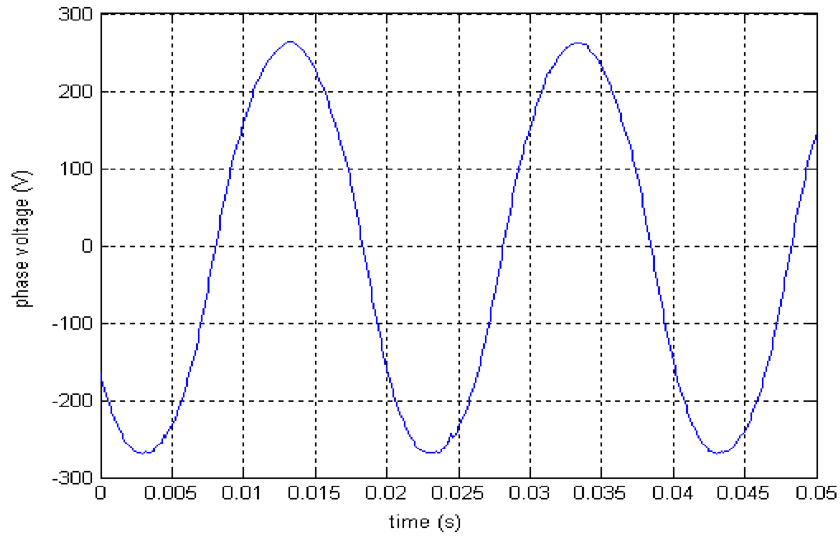

Fig.4.9 Stator phase voltage obtained from Trace program at 50Hz

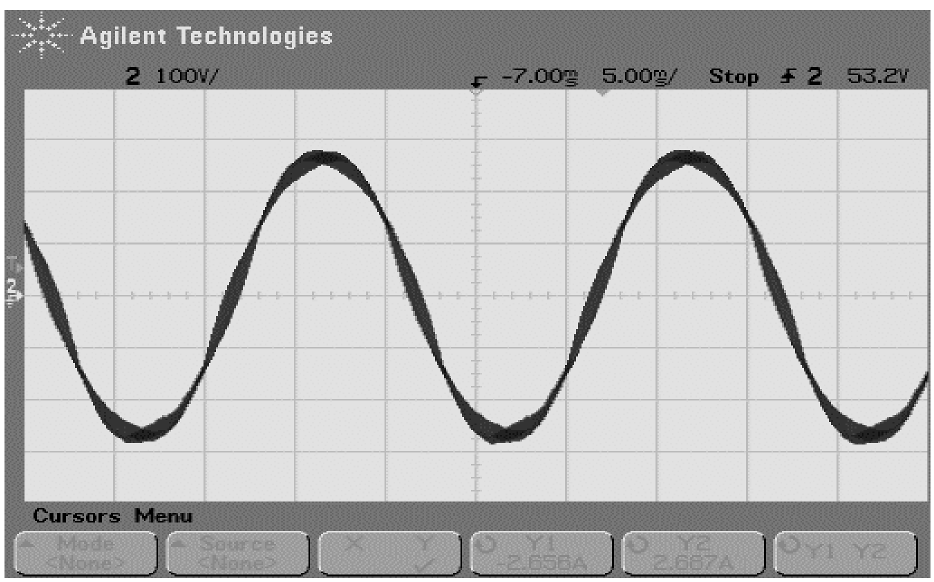

Fig.4.10 Stator phase voltage obtained from oscilloscope at 50Hz

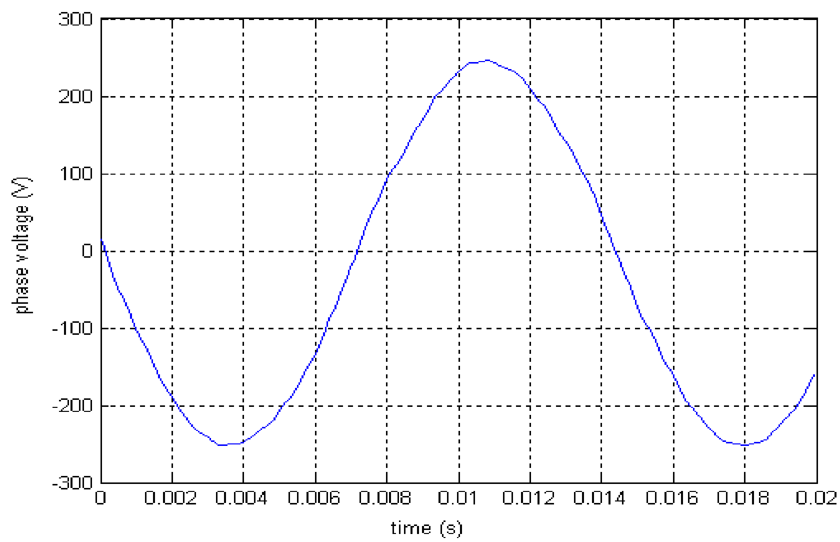

Fig.4.11 Stator phase voltage obtained from Trace program at 70Hz

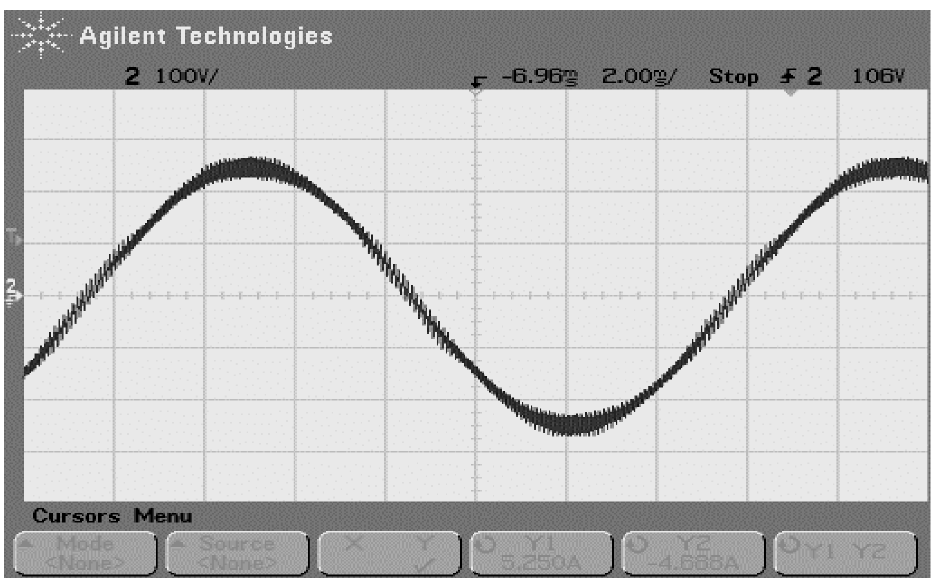

Fig.4.12 Stator phase voltage obtained from oscilloscope at 70Hz

Table.4.2 Measured voltage with Trace program and oscilloscope

Frequency (Hz)	Oscilloscope (Vpp)	Trace (Vpp)
10	111	111
30	300	305
50	330	335
70	497	495

Trace program samples the voltage at 10 kHz and between these measurements graph is interpolated. However, oscilloscope shows the voltage continuously. Therefore, ripples on the voltage are seen in the oscilloscope measurements. As seen from the Figure.4.5 to Figure.4.12 and Table.4.2, TRACE data and oscilloscope data are similar in magnitude and shape. As a result, calibration of voltage measurement module is accepted as successful.

4.5 Calibration of current measurement module

Topology of current measurement module is same with voltage measurement module. Only difference is that current LEM is used instead of voltage LEM. Also calibration procedure is same with voltage calibration procedure. Measured current from oscilloscope and Trace program are shown in Figure.4.13 to Figure.4.20. To measure the current from oscilloscope, clamp current probe is used to sense the current signal. Sensitivity and accuracy of this probe is given in Appendices.

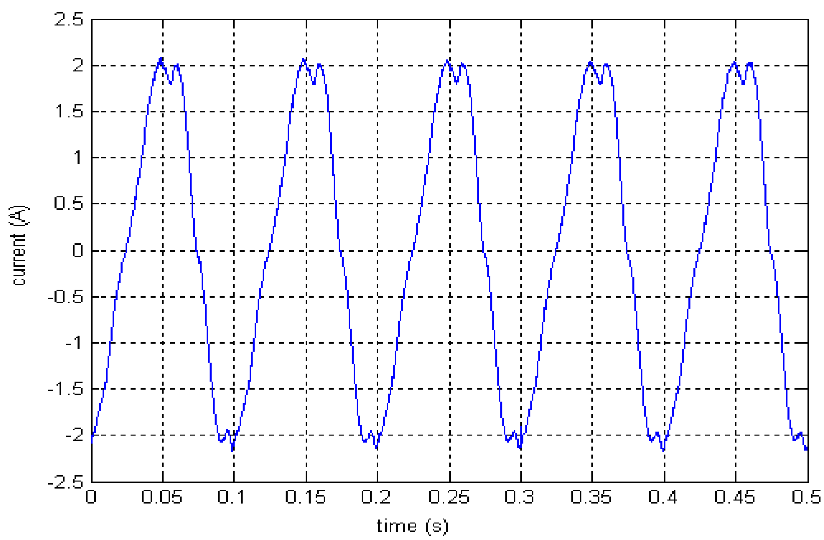

Figure.4.13 Stator phase current obtained from Trace program at 10Hz

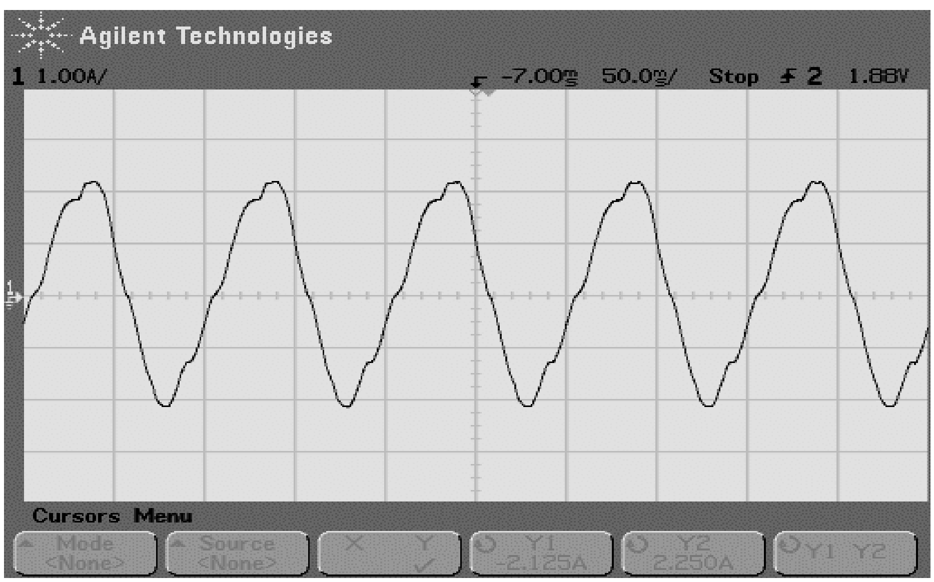

Fig.4.14 Stator phase current obtained from oscilloscope at 10Hz

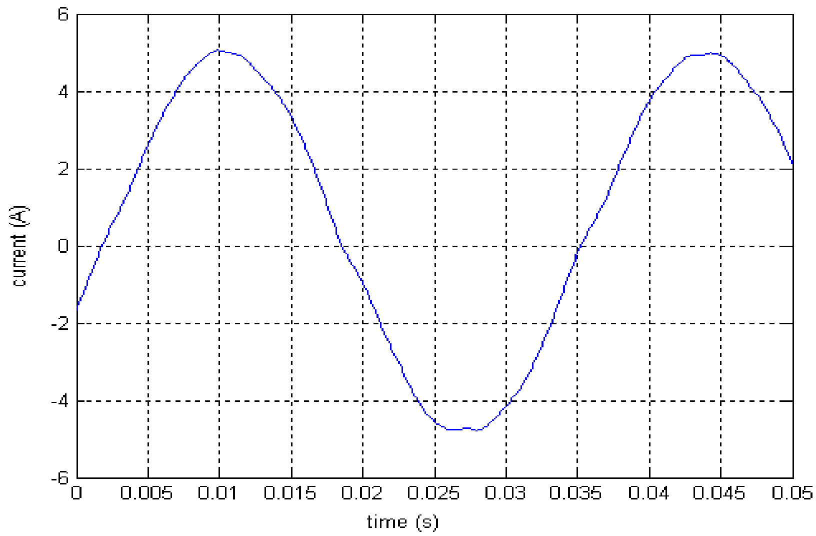

Figure.4.15 Stator phase current obtained from Trace program at 30Hz

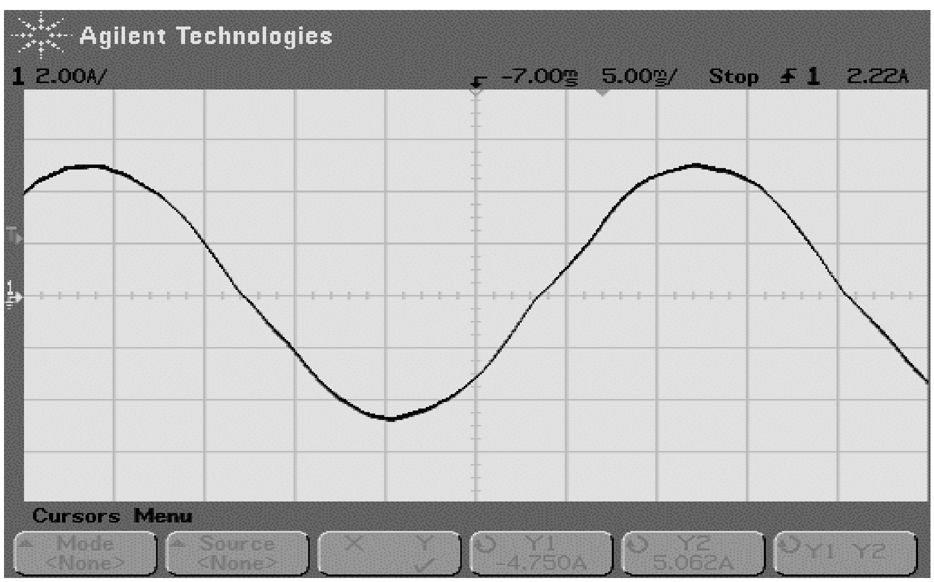

Fig.4.16 Stator phase current obtained from oscilloscope at 30Hz

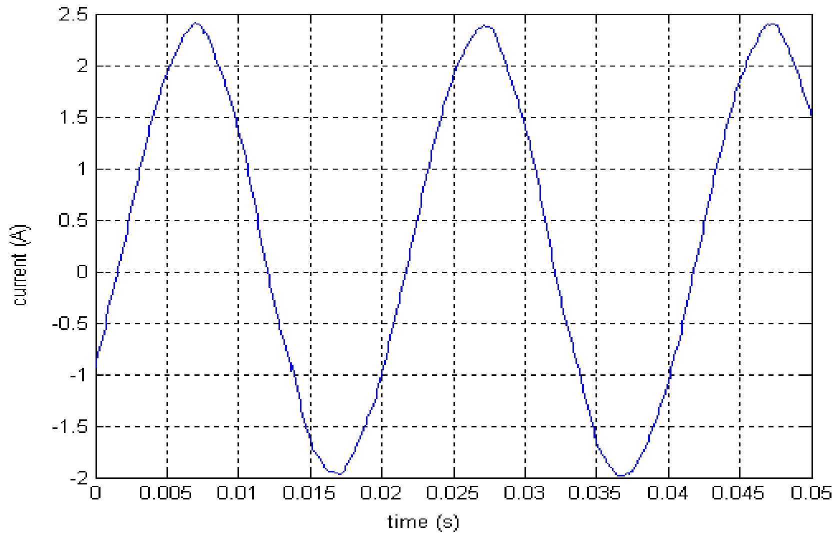

Figure.4.17 Stator phase current obtained from Trace program at 50Hz

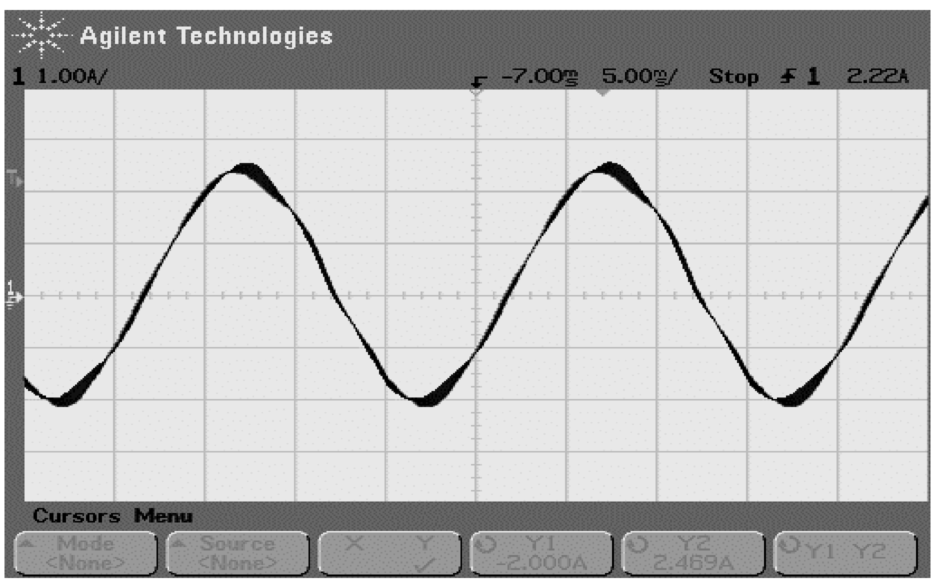

Fig.4.18 Stator phase current obtained from oscilloscope at 50Hz

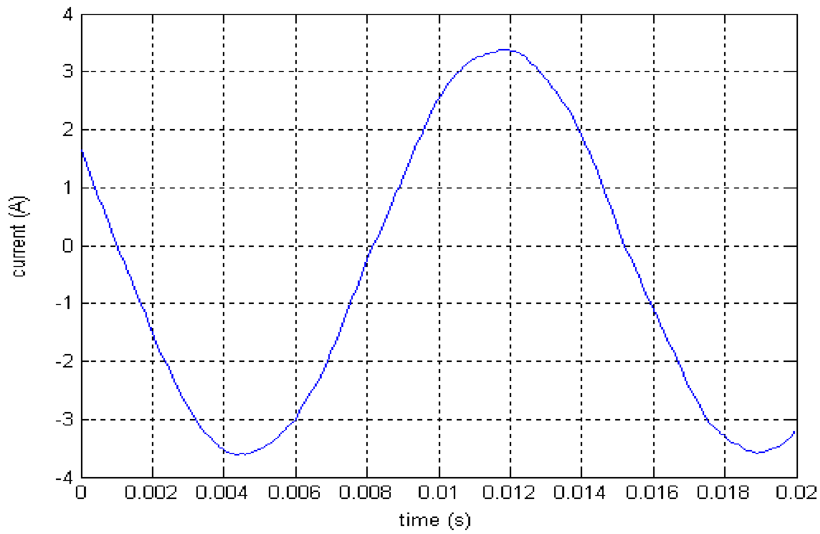

Figure.4.19 Stator phase current obtained from Trace program at 70Hz

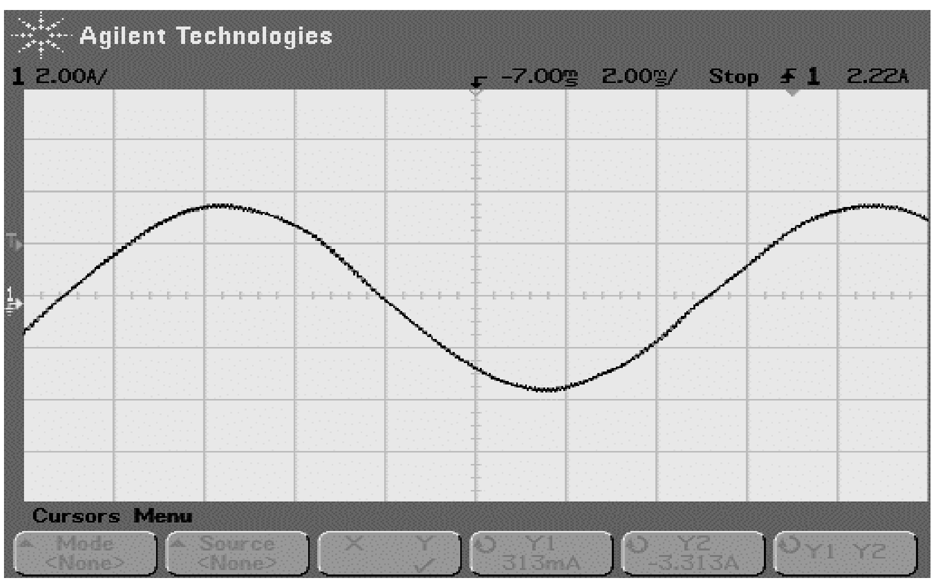

Fig.4.20 Stator phase current obtained from oscilloscope at 70Hz

Table.4.3 Measured current with Trace program and oscilloscope

Frequency (Hz)	Oscilloscope (App)	Trace (App)
10	4.34	4.21
30	9.90	9.78
50	4.33	4.35
70	7.10	7.00

As seen from the Figure.4.13 to Figure.4.20 and Table.4.3, TRACE data and oscilloscope data are similar in magnitude and shape. Therefore, calibration of voltage measurement module is accepted as successful. Only at 10 Hz, shapes of the peaks are different. It is seen that ripple on the signal is suppressed in oscilloscope measurement at 10 Hz. As seen in figures above, dc shift is seen on the measured current. Dc link voltage is oscillating and this causes the dc shift on the current and voltage. This issue is investigated in Appendices.

4.6 Measurement of torque and speed

Since speed is measurement is needed at steady-state conditions, an external optical tachometer and digital tachometer are used to measure speed. When both of the tachometers are used, it is seen that the difference between the outputs of these tachometers is below 1 rpm.

To measure the torque, spring system is used. DC motor is used as a load and Mentor DC motor drive is used to load the motor. Torque is calculated with respect to indicator reading. Sensitivity of the indicator is 0.4 Nm. Hence, torque can be measured with 0.2 Nm error.

4.7 Measurement of rotational losses

To measure the rotational losses, 1.1, 2.2 and 4 kW induction motors are driven with inverter at no-load. V^2-P curves are prepared for 10, 20, 30, 40, 50, 60 and 70Hz and rotational losses are found from these curves. Measured rotational losses versus speed are shown in Table.4.4. Finally rotational loss-speed curves are prepared. These curves are completed with interpolation between measured points. These curves are shown in Appendices.

Table.4.4 Measured rotational losses versus speeds

	1.1 kW		2.2 kW		4 kW	
f	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)
10	1.6	197	2.2	274	1.7	153
20	1.2	382	4.3	554	5.5	541
30	1.1	570	7.5	845	10.0	824
40	3.2	756	11.4	1119	16.4	1116
50	3.7	929	17.1	1396	22.9	1414
60	5	1128	23.8	1711	33.0	1708
70	7.6	1354	32.4	2001	41.5	2017

4.8 Verification of core loss estimation

Core loss is estimated as a function of frequency and slip as shown in equation (4.4). [12][6]

$$P_{core} = \frac{1}{2}\left(\frac{1+s}{1+s_R}\left(\frac{f}{f_R}\right) + \frac{1+s^2}{1+s_R^2}\left(\frac{f}{f_R}\right)^2 \right).P_{coreR} \qquad (4.4)$$

where P_{coreR} denotes core loss at rated condition, s_R slip at rated condition, f_R denotes rated frequency, s denotes slip, f denotes frequency and P_{core} denotes core loss. This equation is valid where flux linkage is kept constant at rated value. To verify this estimation, core loss is measured and compared with estimated value. 2.2 kW induction motor is driven from the mains (f=50Hz) under different load conditions and core loss is calculated from measurement as shown in equation (4.5).

$$P_{core} = P_{in} - P_{scl} - P_{ag} \tag{4.5}$$

where P_{in} denotes input power, P_{scl} denotes stator copper loss and P_{ag} denotes air-gap power. When motor is driven with inverter, input power is calculated by subtracting the conduction loss and switching losses from the dc link power. Details of calculation of inverter losses are investigated in Appendices. Estimated and measured core loss values are shown in Fig.4.21, Table.4.5 and Table.4.6 for 2.2 kW motor.

Table.4.5 Estimated and measured core loss values for mains driven (f=50Hz) 2.2kW induction motor

Torque (Nm)	Speed (rpm)	Measured core loss (W)	Estimated core loss (W)	Error (%)
14.72	1400	139.5	161.95	-13.9
11.12	1426	123.2	160.5	-30.3
6.32	1460	125.6	158.6	-26.3
3.12	1478	191.1	157.6	17.5
1.52	1490	200.8	157	21.8

Table.4.6 Estimated and measured core loss values 2.2kW induction motor when driven with inverter

Frequency (Hz)	Torque (Nm)	Speed (rpm)	Measured core loss (W)	Estimated core loss (W)	Error (%)
10	14.7	199	17.5	24	-37.1
10	14.7	209	19.8	23.4	-18.2
10	14.7	219	22.4	23	-2.7

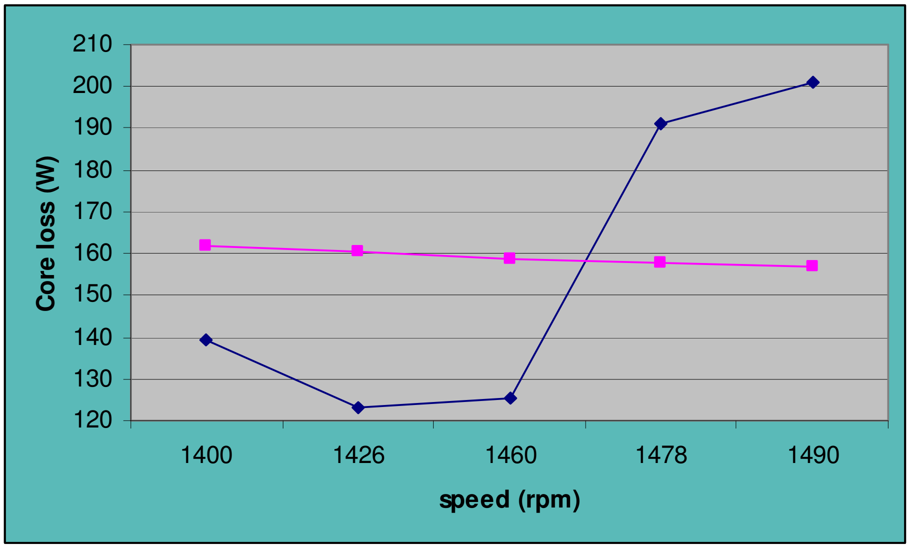

Fig.4.21 Calculated and measured core loss for mains (50Hz) driven motor

Error of estimation of core loss is high. However, this error is less than 2% of rated power.

4.9 Verification of RMS value calculation of stator phase current

It is shown above that current is correctly measured with current LEM. In this section, rms value calculation method is verified. Two phase instantaneous currents are used to estimate rms value of the current. Current is measured with current LEM and output signal of the LEM is filtered by low-pass filter, whose cut-off frequency is set to 2 kHz, to prevent the noise which is imposed on the signal. Measured currents, when motor is driven by svpwm modulated voltage at 30Hz and 70 Hz, are shown in Fig.4.22 and Fig.4.23 respectively.

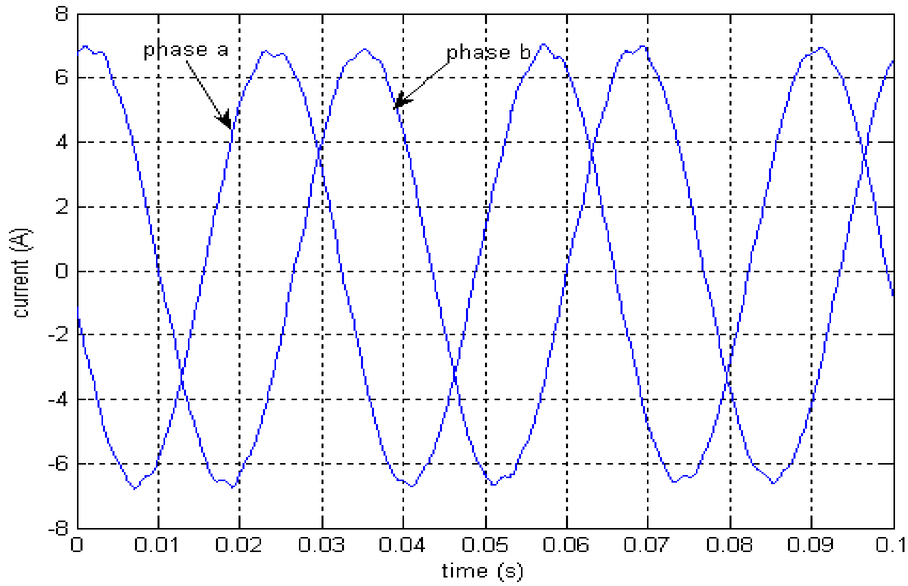

Fig.4.22 Measured stator currents at 30 Hz

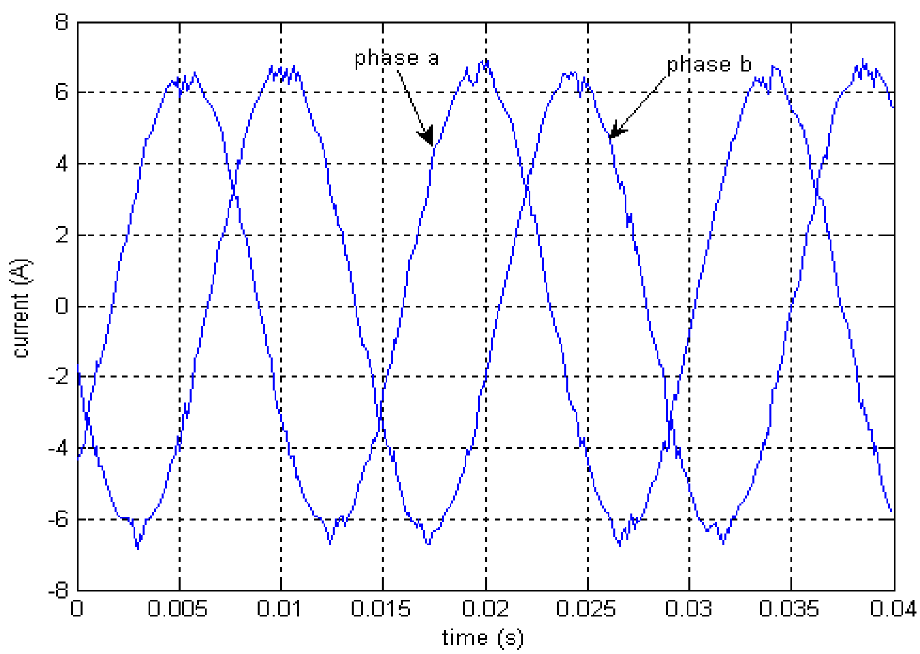

Fig.4.23 Measured stator currents at 70 Hz

It is assumed that summation of instantaneous three phase currents are equal to zero. In this way, α-β conversion is made as below

$$i_\alpha = i_a \tag{4.6}$$

$$i_\beta = \frac{1}{\sqrt{3}}\left(i_c - i_b\right) = \frac{1}{\sqrt{3}}\left(-i_a - 2.i_b\right) \tag{4.7}$$

where,

$$\begin{aligned} i_a &= \hat{I}.\cos(\omega t) \\ i_b &= \hat{I}.\cos(\omega t - 2\pi/3) \\ i_c &= \hat{I}.\cos(\omega t - 4\pi/3) \end{aligned} \tag{4.8}$$

In phasor diagram, norm of the current vector is equal to the peak of the phase current. Hence, equation (4.9) can be written as below

$$\begin{aligned} \hat{I} &= \sqrt{i_\alpha^2 + i_\beta^2} \\ \hat{I} &= \frac{2}{\sqrt{3}}\sqrt{\left(i_a(i_a + i_c) + i_c^2\right)} \end{aligned} \tag{4.9}$$

and rms of the current is found by equation (4.10).

$$I_s = \sqrt{\frac{2}{3}}.\sqrt{\left(i_a(i_a + i_c) + i_c^2\right)} \tag{4.10}$$

To verify this estimation, motor phase current is measured by current probe in the oscilloscope and compared with estimated currents. This process is done when motor is driven with line voltage and inverter and results are shown in Fig.4.24, Fig.4.25, Table.4.7 and Table.4.8. In these figures, average of the all of the estimated current is taken. In Fig.4.24, current is sampled 400 times and rms value is estimated. Average of these 400 value is taken and shown in the figure. In Fig.4.25, this process is applied for 1000 sampled data.

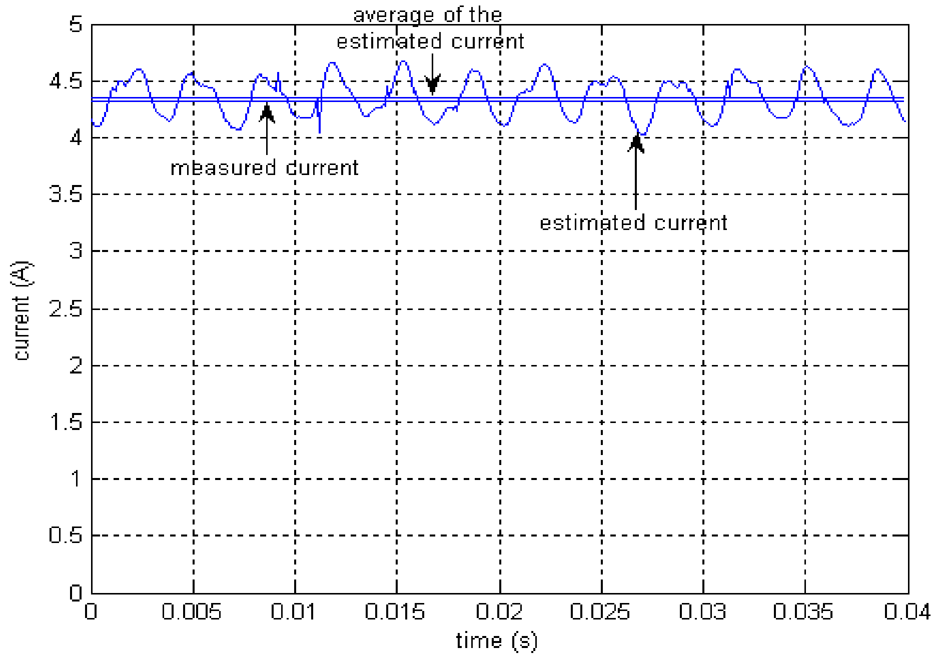

Fig.4.24 Measured and estimated rms value of stator current when motor is driven from the mains (f=50Hz)

Table.4.7 Measured and estimated rms value of stator current when motor is driven from the mains (f=50Hz).

Measured rms value (A)	Estimated rms value (A)	Error (%)
4.865	4.93	-1.3
4.32	4.35	-0.7
3.865	3.89	-0.6
3.45	3.5	-1.4
3.11	3.17	-1.9
2.8	2.85	-1.8
2.54	2.6	-2.4
2.33	2.37	-1.7
2.25	2.28	-1.3
2.18	2.2	-0.9

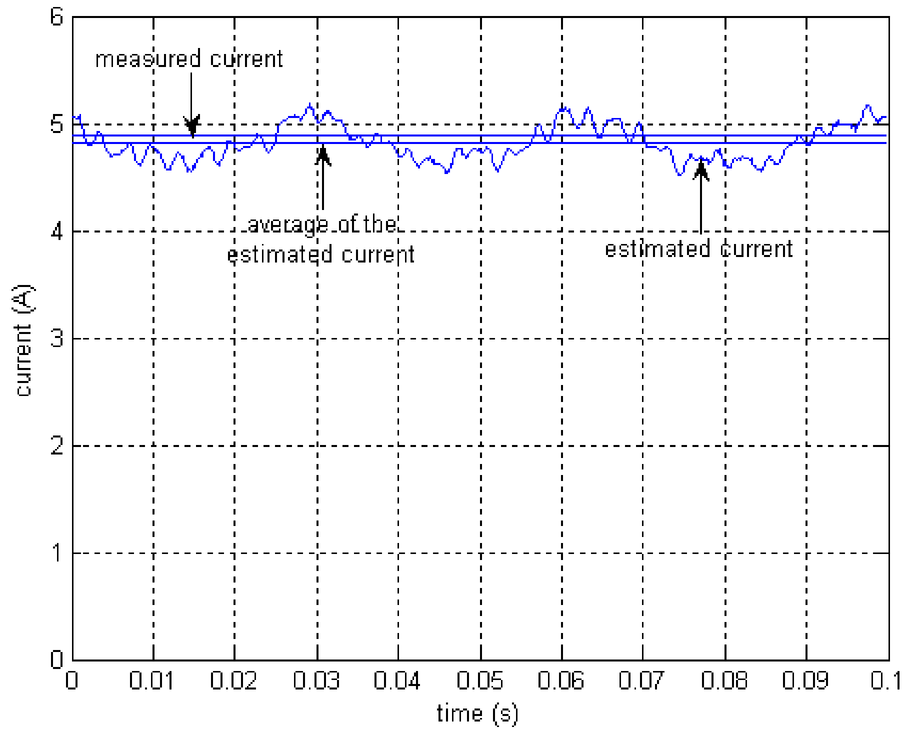

Fig.4.25 Measured and estimated rms value of stator current
when motor is driven at 30Hz with inverter

Table.4.8 Measured and estimated rms value of stator current
when motor is driven with inverter.

Frequency(Hz)	Measured rms value (A)	Estimated rms value (A)	Error (%)
10	5.006	4.991	0.3
10	2.87	2.884	-0.5
30	4.89	4.818	1.5
30	3.03	3.024	0.2
50	5.17	4.991	3.5
50	3	2.951	1.6
70	4.85	4.594	5.3
70	3.58	3.356	6.2

In Fig.4.24, estimated rms value is oscillating. Frequency of this oscillation is 300Hz. It is thought that dc link voltage is oscillating and frequency of the output voltage of the uncontrolled rectifier is seen on estimated rms value of current. If larger capacitances had been selected, oscillation on the current could be reduced. To verify the effect of this oscillation on the speed estimation results, 2.2 kW induction motor is driven with line voltage and results of the estimation methods are compared with results of estimation methods when motor is driven with inverter. Result of this comparison is shown in Chapter 5. In Fig.4.25, another disturbing signal is added to the estimated rms value of current. Frequency of this signal is 30Hz which is same with frequency of produced voltage. It is shown that estimated rms value of stator phase current is very similar to the measured value except 70Hz. Because, noise imposed on the measured signal at high frequencies increases the error.

4.10 Verification of RMS value calculation of stator phase to neutral voltage

It is shown above that voltage is correctly measured with voltage LEM. In this section, rms value calculation method is verified. Main principle of estimation rms value of the phase to neutral voltage is same with estimation of rms value of stator current. Phase voltage is measured with voltage LEM and measured signal is filtered by a low pass filter whose cut-off frequency is set to 2 kHz. Measured voltages, when motor is driven by svpwm modulated voltage at 30Hz and 70 Hz, are shown in Fig.4.26 and Fig.4.27 respectively.

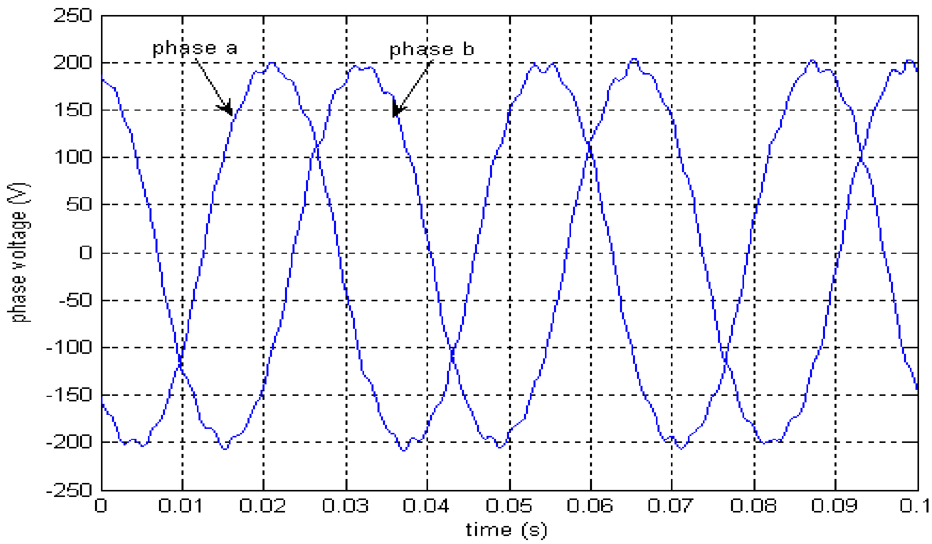

Fig.4.26 Measured phase to neutral voltages at 30Hz.

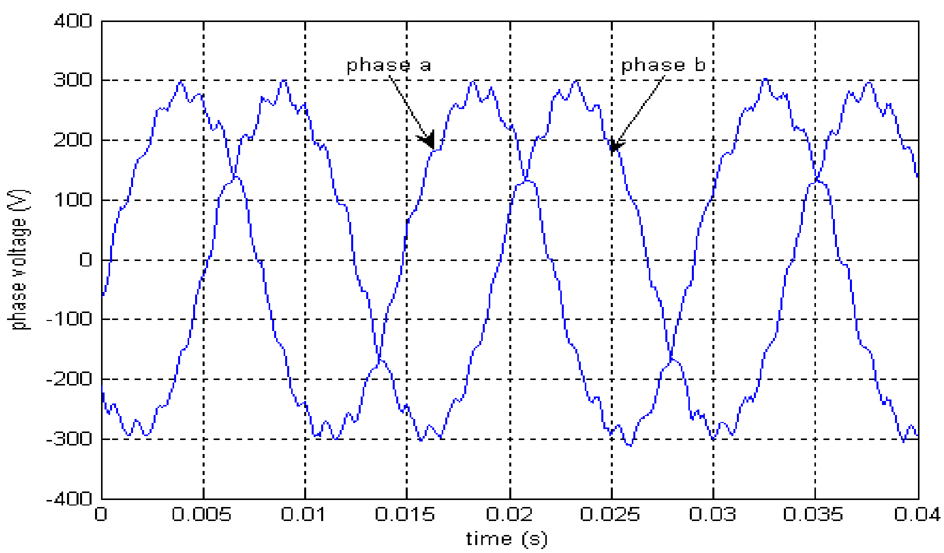

Fig.4.27 Measured phase to neutral voltages at 70Hz

Estimated rms value and measured phase voltages at are shown in Fig.4.28 and Table.4.9.

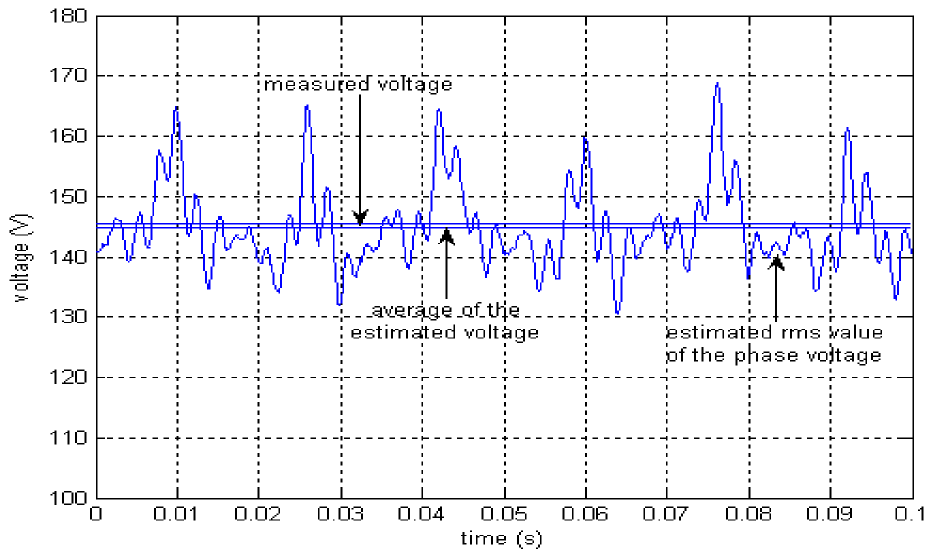

Fig.4.28 Measured and estimated rms value of phase voltage
when motor is driven at 30Hz with inverter

Table.4.9 Measured and estimated rms value of phase voltage
when motor is driven with inverter.

Frequency(Hz)	Measured rms value (V)	Estimated rms value (V)	Error (%)
10	55.15	54.6	1
10	48.58	47.8	1.6
30	145.52	144.9	0.4
30	137.7	140.2	-1.8
50	205.06	204.3	0.4
50	208.6	207.2	0.7
70	213.55	204.5	4.2
70	212.13	205.9	2.9

It is shown that estimated rms value of phase voltage is very similar to the measured value except 70Hz. As shown in Fig.4.27, oscillation imposed on the measured signal at high frequencies, increases the error.

4.11 Verification of estimation of power factor

Two phase instantaneous currents are used to estimate power factor of the motor. By using rms value of the stator phase current and space vector representation of stator current, power factor of the motor is calculated. It is assumed that, phase currents are symmetrical. Symmetrical phase currents mean that currents are sinusoidal, amplitudes are equal and all of the currents are displaced by angle 2π/3 from each other. Magnetic axes of the motor are shown in Fig.4.29.

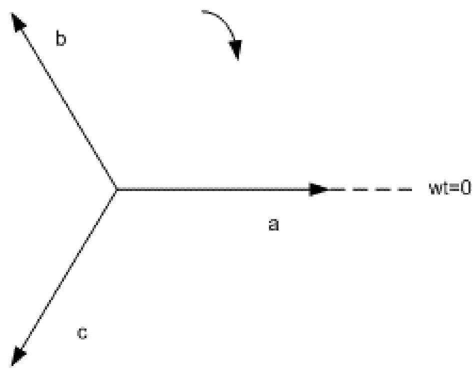

Fig.4.29 Magnetic axes of the motor

Instantaneous phase currents can be written as shown in equation (4.11).

$$\begin{aligned} i_{sa} &= \hat{I}.\cos(\omega t - \varphi) \\ i_{sb} &= \hat{I}.\cos(\omega t - \varphi - 2\pi/3) \\ i_{sc} &= \hat{I}.\cos(\omega t - \varphi + 2\pi/3) \end{aligned} \quad (4.11)$$

where $\hat{I}$ is the peak value of current, ω is its angular frequency and φ is the phase angle. Equality of current vector in stationary reference frame is shown in equation (4.12).

$$\vec{i}_s = i_{sa} + a^2.i_{sb} + a.i_{sc} \quad (4.12)$$

where a denotes $e^{j2\pi/3}$. Substituting equation (4.11) into equation (4.12), current vector in stationary reference frame is written as in equation (4.13).

$$\vec{i}_s = \frac{3}{2}.\hat{I}.e^{j(\omega t-\varphi)} \tag{4.13}$$

In synchronous reference frame, current vector is written as equation (4.14).

$$\vec{i}_s^{\,e} = \frac{3}{2}.\hat{I}.e^{-j\varphi} = \frac{3}{2}.\hat{I}.(\cos\varphi - j.\sin\varphi) \tag{4.14}$$

Using equation (4.14), $\cos\varphi$ (power factor) is written as equation (4.15)

$$\cos\varphi = \frac{\sqrt{2}}{3}.\frac{\mathrm{Re}\{\vec{i}_s^{\,e}\}}{I_s} \tag{4.15}$$

Current vector in stationary reference frame is written as equation (4.16) and real part of this vector is equal to the equation (4.17).

$$\vec{i}_s^{\,e} = \frac{3}{2}.(i_\alpha + ji_\beta).e^{j\omega t} \tag{4.16}$$

$$\mathrm{Re}\{\vec{i}_s^{\,e}\} = \frac{3}{2}.(i_\alpha.\cos(\omega t) - i_\beta.\sin(\omega t)) \tag{4.17}$$

Substituting equation (4.10) and equation (4.17) into equation (4.15), power factor is calculated.

To verify this estimation, 2.2kW induction motor is driven with line voltage and inverter. When motor is driven with line voltage, HIOKI Power Meter is used to measure input power, current and voltage.

$$\cos\varphi = \frac{P_{in}}{\sqrt{3}.V_{l-l}.I_l} \tag{4.18}$$

Measured power factor, which is calculated from equation (4.18), is compared with estimated current and results are shown in Table.4.10.

Table.4.10 Measured and estimated power factor
when 2.2kW induction motor is driven from the mains (f=50Hz)

Measured power factor	Estimated power factor	Error (%)
0.84	0.85	-1.2
0.83	0.82	1.2
0.8	0.82	-2.5
0.77	0.79	-2.6
0.73	0.75	-2.7
0.67	0.68	-1.5
0.59	0.6	-1.7
0.48	0.49	-2.1
0.417	0.421	0.9
0.33	0.31	6.1

It is shown that error is generally less than 3%.

When motor is driven with inverter, dc link power is measured and input power is calculated by subtracting calculated inverter losses from dc link power as shown in equation (4.19).

$$P_{in} = P_{dc} - P_{invloss} \tag{4.19}$$

where P_{dc} denotes dc link power and $P_{invloss}$ denotes inverter losses. Conduction losses and switching losses are added to calculate inverter losses. Calculations of these losses are investigated in Appendices. Then power factor is calculated by equation (4.18). Measured power factor is compared with estimated current and results are shown in Table.4.11.

Table.4.11 Measured and estimated power factor when 2.2kW induction motor is driven with inverter

frequency	Measured power factor	Estimated power factor	Error (%)
10	0.96	0.92	4.2
10	0.89	0.84	5.6
30	0.85	0.82	3.5
30	0.71	0.66	7
50	0.87	0.81	6.9
50	0.74	0.66	10.8
70	0.84	0.82	2.4
70	0.84	0.81	3.6

It is shown that when motor is driven with inverter, error is increasing. Except low frequencies, estimation of power factor is successful. At low frequencies, error at power factor results in larger errors of air-gap power calculation. For instance, 5% error of power factor at 10 Hz results in 10-15% error of air-gap power.

4.12 Simulation of induction motor

To simulate induction motor, exact steady-state induction motor model, which is shown in Fig.3.1, is used. Measured motor parameters are used to simulate motor. As explained above, core loss is calculated in accordance to the slip and frequency. Hence, R_c value is corrected with respect to calculated core loss. Initially, stator voltage drop is neglected and R_c is calculated. Then using equivalent impedance of the model, current and power factor is calculated. R_c value is calculated by considering the voltage drop on the stator branch. This process is repeated up to reach that difference of current and power factor are lower than 1%. Using final value of R_c, motor parameters and applied voltage, torque is calculated for slip from 0 to 1 with 0.001 change. Flow chart of the simulation is shown in Fig.4.30. Torque-speed curves, which are prepared for 10, 30, 50 and 70 Hz, are shown in Fig.4.32. 2.2 kW induction motor is driven from the mains (f=50Hz) from no-load to full-load. Linear portion of torque-speed curve, which is prepared by experiment, is compared with simulation in Fig.4.31.

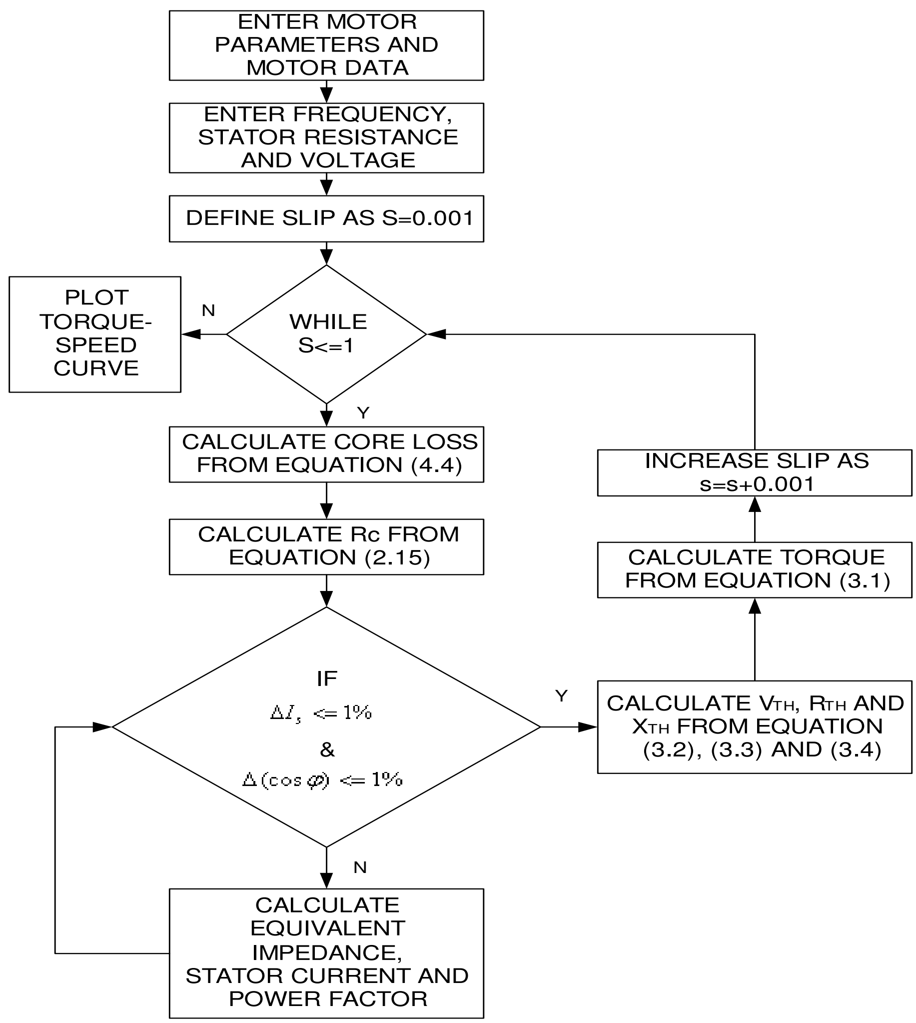

Fig.4.30 Flow chart of simulation model

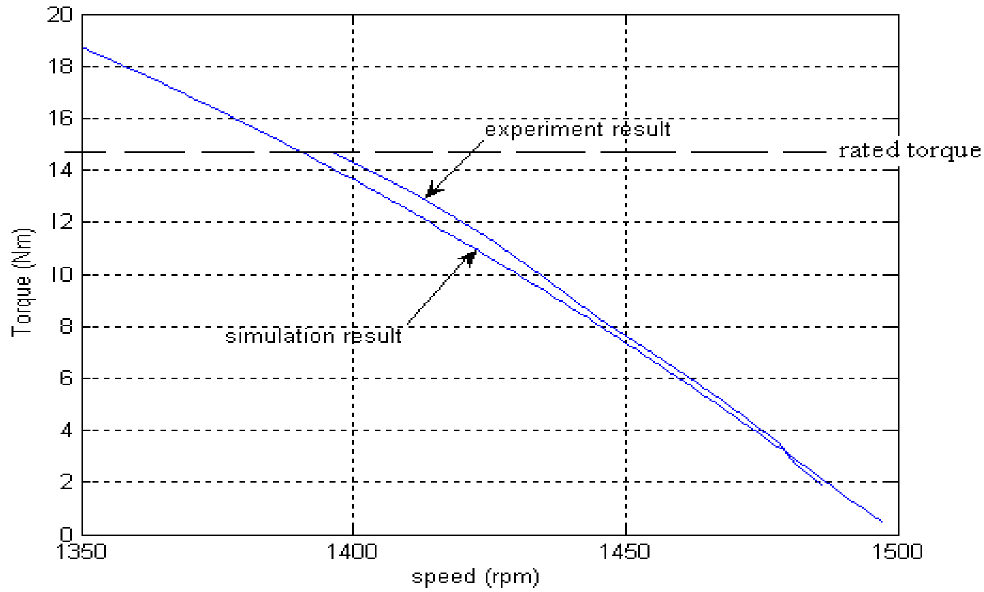

Figure.4.31 Linear portion of torque-speed curves for experiment result and simulation of 2.2 kW motor

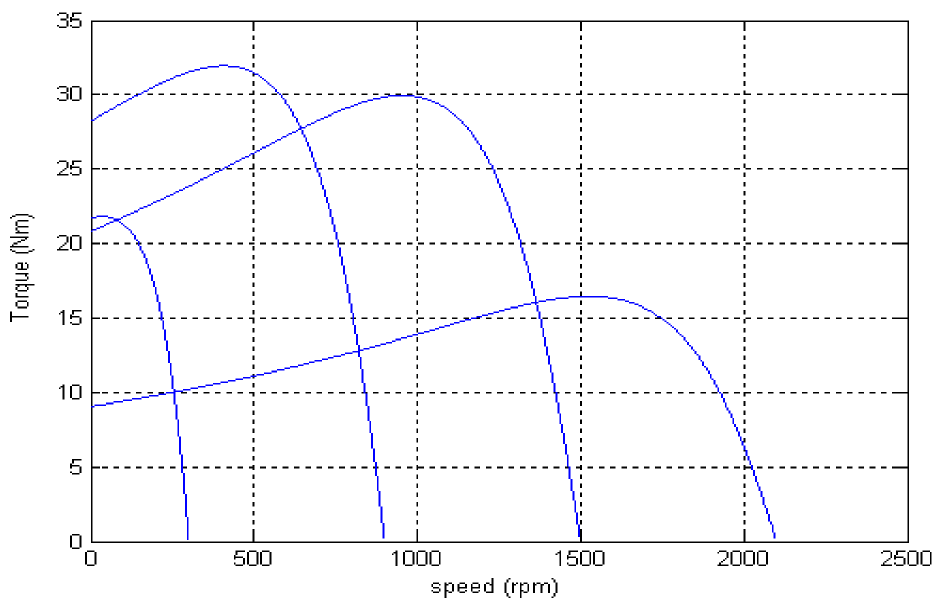

Fig.4.32 Torque-speed curves prepared with simulation for 10, 30, 50 and 70Hz

As seen from Fig.4.31, when load is increasing, difference between simulation result and experiment result is increasing. Error of simulation is less than 10% for 50Hz. Motor model is verified in Chapter 5. Simulation codes are shown in Appendices.

CHAPTER 5

VERIFICATION OF SPEED ESTIMATION METHODS

5.1 Introduction

In this chapter, results of the speed estimation methods presented in Chapter3 are investigated. Since the best accuracy of prediction may be expected when the exact induction motor model is used, as explained in Chapter3, initially accuracy of the exact induction motor model is investigated. Therefore, exact induction motor model is simulated from 10Hz to70Hz and simulation results are compared with test results. Then, accuracy of the speed estimation methods presented in Chapter 3 are investigated. For comparison, results of speed estimation methods are compared with simulation results from the exact induction motor model. This comparison shows the relative accuracy of speed estimation methods with respect to the exact induction motor model. Since the accuracy of the exact induction motor model is already evaluated against tests, the most accurate method of prediction can be identified.

5.2 Verification of steady-state induction motor model

To verify the exact induction motor model shown in Fig.3.1, the induction motor operation is simulated in Matlab environment and compared with test results. The simulation software is described in Chapter 4. First one of the test motor (2.2 kW induction motor) is driven from the mains and measured torque is compared with simulation result as shown in Fig.4.31 and Table.5.1. Since electrical torque is calculated in simulation, rotational loss is added to the load torque from measurements to compare with simulation result.

Table.5.1 Measured torque and torque found from simulation of exact steady-state motor model for mains (50Hz) driven 2.2kW motor

Vs_{l-l} (V)	Speed (rpm)	Measured torque (Nm)	Torque from model (Nm)	Error (%)
380	1445	8.2	7.95	3.0
380	1396	14.6	13.8	5.5

As shown in Fig.4.31 and Table.5.1, torque-speed curves prepared by simulation and tests for 2.2 kW induction motor are similar in shape. When speed is taken as reference and torques from simulation and measurement are compared, 3% error under half load and 6% error under full load are calculated. This is an acceptable accuracy.

To investigate the effects of inverter pulsed waveform on the accuracy of exact induction motor model, 2.2 kW induction motor is driven with inverter at 50 Hz and test results are compared with simulation results.

Speed is taken as reference and torques from measurement and simulation are compared. As shown in Table.5.3, error of the torque found from simulation is 4% under half load and 14% under full load. It is observed that error in torque estimation is increasing when motor is driven with inverter with respect to results obtained when motor is driven from the mains.

When 2.2kW motor is driven with inverter at 50Hz, flux level is lower than rated value since the dc link voltage does not permit higher voltage levels than applied. Therefore, magnetizing reactance and core loss resistance is likely to be different from the reference values obtained for rated flux. Furthermore, the pulsed waveform of the inverter may affect the other parameters too. These may be the error sources. However, this issue was not investigated further in this work.

To obtain the accuracy of the exact induction motor model when induction motor is driven with inverter, 1.1kW, 2.2kW and 4kW induction motors are driven at

10Hz, 30Hz, 50Hz and 70Hz under half load and full load and test results are compared with simulation results.

To produce maximum torque achievable for unit current, flux must be kept constant at rated value for different loads when the motor is inverter driven. This is especially important at low frequencies where the voltage drop on the series impedance becomes comparable to applied voltage. Here however, during the tests the following was done. The flux is in the +5% band of rated flux level for 1.1kW motor, in the +10% band of the rated flux level for 2.2kW motor and in the -5% band of the rated flux level for 4kW motor. During the tests the flux level was kept within the flux levels defined above.

To make realistic predictions, measured voltages during the tests are selected as input voltages of the simulations. Measured phase voltages are shown in Table.5.2, Table.5.3 and Table.5.4. In these tables, measured torques and simulation results are compared.

Table.5.2 Measured torque and torque found from simulation of exact steady-state motor model for 1.1kW motor

f (Hz)	Vs (V)	Speed (rpm)	Measured torque (Nm)	Torque from model (Nm)	Error (%)
10	50.9	136	5.3	6.8	-28.3
10	62.2	91	11.3	13.8	-22.1
30	129.4	550	5.2	6.2	-19.2
30	141.4	501	11.2	12.9	-15.2
50	219.2	954	5.2	6.4	-23.1
50	220.6	899	11.2	12.3	-9.8
70	220.6	1314	5.2	6.0	-15.4
70	220.6	1229	8.3	9.3	-12.0

Table.5.3 Measured torque and torque found from simulation of exact steady-state motor model for 2.2kW motor

f (Hz)	Vs (V)	Speed (rpm)	Measured torque (Nm)	Torque from model (Nm)	Error (%)
10	55.2	194	14.4	13.96	3.1
10	48.6	251	6.8	6.6	2.9
30	145.5	813	14.41	13.22	8.3
30	137.7	859	6.81	6.05	11.2
50	205.1	1384	14.41	12.4	14
50	208.6	1446	6.81	6.54	4
70	213.6	1943	10.21	8.97	12.1
70	212.1	1998	6.81	6.15	9.7

Table.5.4 Measured torque and torque found from simulation of exact steady-state motor model for 4kW motor

f (Hz)	Vs (V)	Speed (rpm)	Measured torque (Nm)	Torque from model (Nm)	Error (%)
10	70.6	250	13.5	12.6	6.7
10	85.9	218	26.7	25.0	6.4
30	212.5	861	13.5	12.3	8.9
30	229.2	829	26.7	23.6	11.6
50	351.7	1459	13.5	12.8	5.2
50	352.3	1424	26.8	21.8	18.7
70	351.8	2026	13.6	11.3	16.9
70	363.6	1970	22.0	19.0	13.6

In Table.5.2, Table.5.3 and Table.5.4, speed is taken as reference and measured torque is compared with torque found from simulation of the exact induction motor model. for 1.1kW motor, measured torque is smaller than the estimated torque and error of the estimation is very high. Since rated torque of this motor is nearly 11Nm, any erroneous measurement may increase error. For 2.2kW and 4kW motors, measured torque is higher than estimated torque.

5.3 Verification of speed estimation methods

To verify the speed estimation methods explained in Chapter3, 1.1, 2.2 and 4kW motors are driven with an inverter. Measurements are taken from 10 Hz to 70Hz at different loads.

Measured currents and voltages are logged by Trace program and stored in a file. Speed estimation methods are simulated in Matlab by using measured data. By this way, any error that may be introduced due to measurements is taken into account in these predictions. Since the simulation software of speed prediction is the same as that would be installed in μP application of the prediction methods, the results found from the simulations are the same as the application processor would calculate.

Speed estimation results are compared with simulation results of the exact steady-state motor model and test results. Speed estimation results are shown in Table.5.5 to Table.5.18.

In this study if error is less than 5%, prediction is accepted as well. If error is between 5% and 10%, prediction is acceptable. If error is over than 10%, prediction is accepted as poor.

Table.5.5 Comparison of Method 1 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.8	3.2	2.5	11.2	1.9	2.1	1.8	-3.7	1.6	-0.4	-6.4	-9.3
20	0.3	0.9	-0.3	1.6	0.2	0.4	-0.1	-2.6	0.1	0.2	-1.6	-1.8
30	0.2	0.0	-0.2	0.4	-0.1	-0.1	-0.2	-2.1	0.0	0.1	-0.4	-0.7
40	0.5	-0.2	-0.3	0.0	0.1	-0.2	-0.4	-2.0	0.2	-0.2	-0.7	-1.5
50	0.6	-0.3	-0.1	-1.2	0.2	-0.4	-0.9	-4.9	0.2	-0.4	-0.6	-1.8
60	0.9	-1.2	-1.9	-6.7	0.2	-1.0	-2.2	-8.6	0.2	-0.8	-1.8	-4.2
70	0.8	-2.0	-3.3	-7.3	0.2	-1.4	-3.4	-5.1	0.3	-1.4	-2.8	-5.0

Table.5.6 Comparison of Method 1 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.8	-1.4	-15.1	-31.9	1.9	-0.4	-3.8	-8.7	1.6	-0.4	-5.1	-6.2
20	0.1	-0.4	-3.5	-4.0	0.0	-0.3	-0.6	-3.8	0.1	0.2	-0.9	-0.4
30	-0.2	-0.7	-2.0	-3.0	-0.3	-0.5	-0.5	-1.8	-0.1	0.0	-0.1	0.2
40	0.0	-1.0	-1.8	-2.0	-0.3	-0.8	-0.7	-1.5	-0.1	-0.4	-0.6	-0.5
50	0.2	-1.1	-1.1	-2.4	-0.3	-0.9	-1.3	-3.1	-0.3	-0.7	-0.6	-0.6
60	0.5	-1.6	-2.7	-8.7	0.0	-1.2	-2.3	-7.5	0.0	-0.8	-1.3	-2.7
70	0.7	-2.3	-4.4	-9.7	0.1	-1.6	-3.4	-5.1	0.2	-1.2	-2.1	-3.9

Evaluation of Method 1 is given below.

a)low frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 1 is poor under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 1 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 1 is not good under full load condition. For other load conditions, performance is good.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 1 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 1 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 1 is good for all load conditions.

c)high frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 1 is poor under full load condition. For other load conditions, performance is good.

- medium motors: The results found indicate that performance of Method 1 is not good under full load condition. For other load conditions, performance is good.
- large motors: Poor performance is expected. The results found indicate that performance of Method 1 is good for all load conditions.

Since stator resistance is neglected in this method, performance is expected to be poor at low frequencies for small motors. This issue is explained in Chapter3. Stator resistance of 1.1kW motor is measured as 6.8Ω where stator resistances of 2.2kW and 4kW motors are measured as 3.3Ω and 3.75Ω respectively. Although stator resistances of used motors are not small, Method 1 predicts speed well for 2.2kW motor.

Since breakdown torque is assumed to be constant, this method is expected to fail in the field weakening region. However, performance of this method is good except full load condition.

It is seen that performance of this method worsens when load increases since voltage drop on the stator resistance increases and torque capability reduces.

Table.5.7 Comparison of Method 2 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	2.6	-1.4	-7.6	10.5	1.0	-0.4	-0.1	-4.1	1.0	-3.8	-11.4	-10.2
20	0.2	0.2	-1.5	1.5	0.2	0.2	-0.3	-2.6	0.1	-0.1	-2.0	-1.9
30	0.1	-0.1	-0.5	0.4	-0.1	-0.2	-0.3	-2.1	0.0	0.0	-0.5	-0.8
40	0.5	-0.3	-0.4	0.0	0.1	-0.2	-0.4	-2.0	0.2	-0.2	-0.8	-1.6
50	0.6	-0.3	-0.1	-1.2	0.2	-0.4	-1.0	-4.9	0.2	-0.4	-0.7	-1.9
60	0.8	-1.3	-2.1	-6.9	0.1	-1.0	-2.3	-8.7	0.2	-0.9	-1.9	-4.3
70	0.6	-2.1	-3.8	-8.3	0.1	-1.6	-3.7	-5.5	0.2	-1.5	-3.0	-5.3

Table.5.8 Comparison of Method 2 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	2.6	-6.2	-26.9	-32.8	1.0	-3.0	-5.8	-9.1	1.0	-3.8	-10.1	-7.1
20	0.0	-1.1	-4.8	-4.1	0.0	-0.5	-0.9	-3.9	0.1	-0.1	-1.3	-0.5
30	-0.2	-0.8	-2.4	-3.0	-0.3	-0.6	-0.5	-1.8	-0.1	-0.1	-0.3	0.2
40	0.0	-1.1	-1.9	-2.0	-0.3	-0.8	-0.7	-1.5	-0.2	-0.4	-0.7	-0.5
50	0.2	-1.1	-1.1	-2.4	-0.3	-0.9	-1.4	-3.2	-0.3	-0.7	-0.6	-0.6
60	0.4	-1.7	-2.9	-8.9	0.0	-1.3	-2.4	-7.6	0.0	-0.8	-1.4	-2.7
70	0.5	-2.4	-4.9	-10.7	0.1	-1.7	-3.8	-5.5	0.1	-1.4	-2.3	-4.1

Evaluation of Method 2 is given below.

a)low frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 2 is poor under full load and half load conditions. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 2 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 2 is poor under full load and half load conditions. For other load conditions, performance is good.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 2 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 2 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 2 is good for all load conditions.

c)high frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 2 is not good under full load condition. For other load conditions, performance is good.

- medium motors: The results found indicate that performance of Method 2 is not good under full load condition. For other load conditions, performance is good.
- large motors: Good performance is expected. The results found indicate that performance of Method 2 is not good under full load condition. For other load conditions, performance is good.

This method is expected to improve the performance of Method 1 in the field weakening region. However, results found indicate that performance of Method 2 is worse than Method 1 in the field weakening region.

Table.5.9 Comparison of Method 3 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	4.4	6.2	10.7	37.3	2.0	3.2	4.8	4.7	1.7	0.4	-4.1	-1.7
20	0.4	1.8	1.6	7.5	0.2	0.7	0.7	-0.6	0.2	0.4	-1.0	0.0
30	0.2	0.4	0.7	3.0	-0.1	0.0	0.1	-1.2	0.0	0.2	-0.1	0.0
40	0.5	0.0	0.3	1.4	0.1	-0.1	-0.2	-1.5	0.2	-0.1	-0.5	-1.2
50	0.7	-0.1	0.3	-0.3	0.2	-0.3	-0.8	-4.6	0.2	-0.3	-0.5	-1.6
60	0.9	-1.1	-1.6	-6.0	0.2	-0.9	-2.1	-8.3	0.3	-0.8	-1.7	-4.0
70	0.9	-1.9	-3.0	-6.9	0.2	-1.4	-3.3	-4.9	0.3	-1.4	-2.7	-4.9

Table.5.10 Comparison of Method 3 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	4.4	1.7	-5.7	5.9	2.0	0.7	-0.6	0.1	1.7	0.4	-2.8	1.1
20	0.1	0.4	-1.6	2.2	0.1	0.0	0.1	-1.8	0.2	0.4	-0.3	1.3
30	-0.1	-0.3	-1.1	-0.3	-0.3	-0.3	-0.1	-1.0	-0.1	0.1	0.1	1.0
40	0.0	-0.8	-1.2	-0.6	-0.3	-0.7	-0.5	-1.1	-0.1	-0.3	-0.4	-0.1
50	0.3	-1.0	-0.7	-1.5	-0.3	-0.8	-1.2	-2.8	-0.3	-0.7	-0.4	-0.4
60	0.6	-1.5	-2.4	-8.0	0.0	-1.2	-2.2	-7.3	0.0	-0.7	-1.2	-2.5
70	0.8	-2.2	-4.1	-9.3	0.1	-1.5	-3.4	-4.9	0.2	-1.2	-2.0	-3.8

Evaluation of Method 3 is given below.

a)low frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 3 is poor except no-load condition.
- medium motors: The results found indicate that performance of Method 3 is good for all load conditions.
- large motors: Poor performance is expected. The results found indicate that performance of Method 3 is good for all load conditions.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 3 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 3 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 3 is good for all load conditions.

c)high frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 3 is not good under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 3 is not good under full load condition. For other load conditions, performance is good.
- large motors: Poor performance is expected. The results found indicate that performance of Method 3 is good for all load conditions.

Table.5.11 Comparison of Method 4 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.1	2.4	5.1	9.2	2.3	4.1	6.1	6.9	1.6	1.7	0.9	2.1
20	0.2	0.2	0.2	0.7	0.3	1.1	1.2	2.4	0.1	0.5	-0.1	0.5
30	0.1	-0.4	-0.2	0.0	-0.1	0.3	0.5	0.4	0.0	0.1	0.0	0.0
40	0.4	-0.6	-0.4	-0.7	0.1	0.1	0.0	-0.2	0.4	-0.1	-0.3	-1.0
50	0.5	-0.5	-0.4	-1.1	0.3	-0.1	-0.2	-1.5	0.2	-0.3	-0.4	-0.8
60	1.0	-1.0	-1.1	-2.6	0.4	-0.3	-0.4	-1.0	0.4	-0.4	-0.6	-1.3
70	1.3	-1.6	-1.7	-3.1	0.5	-0.4	-0.6	-0.7	0.5	-0.8	-0.9	-1.5

Table.5.12 Comparison of Method 4 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.1	-2.3	-12.5	-36.4	2.3	1.6	0.7	2.4	1.6	1.7	2.1	4.9
20	-0.1	-1.1	-3.1	-4.9	0.1	0.4	0.7	1.2	0.1	0.5	0.6	1.8
30	-0.2	-1.1	-2.0	-3.4	-0.3	-0.1	0.2	0.6	-0.1	0.0	0.3	1.0
40	-0.1	-1.3	-1.9	-2.7	-0.3	-0.5	-0.2	0.3	0.0	-0.3	-0.3	0.1
50	0.1	-1.4	-1.5	-2.3	-0.2	-0.6	-0.6	0.2	-0.3	-0.6	-0.4	0.4
60	0.6	-1.5	-1.9	-4.5	0.2	-0.6	-0.5	0.0	0.1	-0.4	-0.1	0.2
70	1.3	-1.9	-2.8	-5.4	0.5	-0.6	-0.6	-0.7	0.5	-0.6	-0.3	-0.4

Evaluation of Method 4 is given below.

a)low frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 4 is poor under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 4 is poor under full load and half load conditions. For other load conditions, performance is good.
- large motors: Good performance is expected. The results found indicate that performance of Method 4 is good for all load conditions.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 4 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 4 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 4 is good for all load conditions.

c)high frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 4 is not good under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 4 is good for all load conditions.
- large motors: Poor performance is expected. The results found indicate that performance of Method 4 is good for all load conditions.

Table.5.13 Comparison of Method 5 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.4	3.4	6.9	11.7	2.4	4.5	6.8	8.0	1.6	2.1	1.5	3.1
20	0.2	0.6	0.9	1.9	0.3	1.3	1.5	2.9	0.1	0.6	0.1	0.8
30	0.1	-0.2	0.2	0.7	-0.1	0.4	0.6	0.6	0.0	0.2	0.2	0.2
40	0.4	-0.5	-0.2	-0.3	0.1	0.2	0.1	0.0	0.4	-0.1	-0.3	-0.9
50	0.5	-0.5	-0.3	-0.8	0.3	0.0	-0.1	-1.3	0.2	-0.3	-0.4	-0.7
60	1.0	-1.0	-1.0	-2.3	0.4	-0.3	-0.3	-0.9	0.4	-0.4	-0.6	-1.2
70	1.4	-1.6	-1.6	-2.9	0.5	-0.4	-0.5	-0.6	0.6	-0.7	-0.9	-1.4

Table.5.14 Comparison of Method 5 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.4	-1.2	-10.4	-32.7	2.4	2.1	1.4	3.5	1.6	2.1	2.7	5.8
20	0.0	-0.7	-2.3	-3.7	0.1	0.6	0.9	1.7	0.1	0.6	0.9	2.2
30	-0.2	-0.9	-1.6	-2.7	-0.3	0.0	0.4	0.9	-0.1	0.1	0.4	1.2
40	-0.1	-1.2	-1.7	-2.3	-0.3	-0.4	-0.1	0.5	0.0	-0.3	-0.2	0.2
50	0.1	-1.3	-1.3	-2.0	-0.2	-0.6	-0.5	0.4	-0.2	-0.6	-0.3	0.5
60	0.7	-1.4	-1.8	-4.3	0.2	-0.5	-0.4	0.2	0.1	-0.3	-0.1	0.3
70	1.3	-1.9	-2.7	-5.2	0.5	-0.5	-0.5	-0.6	0.5	-0.6	-0.2	-0.3

Evaluation of Method 5 is given below.

a)low frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 5 is poor under full load and half load conditions. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 5 is poor under full load and half load conditions. For other load conditions, performance is good.
- large motors: Good performance is expected. The results found indicate that performance of Method 5 is good for all load conditions.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 5 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 5 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 5 is good for all load conditions.

c)high frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 5 is good for all load conditions.

- medium motors: The results found indicate that performance of Method 5 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 5 is good for all load conditions.

This method is expected to improve the performance of Method 4 in the field weakening region. The results found indicate that performance of Method 5 is better than Method 4 in the field weakening region. However, performance of Method 5 is a bit worse than Method 4 at low frequencies for small and medium motors.

Table.5.15 Comparison of Method 6 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.1	0.3	-0.9	1.6	1.9	1.3	0.2	-4.0	1.2	-0.7	-4.7	-8.1
20	0.2	0.2	-0.4	-0.4	0.3	0.7	0.2	-0.2	0.1	0.1	-0.9	-1.3
30	0.1	-0.3	-0.1	0.3	-0.1	0.2	0.2	-0.2	0.0	0.1	-0.1	-0.4
40	0.4	-0.4	-0.2	-0.2	0.1	0.1	0.0	-0.3	0.4	-0.1	-0.4	-1.1
50	0.6	-0.4	-0.2	-0.5	0.3	0.0	-0.1	-1.4	0.2	-0.3	-0.4	-0.8
60	1.0	-1.0	-0.9	-1.5	0.4	-0.3	-0.3	-0.6	0.4	-0.4	-0.6	-1.2
70	1.4	-1.6	-1.5	-2.2	0.5	-0.4	-0.5	-0.5	0.6	-0.7	-0.8	-1.3

Table.5.16 Comparison of Method 6 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	3.1	-4.5	-19.1	-46.2	1.9	-1.3	-5.6	-9.0	1.2	-0.7	-3.5	-5.1
20	0.0	-1.1	-3.6	-6.1	0.1	0.0	-0.3	-1.4	0.1	0.1	-0.2	0.0
30	-0.2	-1.0	-1.9	-3.2	-0.3	-0.1	0.0	0.0	-0.1	0.0	0.1	0.6
40	-0.1	-1.2	-1.7	-2.2	-0.3	-0.5	-0.3	0.2	0.0	-0.3	-0.3	0.0
50	0.2	-1.3	-1.3	-1.8	-0.2	-0.6	-0.6	0.2	-0.2	-0.6	-0.4	0.5
60	0.7	-1.4	-1.7	-3.4	0.2	-0.5	-0.4	0.4	0.1	-0.3	-0.1	0.4
70	1.3	-1.9	-2.6	-4.5	0.5	-0.5	-0.5	-0.5	0.5	-0.6	-0.2	-0.2

Evaluation of Method 6 is given below.

a)low frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 6 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 6 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 6 is not good under full load condition. For other load conditions, performance is good.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 6 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 6 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 6 is good for all load conditions.

c)high frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 6 is good for all load conditions.
- medium motors: The results found indicate that performance of Method 6 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 6 is good for all load conditions.

Table.5.17 Comparison of Method 7 with simulation of exact motor model for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	2.4	-2.3	-5.7	-9.8	1.5	-0.3	-2.9	-10.4	-0.2	-3.8	-9.7	-18.5
20	0.1	-1.6	-4.1	-8.5	0.1	-0.6	-2.2	-5.6	-0.1	-1.4	-3.4	-6.5
30	0.0	-1.4	-2.8	-5.8	-0.1	-0.7	-1.5	-4.0	0.0	-0.9	-1.9	-3.8
40	0.2	-1.2	-2.1	-4.5	0.1	-0.5	-1.3	-3.2	0.0	-0.7	-1.4	-2.9
50	0.3	-1.0	-1.6	-4.2	0.2	-0.5	-1.3	-4.4	0.0	-0.5	-1.1	-2.5
60	0.6	-1.4	-2.4	-6.1	0.2	-0.8	-1.7	-4.5	0.0	-0.6	-1.4	-3.1
70	0.7	-2.0	-3.0	-5.4	0.3	-1.0	-2.0	-2.7	0.0	-0.8	-1.6	-2.9

Table.5.18 Comparison of Method 7 with test result for 1.1kW, 2.2kW and 4kW motors

Frequency (Hz)	1.1 kW				2.2 kW				4kW			
	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)	No load (% error)	1/4 load (% error)	1/2 load (% error)	1/1 load (% error)
10	2.4	-7.1	-24.7	-62.7	1.5	-2.9	-8.7	-15.7	-0.2	-3.8	-9.0	-16.9
20	-0.2	-3.0	-7.4	-14.6	0.0	-1.3	-2.7	-6.9	-0.1	-1.4	-3.1	-5.9
30	-0.3	-2.1	-4.6	-9.4	-0.3	-1.0	-1.8	-3.8	-0.1	-0.9	-1.8	-3.4
40	-0.3	-2.0	-3.6	-6.6	-0.4	-1.1	-1.5	-2.7	-0.2	-0.7	-1.4	-2.4
50	-0.1	-1.8	-2.7	-5.4	-0.3	-1.1	-1.7	-2.7	-0.2	-0.6	-1.1	-2.0
60	0.2	-1.9	-3.2	-8.0	0.0	-1.1	-1.8	-3.4	-0.1	-0.6	-1.2	-2.5
70	0.7	-2.3	-4.1	-7.7	0.2	-1.2	-2.1	-2.7	-0.1	-0.7	-1.4	-2.5

Evaluation of Method 7 is given below.

a)low frequency:

- small motors: Poor performance is expected. The results found indicate that performance of Method 7 is not good under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 7 is not good under full load condition. For other load conditions, performance is good.
- large motors: Poor performance is expected. The results found indicate that performance of Method 7 is not good under full load and half load conditions. For other load conditions, performance is good.

b)medium frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 7 is not good under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 7 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 7 is good for all load conditions.

c)high frequency:

- small motors: Good performance is expected. The results found indicate that performance of Method 7 is not good under full load condition. For other load conditions, performance is good.
- medium motors: The results found indicate that performance of Method 7 is good for all load conditions.
- large motors: Good performance is expected. The results found indicate that performance of Method 7 is good for all load conditions.

CHAPTER 6

CONCLUSION

The aim of this study is achieving speed estimation accuracy and torque estimation accuracy with minimum number of calculations, minimum measurements and minimum requirements for the motor parameters.

Some of the speed estimation methods require knowledge of motor parameters for better speed estimation accuracy. Since no-load and locked rotor tests are sometimes impractical to do and on-line parameter estimation methods place an important burden of microprocessor, some methods are proposed to estimate motor parameters off-line from manufacturer data. If the drive is capable of measuring voltage and current off-line parameter measurement may also be possible.

Since manufacturer data may be erroneous, label data for motors is determined from tests. When the parameter estimation results given in Chapter 2 are investigated, it is seen that error of estimated parameters are very high. If average of these estimation errors are taken for three test motors, averages of the errors are higher than 13% for 1.1kW motor, 25% for 2.2kW motor and 17% for 4kW motor.

Since these parameters are used to estimate torque-speed curve of the induction motors, it is wise to compare the estimated torque-speed curves (at 50 Hz) which are calculated from estimated parameters and parameters calculated from no-load and locked rotor tests results. When the torque-speed curves calculated from estimated parameters and parameters calculated from no-load and locked rotor tests results are investigated, Method 4 given in Chapter 2 can be identified as the best parameter estimation method giving overall good prediction for the whole torque-speed curve of the three motors. This comparison is based on the starting torque, breakdown torque and linear region of the torque-speed curve. Average of the error of estimated starting torque is nearly 11% and average of the error of estimated breakdown torque is nearly 8% for Method 4.

Rated voltage, rated current, rated power factor, output power, frequency and rated motor speed values are used in Method 4, which are all available on the motor label.

Normally an induction motor is operated in the portion of torque-speed curve between no-load speed and full-load speed. For this reason, the parameter predicted from various methods discussed in Chapter 2 are also assesed regarding their accuracy of prediction of the this region of the torque-speed characteristics. When the results are investigated, again Method 4 is identified as the best estimation method giving good prediction for the linear region of torque-speed curve.

At 50 Hz, when rated speed is taken as reference and comparison is based on the torque prediction accuracy, torque prediction error of Method 4 is lower than 10%. When torque is taken as reference and comparison is based on the speed, error of Method 4 is nearly 1%. It must be noted however, that this error may be expected to be larger at low speeds (frequencies).

Performances (stator current, rated torque and power factor) of the test motors are calculated from estimated parameters and parameters from no-load and locked rotor tests results are compared also with measured motor performance at rated torque condition (50Hz). Comparisons are based on the torque, stator current and power factor and average of the estimation errors are considered at rated speed. Method 3 and Method 1 are better than other methods for 1.1kW motor. Method 2 is better than other methods for 2.2kW motor. For 4kW motor, Method 2 and Method 3 are more suitable than other methods. When all test motors are considered, Method 3 can be identified as the best estimation method amongst these methods. In conclusion, it can be said that the study in Chapter 2 led to methods of parameter prediction which give acceptably good motor performance prediction at rated speed. In other words the methods identified as better than others may be employed by an inexpensive drive, to predict motor speed (from slow voltage and current measurements) and hence to control motor speed or torque.

Since the most important aim of this study is achieving speed estimation accuracy with minimum number of calculations and measurements, first speed estimation methods found in literature are investigated. Two of these methods, suitable for low cost motor drives, are briefly explained in Chapter3. Since these methods are expected not to be suitable for heavy load conditions at low frequencies and in the field weakening region, some methods are proposed to achieve speed estimation accuracy with similar calculation burden for all load conditions and frequencies.

Since the best accuracy of speed prediction may be expected when the exact induction motor model is used, as explained in Chapter3, initially accuracy of the exact induction motor model is investigated. First a 2.2kW motor is driven from mains and tests results are compared with simulation results. When rated speed is taken as reference, measured torque is compared with estimated torque, prediction error is found to be lower than 6%. However, when this comparison is repeated for inverter driven 2.2kW motor, the torque prediction error is found to increase upto 14%.

When 2.2kW motor is driven with inverter at 50Hz, flux level is lower than rated value since the dc link voltage does not permit higher voltage levels than applied. Therefore, magnetizing reactance and core loss resistance is likely to be different from the reference values obtained for rated flux. Furthermore, the pulsed waveform of the inverter may affect the other parameters too. These may be the error sources. However, this issue was not investigated further in this work.

As given above the best accuracy of speed prediction may be expected when the exact induction motor model is used. Therefore, for evaluation of speed estimation methods, speed estimation results are compared with simulation results of the exact steady-state motor model.

Note that to have realistic simulation of the tests, in the simulation program recorded voltage and current values are used for simulations.

In this study, medium frequency is defined as between 20 Hz and 50 Hz. Frequencies over 50 Hz are named as high frequency. Low frequency is defined as below 20Hz in this study. Since 1.1kW, 2.2kW and 4 kW motors are available in laboratory and capacity of the inverter is not suitable for larger motors, these motors are used in the experiments. In this study, 1.1 kW motor is named as small motor and 4kW motor is named as large motor. Since stator resistance of 2.2kW motor is smaller than 4kW motor, 2.2kW motor can also be classified as a large motor.

Table.6.1 Evaluation of speed estimation methods

Methods	Small motors				Large motors			
	Low speed		High speed		Low speed		High speed	
	Light load	Heavy load	Light load	Heavy load	Light load	Heavy load	Light load	Heavy load
M1	X		X		X	X	X	
M2	X		X		X	X	X	
M3	X		X		X	X	X	
M4	X		X	X	X	X	X	X
M5	X		X	X	X	X	X	X
M6	X	X	X	X	X	X	X	X
M7	X		X	X	X		X	X

The results found are given in detail in Chapter 5. In summary the following is observed:

- Performance Method 1 is good under heavy loads at low speeds for large motors and under light loads as expected.
- Performance of Method 2 is expected to be good at high frequencies. However, performance of Method 2 is poor under heavy load conditions in the field weakening region.
- Performance of Method 3 is expected to be poor for heavy load conditions. However, performance of this method is good for large motors even under heavy loads.
- Performance of Method 4 is expected to be good for heavy loads at low freqeuncies. However, performance of this method is poor at heavy load conditions for small motors.
- Performance of Method 5 is expected to be good for all load conditions and for each type of motors. However, this method failed under heavy loads at low frequencies for small motors.
- Performance Method 6 is good for all conditions as expected.
- Performance Method 7 is good under heavy loads at high speeds and under light loads as expected

When the speed estimation results given in Chapter5 are investigated, Method 6 can be identified as the best estimation method giving good performance for all load conditions and frequencies. Method 4 and Method 5 also give good prediction performance.

Base frequency, rated voltage, rated current, speed, power factor, output power, efficiency, number of poles, breakdown torque and all motor parameters are used in these methods. Voltage and two phase instantaneous currents are measured in this method.

In the motor drive used for laboratory tests, two phase instantaneous voltages and currents can be measured with voltage and current LEMs. Therefore, instantaneous current and voltage values measured are used in the prediction of speed via calculation of air-gap power. In alternative way of calculating, input power of the motor is determined by measuring dc-link voltage and current as explained in Chapter 4. If rms value of current is measured, stator copper loss and finally air-gap power can be calculated.

The rms value of current is easy to measure and does not require a fast A/D converter. For example the arangement given in Fig.6.1 can be used. This approach determines the average value of current, rms value is simply found by multiplying the capacitor reading by $(1/2)^{½}$ and an appropriate constant.

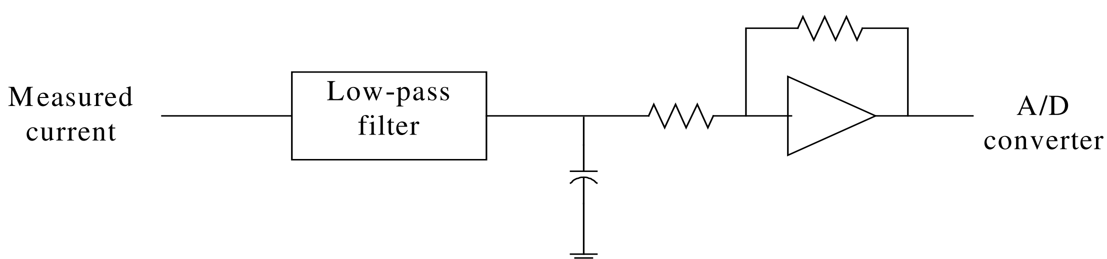

Fig.6.1 Measurement module for rms value of current

Although these speed estimation methods require all motor parameters, all of these parameters can be estimated from manufacturer data as discussed in Chapter 2.

Further work:

The remains much to be done:

a) Exact model of 1.1kW motor must be verified again.
b) Load tests can be repeated by using a torque transducer.
c) In order to reduce the necessity for usage of the motor parameters, breakdown torque and slip under breakdown torque condition can be estimated. Effect of these estimations to the speed prediction results can be examined.
d) The effect of inverter voltage waveform on motor parameters can be investigated.
e) The effect of calculation of air-gap power by measuring dc-link voltage and current and also measuring rms value of current can be investigated.

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APPENDIX A

MANUFACTURER DATA OF TEST MOTORS

Manufacturer data of used motors, which are produced by Elsan Elektrik A.Ş., are given below.

Table.A.1 Manufacturer data of test motors

	Motor 1	Motor 2	Motor 3
Output power (kW)	1.1 kW	2.2 kW	4 kW
Nominal current (A)	3.1	5.2	8.6 (Δ)
Nominal speed (rpm)	907	1420	1423
Power factor	0.77	0.81	0.85
Efficiency (%)	70	80	83
Number of poles	6	4	4
Nominal moment (Nm)	11.6	14.8	26.8
Breakdown torque (T_{bd}/T_r)	1.9	2.6	2.8

Table.A.2 Motor label data determined from tests

	Motor 1	Motor 2	Motor 3
Output power (kW)	1073.2 W	2106.6 W	4021.7 W
Nominal voltage (V)	380	380	380
Nominal current (A)	3.15	4.85	9.11 (Δ)
Nominal speed (rpm)	915	1397	1433
Power factor	0.7524	0.8458	0.8261
Number of poles	6	4	4
Nominal moment (Nm)	11.2	14.4	26.8
Stator winding resistance (R_s)	6.8	3.7	4.05

APPENDIX B

PARAMETER MEASUREMENT

To calculate motor parameters, no-load and locked rotor tests are done. Results of these tests are given below.

Table.B.1 No-load and locked rotor tests results

	Vnl (V)	Inl (A)	Pnl (W)	Vlr (V)	Ilr (A)	Plr (W)	Rs (Ω)	Prot (W)
Motor1	380	1.99	200	124.4	3.11	389	6.8	4.2
Motor2	380	2.12	150	110.6	5.22	559	3.3	15
Motor3	380	4.61	390	78.5	8.82	628	3.9	23.4

In the measurements, HIOKI Power meter is used. Phase-to-phase voltages and line currents are measured. In tests, motor models are assumed to be as shown in Fig.B.1 and Fig.B.2.

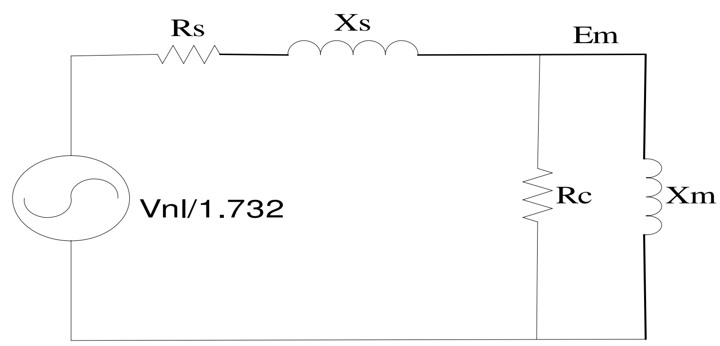


Fig.B.1 Induction motor model in no-load test

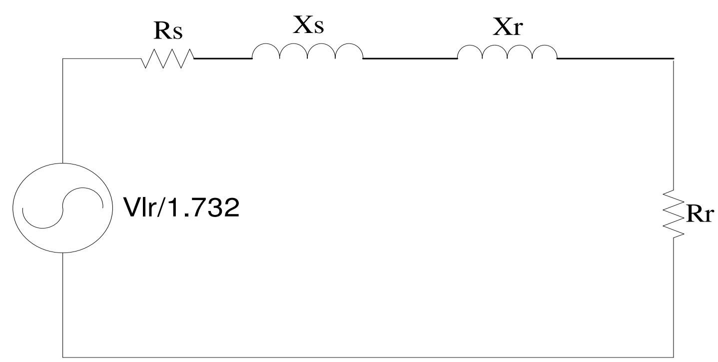


Fig.B.2 Induction motor model in locked rotor test

The parameters are calculated as follows.

Using Fig.B.2, real part of the equivalent impedance is written as below

$$R_{lr} = \frac{P_{lr}}{3.I_{lr}^2} \tag{B-1}$$

Stator leakage reactance is assumed to be equal to rotor leakage reactance and calculated as below

$$Z_{lr} = \frac{V_{lr}}{\sqrt{3}.I_{lr}} \tag{B-2}$$

$$X_{lr} = \sqrt{Z_{lr}^2 - R_{lr}^2} \tag{B-3}$$

$$X_s = \frac{X_{lr}}{2} \quad \text{(B-4)}$$

Referred rotor resistance is calculated from equation (B-5)

$$R_r = R_{lr} - R_s \quad \text{(B-5)}$$

To calculate magnetizing reactance and core loss resistance, Fig.B.1 is used. Complex components of equivalent impedance is calculated as below

$$R_{nl} = \frac{P_{nl} - P_{rot}}{3.I_{nl}^2} \quad \text{(B-6)}$$

$$Z_{nl} = \frac{V_{nl}}{\sqrt{3}.I_{nl}} \quad \text{(B-7)}$$

$$X_{nl} = \sqrt{Z_{nl}^2 - R_{nl}^2} \quad \text{(B-8)}$$

To calculate core loss resistance, E_m is calculated as below

$$E_m = \frac{V_{nl}}{\sqrt{3}} - \left(R_s + j.X_s\right).I_s\angle -\varphi \quad \text{(B-9)}$$

Core loss resistance is calculated from equation (B-10)

$$R_c = \frac{3.\left|E_m\right|^2}{P_{nl} - P_{rot} - P_{scl}} \quad \text{(B-10)}$$

To calculate magnetizing reactance, real part of equivalent impedance is used

$$real(R_c \,//\, X_m) = R_{nl} - R_s \quad \text{(B-11)}$$

$$X_m = \sqrt{\frac{(R_{nl} - R_s).R_c^2}{R_c - R_{nl} + R_s}} \quad \text{(B-12)}$$

The calculated parameters for the test motors can be found in Chapter 2.

APPENDIX C

PARAMETER ESTIMATION CODES

C-1 Method 1

```
Rs=6.6;
Rs=Rs*1.1;
V=220;
I=3.1;
f=50;                                   input data
pf=0.74;
p=6;
n=907;
Pout=1100;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fi=acos(pf);
ns=120*f/p;
s=(ns-n)/ns;
Pfw=0.01*Pout;
Prcl=(Pout+Pfw)*s/(1-s);                calculation of Rr
a=Prcl/s^2;
b=(2*Rs*Prcl/s)-(3*V^2);
c=Prcl*Rs^2;
delta=b^2-4*a*c;
Rr=(-b+sqrt(delta))/(2*a)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
Pscl=3*V^2*Rs/(Rs+Rr/s)^2;
Ploss=(3)*V*I*pf-Pout;
Pcore=Ploss-Pscl-Prcl-Pfw;                          calculation of Rc
Rc=3*V^2/Pcore
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Xm=V/(I*sin(fi))                                    calculation of Xm
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
aa=4*(1/Xm-tan(fi)/Rc);
bb=2;
cc=((Rs+Rr/s)^2*(1/Xm-tan(fi)/Rc)-tan(fi)*(Rs+Rr/s));
delta=bb^2-4*aa*cc;
Xs1=(-bb+sqrt(delta))/(2*aa)                        calculation of Xs
```

C-2 Method 2

```
Rs=2.1;
V=220;
I=7.1;
f=50;
pf=0.8;                                             input data
n=1420;
ns=1500;
Pout=3000;
%%%%%%%%%%%%%%%%%%%%%%%%%%
s=(ns-n)/ns;
fi=acos(pf);
Rs=Rs*1.1;
Pfw=0.01*Pout;
Prcl=(Pout)*s/(1-s);
Pscl=3*I^2*Rs;
Ploss=(3)*V*I*pf-Pout;                              calculation of Rc
Pcore=Ploss-Pscl-Prcl-Pfw;
```

```
Rc=3*V^2/Pcore
%%%%%%%%%%%%%%%%%%%%%%%%%
Xm=V/(I*sin(fi))                                        calculation of Xm
%%%%%%%%%%%%%%%%%%%%%%%%%
a=(tan(fi))^2/s^2+(3*V^2/Prcl)^2*(tan(fi)/Rc-
1/Xm)^2+6*V^2*tan(fi)/(s*Prcl)*(tan(fi)/Rc-1/Xm)+1/s^2;
b=2*Rs*(tan(fi))^2/s+6*V^2*Rs*tan(fi)/Prcl*(tan(fi)/Rc-1/Xm)+2*Rs/s-3*V^2/Prcl;
c=(Rs*tan(fi))^2+Rs^2;                                  calculation of Rr
delta=b^2-4*a*c;
Rr=(-b+sqrt(delta))/(2*a)
%%%%%%%%%%%%%%%%%%%%%%%%%
Xs=sqrt((3*V^2*Rr/Prcl-(Rs+Rr/s)^2)/4)                  calculation of Xs
```

C-3 Method 3 & Method 4

```
V=220;
R1=4.5;
R1=1.1*R1;
I=2.7;
Pout=1000;
Pfric=0.01*Pout;
ws=3000;
wm=2830;
pf=0.76;
%%%%%%%%%%%%%%%%
fi=acos(pf);
tn1=tan(fi)
s=(ws-wm)/ws;
Prcl=(Pout+Pfric)*(s/(1-s));
Pin=3*V*I*pf;
Pcore=Pin-Pout-(3*I^2*R1)-Prcl-Pfric;
Pgap=Pout+Pfric+Prcl;
```

```
n=20;
X1=0;
tum_sonuc=[];
while (n>0)
   E=(V-(R1+X1*i)*(I*cos(fi)-I*sin(fi)*i));
   E=abs(E);
   a=Prcl/(s^2);
   b=(-3)*E^2;
   c=Prcl*X1^2;
   delta=b^2-4*a*c;
   if delta<0
      disp ('kökler imajiner')
   else
      R2=((-b)+sqrt(delta))/(2*a);
   end
   Rc=(3*E^2/Pcore);
   Xm=E/(1*I*sin(fi));
   aa=R2^2/s^2;
   bb=(2*R1*R2*Xm^2/s)-(3*V^2*R2*Xm^2/(s*Pgap));
   cc=R1^2*Xm^4;
   delta2=bb^2-4*aa*cc;
   if delta2<0
      disp ('kökler imajiner')
   else
      dd=(-bb+sqrt(delta2))/(2*aa);
   end
   X1=(sqrt(dd)-Xm);
   a=(Xm*R2/s+Rc*X1+Rc*Xm);
   b=(X1*Xm-Rc*R2/s);
   tn=(X1*(a^2+b^2)+a*(X1*Xm*Rc)-
b*(Rc*Xm*R2/s))/(R1*(a^2+b^2)+a*(Rc*Xm*R2/s)+b*(X1*Xm*Rc));
   n=n-1;
   sonuc=[R1 R2 X1 Xm Rc tn];
```

```
    tum_sonuc=[tum_sonuc; sonuc];
end
```

C-4 Method 5

```
v=220;
Is=7.1;
rs=2.1;
Pout=3000;
pole=4;
f=50;
nm=1420;
pf=0.8;
%%%%%%%%
sonuc=[];
tumsonuc=[];
n=120*f/pole;
w=4*pi*f/pole;
s=(n-nm)/n;
fi=acos(pf);
Pin=3*v*Is*pf;
eff=Pout/Pin;
Im=0.95*Is*sin(fi);
xm=(v-rs*Is)/Im
Ir=sqrt(Is^2-(Im)^2);
xs=(3*v*Is*sin(fi)-3*xm*(Im)^2)/(3*Is^2+3*Ir^2);
Piron=Pin*(1-eff/(1-s))-3*rs*Is^2;
rc=3*v^2/Piron;
i=1;
while i>0
Ir=sqrt(Is^2-(Im)^2)-(v-rs*Is)/rc;
xs=(3*v*Is*sin(fi)-3*xm*(Im)^2)/(3*Is^2+3*Ir^2)
```

```
Pmec=0.005*Pout;
Pstr=0.005*Pout;
Tem=(Pout+Pmec)/((1-s)*w);
rr=Tem*s*w/(3*Ir^2)
Piron=Pin-3*rs*Is^2-Pstr-3*(rr/s)*Ir^2;
i=i-1;
Em=v-(rs+xs*i)*Is*(cos(fi)-sin(fi)*i);
Em=abs(Em);
rc=3*Em^2/Piron
sonuc=[rr xs xm rc];
tumsonuc=[tumsonuc; sonuc];
end
```

APPENDIX D

COMPARISON OF ESTIMATED MOTOR PARAMETERS FROM NAME-PLATE DATA

To investigate the effect of erroneous data of name-plate for calculation of motor parameters and preparation of torque-speed curve, motor parameters are estimated from name-plate data and torque-speed curves are prepared in accordance to these parameters. In Table D.1, TableD.2 and TableD.3, calculated and estimated motor parameters are given.

Table.D.1 Calculated and estimated motor parameters for 1.1kW induction motor

parameter	Measured value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	6.8	6.8	-	6.8	-	6.8	-	6.8	-	6.8	-
Rr	6.6	9.7	-46.7	9.8	-47.5	8.8	-32.5	8.0	-20.4	7.6	-15.0
Xs	9.4	0.0	100.0	4.6	51.0	5.3	43.6	10.5	-11.7	4.2	55.0
Xm	87.8	111.0	-26.4	111.2	-26.6	99.2	-13.0	99.9	-13.8	105.9	-20.6
Rc	1014.0	536.0	47.1	933.0	8.0	748.0	26.2	685.0	32.4	804.0	20.7

Table.D.2 Calculated and estimated motor parameters for 2.2kW induction motor

parameter	Measured value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	3.3	3.3	-	3.3	-	3.3	-	3.3	-	3.3	-
Rr	3.5	2.9	16.9	3.0	16.4	2.8	21.2	2.5	28.0	2.5	29.0
Xs	5.1	0.0	100.0	1.3	74.0	1.8	65.0	5.2	-2.6	1.9	62.0
Xm	98.4	72.0	26.8	72.1	26.7	66.3	32.6	66.7	32.0	70.0	29.0
Rc	1435.0	497.0	65.0	873.0	39.0	744.0	48.0	679.0	53.0	769.0	46.0

Table.D.3 Calculated and estimated motor parameters for 4kW induction motor

parameter	Measured value	Method1		Method2		Method3		Method4		Method5	
		Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)	Est.	Err. (%)
Rs	3.9	3.9	-	3.9	-	3.9	-	3.9	-	3.9	-
Rr	4.2	5.0	-19.7	5.0	-20.8	4.9	-16.5	4.4	-6.5	4.6	-10.3
Xs	6.6	0.0	100.0	1.1	83.7	1.8	72.4	8.3	-26.0	2.4	64.0
Xm	136.5	145.3	-6.4	145.3	-6.4	137.7	-0.9	139.0	-1.8	145.1	-6.3
Rc	1382.0	1184.0	14.0	1682.0	-21.7	1524.0	-10.3	1403.0	-1.5	1546.0	-11.9

Since it is wise to compare the torque-speed characteristics, which are calculated from estimated parameters and parameters calculated from no-load and locked rotor tests results. Torque-speed curves are prepared in accordance to the exact equivalent circuit shown in Fig.2.4. These torque-speed curves are shown in Fig.D.1, Fig.D.2 and Fig.D.3.

Since the drive is normally operated in the portion of torque-speed curve between no-load speed and full-load speed, it is wise to compare the performances of these estimation methods in the linear region of torque-speed curve. Therefore, torque-speed curves are prepared for linear region as shown in Fig.D.4, Fig.D.5 and Fig.D.6.

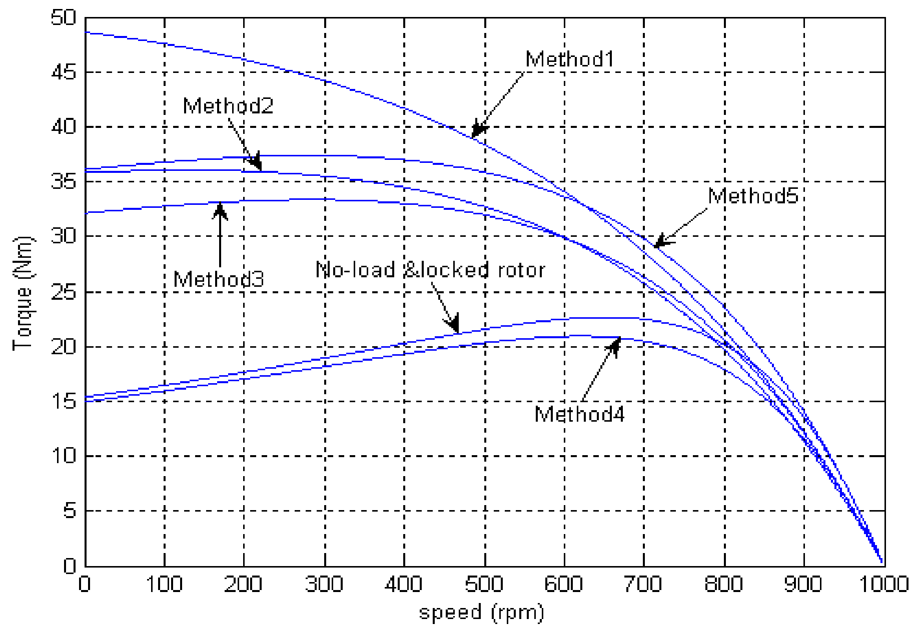


Fig.D.1 Torque-speed curves for 1.1kW induction motor

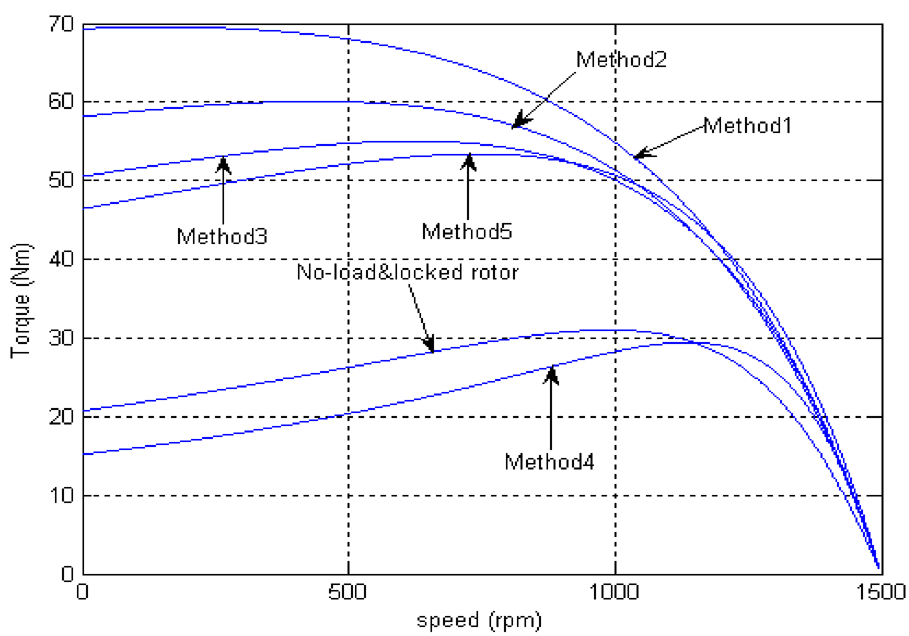


Fig.D.2 Torque-speed curves for 2.2kW induction motor

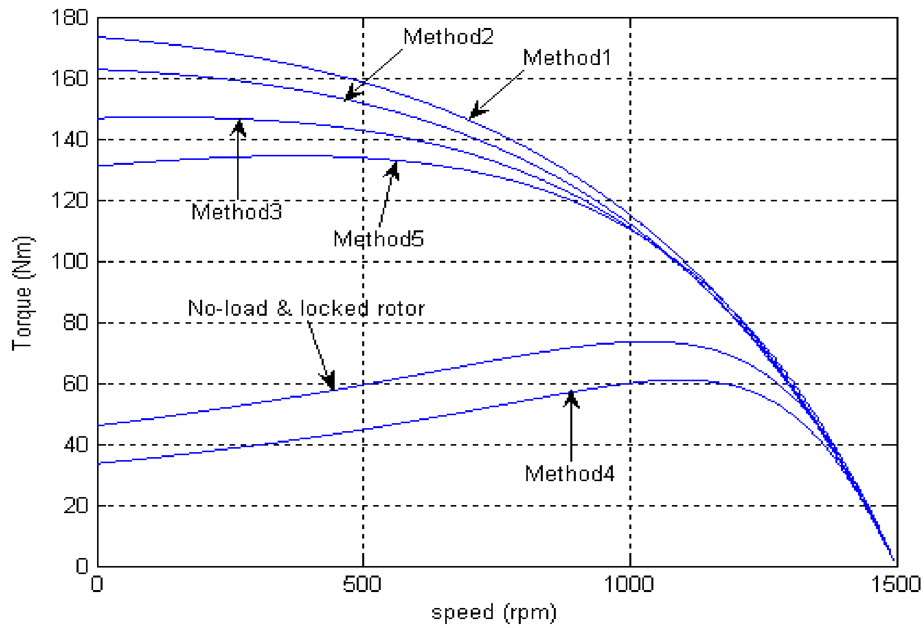


Fig.D.3 Torque-speed curves for 4kW induction motor

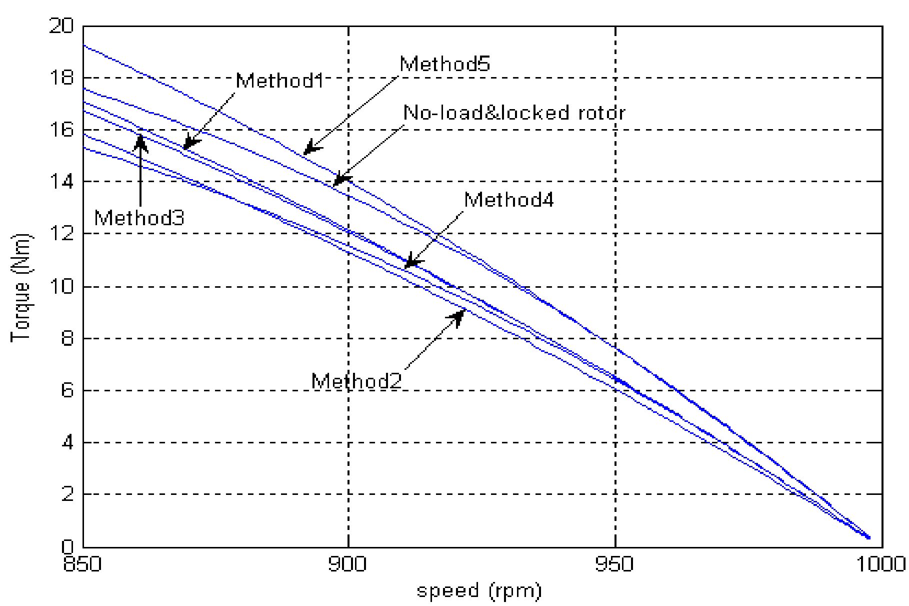


Fig.D.4 Torque-speed curves for 1.1kW induction motor

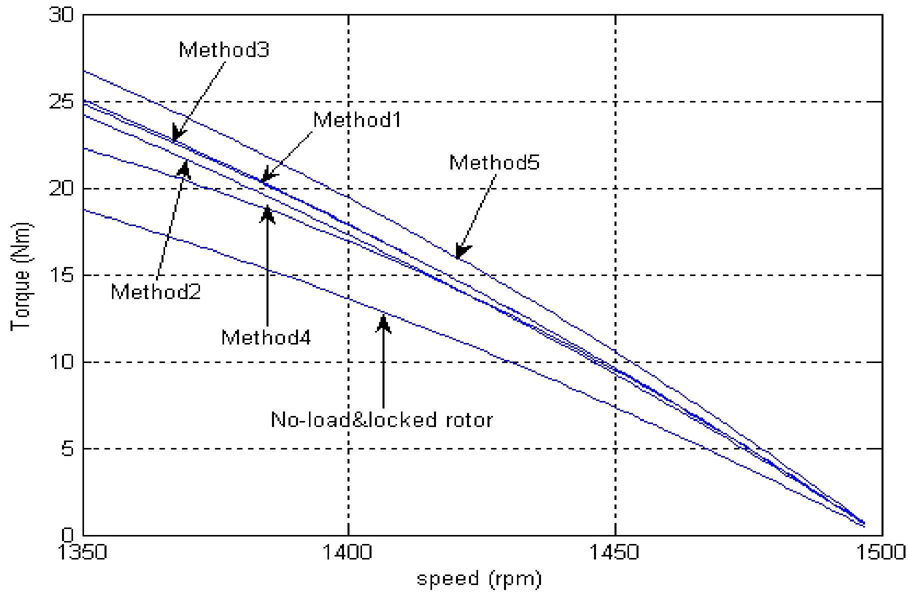


Fig.D.5 Torque-speed curves for 2.2kW induction motor

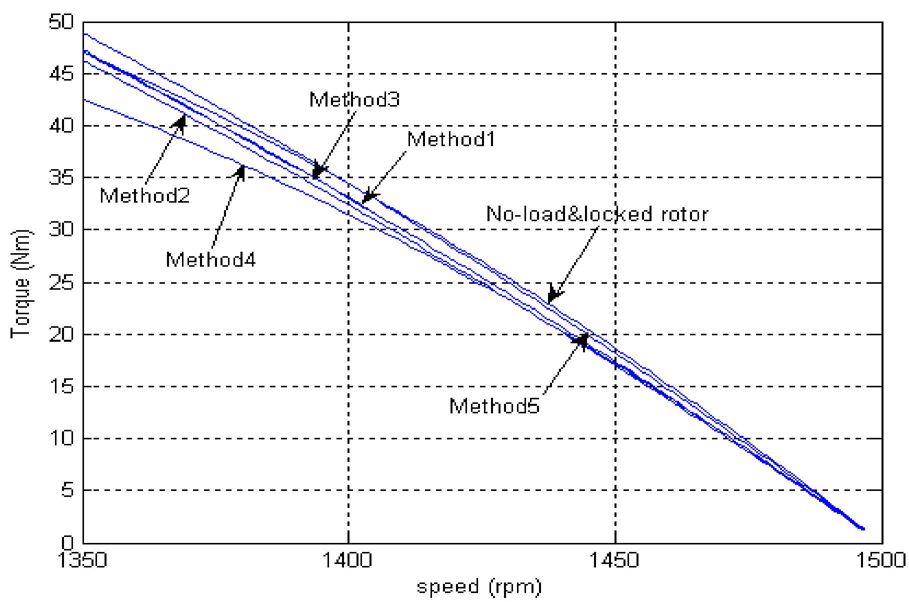


Fig.D.6 Torque-speed curves for 4kW induction motor

APPENDIX E

ROTATIONAL LOSS CURVES OF TEST MOTORS

To calculate rotational loss of test motors, these test motors are driven with inverter from 10 Hz to 70 Hz at no-load. Voltage filtered by low-pass filter and input power of the motor are measured with oscilloscope. V^2-P curves are prepared to calculate rotational loss of test motors.

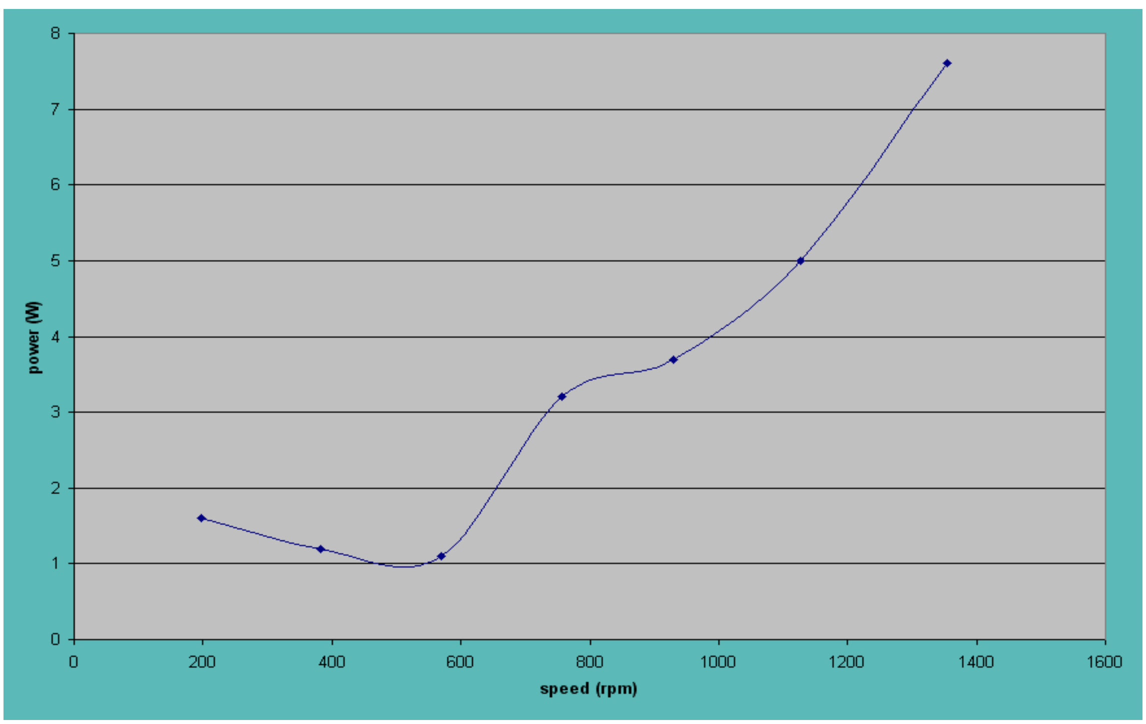


Fig.E.1 Rotational loss curve of 1.1 kW induction motor

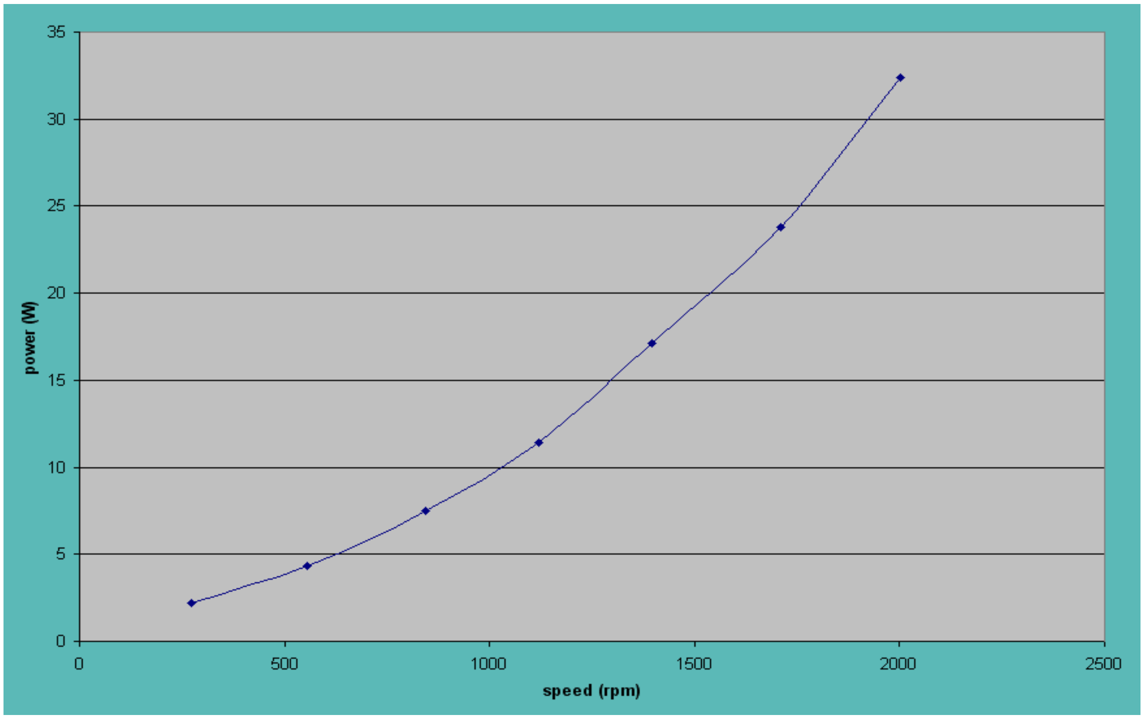


Fig.E.2 Rotational loss curve of 2.2 kW induction motor

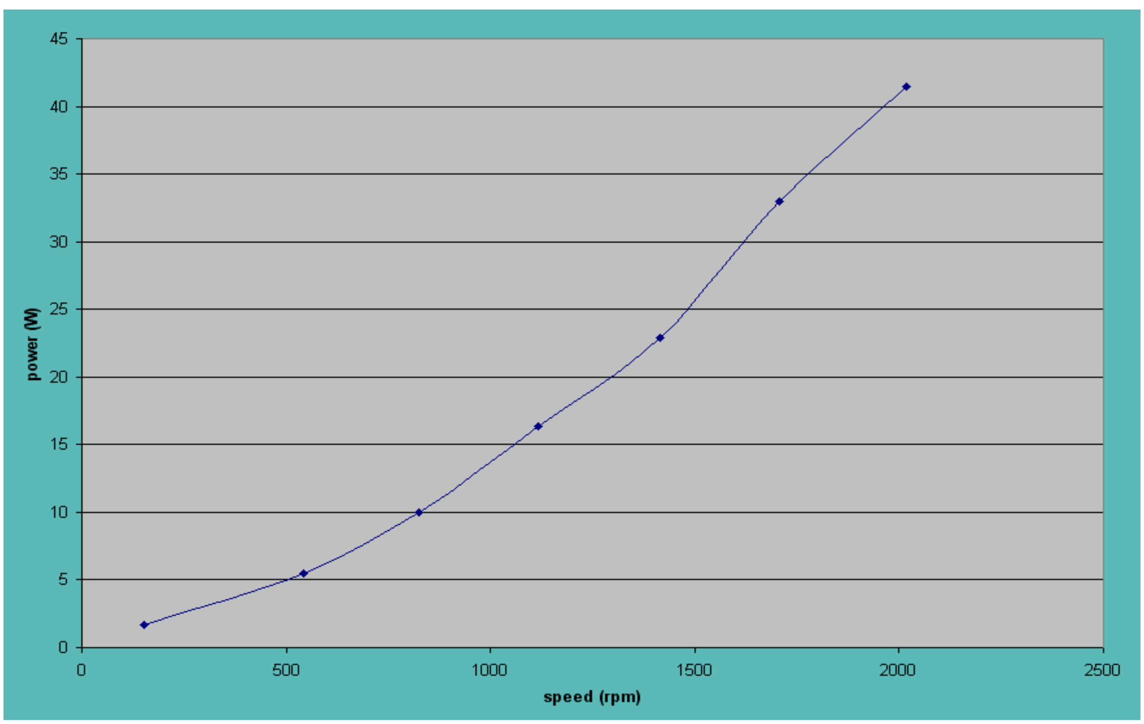


Fig.E.3 Rotational loss curve of 4 kW induction motor

APPENDIX F

MOTOR SIMULATION CODES

```
DATA=DLMREAD('input.txt','\t');
p=4;
Xs=6.5664;
Xm=136.48;
Ls=Xs/(2*pi*50);
Lm=Xm/(2*pi*50);
Pcorer=369.5;
nsr=1500;
nr=1420;
sr=(nsr-nr)/nsr;
sonuc=[];
tumsonuc=[];
sayac1=1;

while (sayac1<=7)
    f=DATA(sayac1,1);
    vs=DATA(sayac1,2);
    Rs=DATA(sayac1,6);
    Rr=4.0124*Rs/3.9;
    Xm=2*pi*f*Lm;
    Xs=2*pi*f*Ls;
    ws=4*f*pi/p;
    s=0.001;
    sayacs=2;
    while (s<=1)
        I=0.001;
        fark=2;
        fi=0.001;
        farkfi=1;
        Pcore=(Pcorer/2)*((1+s)*f/((1+sr)*50)+(1+s^2)*f^2/((1+sr^2)*50^2));
        Rc=3*vs^2/Pcore;
        while fark>=0.01&&farkfi>=0.02
            Zr=Rr/s+Xs*i;
            Zm=(Rc*Xm*i)/(Rc+Xm*i);
            Zs=Rs+Xs*i;
```

```
            Z=Zs+Zr*Zm/(Zr+Zm);
            Is=(vs/Z);
            fis=real(Z)/abs(Z);
            farkfi=(fis-fi)/fi;
            fark=(abs(Is)-I)/I;
            es=abs(vs-Zs*Is);
            I=abs(Is);
            fi=fis;
            Rc=3*es^2/Pcore;
        end
        Zth=(Zs*Zm)/(Zs+Zm);
        Xth=imag(Zth);
        Rth=real(Zth);
        Vth=vs*abs(Zm)/abs(Zs+Zm);
        w=(1-s)*ws;
        n=120*f*(1-s)/p;
        T=(3*Vth^2*(Rr/s))/(ws*((Rth+Rr/s)^2+(Xth+Xs)^2));
        sonuc(1,1)=f;
        sonuc(2,1)=f;
        sonuc(1,sayacs)=n;
        sonuc(2,sayacs)=T;
        sayacs=sayacs+1;
        s=s+0.001;
    end
    tumsonuc=[tumsonuc; sonuc];
    sayac1=sayac1+1;
    plot (sonuc(1,1000:-1:2),sonuc(2,1000:-1:2)),grid on;
    hold on;
end
```

APPENDIX G

SPEED ESTIMATION CODES

G-1 Method 1 & Method 2

```
%%%%%%%
vsr=220;            %rated line voltage
Isr=5.2;            %rated line current
Poutr=2200;         %rated power
pf=0.81;            %power factor
fr=50;              %rated frequency
nr=1420;            %rated speed
Ko=2.6;             %Tbd/Tr
Tr=14.8;            %rated torque
pole=4;             %pole number
%%%%%%%%%%%%%%%%%%%%
Xm=98.374;
Xs=5.07;
%%%%%%%%%
Lm=Xm/(2*pi*fr);
Ls=Xs/(2*pi*fr);
%%%%%%
sonuc=[];
tumsonuc1=[];
DATA=DLMREAD('input.txt','\t');
%%%%%%%
```

```
sayac1=1;
while sayac1 <=7
hiz=DATA(sayac1,3);
fm=DATA(sayac1,1);
f=fm;
vs=DATA(sayac1,2);
Rs=DATA(sayac1,6);
Rr=3.43*Rs/3.2;
%%%%%%%%
ns=120*f/pole;
w=ns*pi/30;
s=(ns-hiz)/ns;
Pinr=3*vsr*Isr*pf;
eff=Poutr/Pinr;
nsr=120*fr/pole;
sr=(nsr-nr)/nsr;
Pcorer=160.8;
%%%%%%%%%
Xm=Lm*2*pi*f;
Xs=Ls*2*pi*f;
Rth=Rs*(Xm/(Xm+Xs))^2;
Vth=vs*Xm/(Xs+Xm);
Tm=3*Vth^2/(2*w*(Rth+sqrt(Rth^2+4*Xs^2)));
sm=Rr/sqrt(Rth^2+4*Xs^2);
%%%%%%%%%%%%%%%%%%%%%
Is=DATA(sayac1,4);
Is_real=DATA(sayac1,5);
%%%%%%%%%%%%%%%%%%%%%%%%%
es=vs-Rs*Is;
es=abs(es);
%%%%%%%%%%
Pcore=(Pcorer/2)*((1+s)*f/((1+sr)*fr)+(1+s^2)*f^2/((1+sr^2)*fr^2));
Pgap=3*vs*Is_real-3*Rs*Is^2-Pcore;
```

```
K=Ko+sqrt(Ko^2-1);
slin=pole*sr*fr/(Tr*pi);
A=pole/(4*pi*K*Ko*Tr*sr*fr);
B=(pole/(4*pi*Ko*Tr))^2;
C=A*Pgap;
if C==2
   f_slip=B/(A*fm);
else
   f_slip=(sqrt(fm^2+(K*slin*Pgap/(2*Ko))-B*Pgap^2)-fm)/(2-A*Pgap);
end
n_slip=120*f_slip/pole;
n_slip=abs(n_slip);
n1=ns-n_slip;
n1=abs(n1);
err1=(hiz-n1)*100/hiz;
%%%%%%%%%%%%
%%%%method 2
Ko2=Tm/Tr;
K=Ko2+sqrt(Ko2^2-1);
A=pole/(4*pi*K*Ko2*Tr*sr*fr);
B=(pole/(4*pi*Ko2*Tr))^2;
C=A*Pgap;
if C==2
   f_slip=B/(A*fm);
else
   f_slip=(sqrt(fm^2+(K*slin*Pgap/(2*Ko2))-B*Pgap^2)-fm)/(2-A*Pgap);
end
n_slip=120*f_slip/pole;
n_slip=abs(n_slip);
n2=ns-n_slip;
n2=abs(n2);
err2=(hiz-n2)*100/hiz;
sonuc=[hiz n1 err1 n2 err2];
```

```
tumsonuc1=[tumsonuc1; sonuc];
sayac1=sayac1+1;
end
```

G-2 Method 3 & Method 4 & Method 5

```
Vsr=220;
pf=0.81;
Isr=5.2;
Poutr=2200;
fr=50;
p=4;
nr=1420;
Ko=2.6;
%%%%%%%%
Xm=98.374;
Xs=5.07;
%%%%%%%%
Lm=Xm/(2*pi*fr);
Ls=Xs/(2*pi*fr);
%%%%%%%%
sonuc=[];
tumsonuc2=[];
DATA=DLMREAD('input.txt','\t');
%%%%%%%%%%%%%%%%
sayac1=1;
while sayac1 <=7
%%%%%%%%%%
hiz=DATA(sayac1,3);
nm=hiz;
f=DATA(sayac1,1);
fm=f;
```

```
vs=DATA(sayac1,2);
Rs=DATA(sayac1,6);
Rr=3.43*Rs/3.2;
%%%%%%%%%%%METHOD 4 & METHOD 5
Xm=Lm*2*pi*f;
Xs=Ls*2*pi*f;
n=120*f/p;
nsr=120*fr/p;
w=n*pi/30;
wr=nr*pi/30;
Tr=Poutr/wr;
Rth=Rs*(Xm/(Xm+Xs))^2;
Vth=vs*Xm/(Xs+Xm);
Tm=3*Vth^2/(2*w*(Rth+sqrt(Rth^2+4*Xs^2)));
sm=Rr/sqrt(Rth^2+4*Xs^2);
%%%%%%
Is=DATA(sayac1,4);
Is_real=DATA(sayac1,5);
%%%%%%%%%
nsr=120*fr/p;
sr=(nsr-nr)/nsr;
s=(n-nm)/n;
%%%%%%%%
Pinr=3*Vsr*Isr*pf;
eff=Poutr/Pinr;
Pcorer=160.8;
Pcore=(Pcorer/2)*((1+s)*f/((1+sr)*fr)+(1+s^2)*f^2/((1+sr^2)*fr^2));
%%%%%%%%
Pin=3*vs*Is_real;
Pscl=3*Rs*(abs(Is))^2;
Pgap=Pin-Pscl-Pcore;
Pgap=abs(Pgap);
T=Pgap/w;
```

```
%%%%%%%%
a=Rs/Rr;
b=2*a*sm;
c=2*Tm*(1+a*sm);
d=(c-b*T)/T;
delta=(d*sm)^2-4*sm^2;
s=(d*sm-sqrt(delta))/2;
s=abs(s);
speed4a=120*f*(1-s)/p;
speed4a=abs(speed4a);
err4a=(hiz-speed4a)*100/hiz;
%%%%%%%%
a=Rth/Rr;
b=2*a*sm;
c=2*Tm*(1+a*sm);
d=(c-b*T)/T;
delta=(d*sm)^2-4*sm^2;
s=(d*sm-sqrt(delta))/2;
s=abs(s);
speed5a=120*f*(1-s)/p;
speed5a=abs(speed5a);
err5a=(hiz-speed5a)*100/hiz;
%%%%%%%%method 3
sl=T*(nsr-nr)/Tr;
sl=abs(sl);
n3=n-sl;
n3=abs(n3);
err3=(hiz-n3)*100/hiz;
sonuc=[n3 err3 speed4a err4a speed5a err5a];
tumsonuc2=[tumsonuc2; sonuc];
sayac1=sayac1+1;
end
```

G-3 Method 6 & Method 7

```
Vsr=220;
pf=0.81;
Isr=5.2;
Poutr=2200;
fr=50;
p=4;
nr=1420;
%%%%%%%
Ko=2.6;
Xm=98.374;
Xs=5.07;
Ls=Xs/(2*pi*fr);
Lm=Xm/(2*pi*fr);
%%%%%%%
sonuc=[];
tumsonuc3=[];
DATA=DLMREAD('input.txt','\t');
%%%%%%%%%%%%%%
sayac1=1;
while sayac1 <=7
%%%%%%%%%%%%%
hiz=DATA(sayac1,3);
nm=hiz;
f=DATA(sayac1,1);
fm=f;
vs=DATA(sayac1,2);
Rs=DATA(sayac1,6);
Rr=3.43*Rs/3.2;
%%%%%%%
n=120*f/p;
w=n*pi/30;
```

```
wr=nr*pi/30;
nsr=120*fr/p;
sr=(nsr-nr)/nsr;
Tr=Poutr/wr;
%%%%%%%%%
Xm=Lm*2*pi*f;
Xs=Ls*2*pi*f;
Rth=Rs*(Xm/(Xm+Xs))^2;
Vth=vs*Xm/(Xs+Xm);
Tm=3*Vth^2/(2*w*(Rth+sqrt(Rth^2+4*Xs^2)));
sm=Rr/sqrt(Rth^2+4*Xs^2);
%%%%%%%%%%%%%
s=(n-nm)/n;
%%%%%%%%%%%
Is=DATA(sayac1,4);
Is_real=DATA(sayac1,5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
es=vs-Rs*Is;
es=abs(es);
%%%%%%%%
Pinr=3*Vsr*Isr*pf;
eff=Poutr/Pinr;
s=(n-nm)/n;
Pcorer=160.8;
Pcore=(Pcorer/2)*((1+s)*f/((1+sr)*fr)+(1+s^2)*f^2/((1+sr^2)*fr^2));
%%%%%%%%
Pin=3*vs*Is_real;
Pscl=3*Rs*(abs(Is))^2;
Pgap=Pin-Pscl-Pcore;
Pgap=abs(Pgap);
T=Pgap/w;
%%%%%%%%
Xm=2*pi*f*Lm;
```

```
Xs=2*pi*f*Ls;
Z=(Xm*i)*(Rr/sm+Xs*i)/(Rr/sm+Xs*i+Xm*i);
Ism=vs/(Rs+2*pi*f*Ls*i+Z);
esm=vs-Rs*Ism;
esm=abs(esm);
a=es/esm;
b=((a^2)*Tm*sm/T);
delta=b^2-sm^2;
s=b-sqrt(delta);
s=abs(s);
speed6a=120*f*(1-s)/p;
speed6a=abs(speed6a);
err6a=(hiz-speed6a)*100/hiz;
%%%%%%%
I2m=sqrt(Tm*sm*w/(3*Rr));
esm=I2m*abs(Rr/sm+Xs*i);
s=(n-nm)/n;
I2=sqrt(T*s*w/(3*Rr));
es=vs-abs(Rs+Xs*i)*Is;
%%%%%%%
a=es/esm;
b=((a^2)*Tm*sm/T);
delta=b^2-sm^2;
s=b-sqrt(delta);
s=abs(s);
speed6b=120*f*(1-s)/p;
speed6b=abs(speed6b);
err6b=(hiz-speed6b)*100/hiz;
%%%%%%%%%%%%%%%%%%%
sonuc=[speed6a err6a speed6b err6b];
tumsonuc3=[tumsonuc3; sonuc];
sayac1=sayac1+1;
end
```

APPENDIX H

LEM CURRENT PROBE

&

LEM CURRENT AND VOLTAGE TRANSDUCER

Datasheets are given below for current transducer, voltage transducer and current probe. As shown below accuracy of transducers and probe are less than 1%. Also frequency range is larger than modulation frequency used in this study. Therefore, it is excepted that this devices can measure actual voltage and current.

LEM

Current Transducer LA 55-P/SP23

I_{PN} = 50 A

For the electronic measurement of currents : DC, AC, pulsed...., with a galvanic isolation between the primary circuit (high power) and the secondary circuit (electronic circuit).

Electrical data

I_{PN}	Primary nominal r.m.s. current		50	A
I_P	Primary current, measuring range		0 .. ± 70	A

R_M	Measuring resistance @		T_A = 70°C $R_{M\,min}$	T_A = 70°C $R_{M\,max}$	T_A = 85°C $R_{M\,min}$	T_A = 85°C $R_{M\,max}$	
	with ± 12 V	@ ± 50 A_{max}	10	100	60	95	Ω
		@ ± 70 A_{max}	10	50	60 [1]	60 [1]	Ω
	with ± 15 V	@ ± 50 A_{max}	50	160	135	155	Ω
		@ ± 70 A_{max}	50	90	135 [2]	135 [2]	Ω

I_{SN}	Secondary nominal r.m.s. current	50	mA
K_N	Conversion ratio	1 : 1000	
V_C	Supply voltage (± 5 %)	± 12 .. 15	V
I_C	Current consumption	10(@ ±15V)+I_S	mA
V_d	R.m.s. voltage for AC isolation test, 50 Hz, 1 mn	2.5	kV

Accuracy - Dynamic performance data

X	Accuracy @ I_{PN}, T_A = 25°C	@ ± 15 V (± 5 %)	± 0.45		%
		@ ± 12 .. 15 V (± 5 %)	± 0.70		%
ε_L	Linearity		< 0.15		%
			Typ	Max	
I_O	Offset current @ I_P = 0, T_A = 25°C			± 0.10	mA
I_{OM}	Residual current[3] @ I_P = 0, after an overload of 3 x I_{PN}			± 0.30	mA
I_{OT}	Thermal drift of I_O	0°C .. + 70°C	± 0.1	± 0.25	mA
		- 25°C .. + 85°C	± 0.2	± 0.60	mA
t_{ra}	Reaction time @ 10 % of $I_{P\,max}$		< 500		ns
t_r	Response time @ 90 % of $I_{P\,max}$		< 1		µs
di/dt	di/dt accurately followed		> 200		A/µs
f	Frequency bandwidth (- 1 dB)		DC .. 200		kHz

General data

T_A	Ambient operating temperature		- 25 .. + 85	°C
T_S	Ambient storage temperature		- 40 .. + 90	°C
R_S	Secondary coil resistance @	T_A = 70°C	80	Ω
		T_A = 85°C	85	Ω
m	Mass		26	g
	Standards [4]		EN 50178	

Notes : [1] Measuring range limited to ± 60 A_{max}
[2] Measuring range limited to ± 55 A_{max}
[3] Result of the coercive field of the magnetic circuit
[4] A list of corresponding tests is available

Features

- Closed loop (compensated) current transducer using the Hall effect
- Printed circuit board mounting
- Insulated plastic case recognized according to UL 94-V0.

Special features

- **X** = ± 0.45 % @ ± 15 V (± 5 %)
- I_O = ± 0.1 mA
- I_{OT} = ± 0.25 mA max. (0°C .. + 70°C).

Advantages

- Excellent accuracy
- Very good linearity
- Low temperature drift
- Optimized response time
- Wide frequency bandwidth
- No insertion losses
- High immunity to external interference
- Current overload capability.

Applications

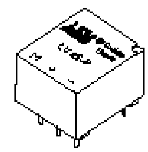
- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Switched Mode Power Supplies (SMPS)
- Power supplies for welding applications.

981208/1

Voltage Transducer LV 25-P/SP5

I_{PN} = 10 mA
V_{PN} = 10 .. 1500 V

For the electronic measurement of voltages : DC, AC, pulsed..., with a galvanic isolation between the primary circuit (high voltage) and the secondary circuit (electronic circuit).



Electrical data

I_{PN}	Primary nominal r.m.s. current		10		mA
I_P	Primary current, measuring range		0 .. ± 14		mA
R_M	Measuring resistance		$R_{M\,min}$	$R_{M\,max}$	
	with ± 15 V	@ ± 10 mA_{max}	100	340	Ω
		@ ± 14 mA_{max}	100	180	Ω
I_{SN}	Secondary nominal r.m.s. current		25		mA
K_N	Conversion ratio		2500 : 1000		
V_C	Supply voltage (± 5 %)		± 15		V
I_C	Current consumption		10 + I_S		mA
V_d	R.m.s. voltage for AC isolation test, 50 Hz, 1 mn		4.1		kV

Accuracy - Dynamic performance data

X_G	Overall Accuracy @ I_{PN}, T_A = 25°C		± 0.8		%
ε_L	Linearity		< 0.2		%
			Typ	Max	
I_O	Offset current @ I_P = 0, T_A = 25°C			± 0.15	mA
I_{OT}	Thermal drift of I_O	- 25°C .. + 85°C	± 0.25	± 0.50	mA
		- 40°C .. + 85°C	± 0.30	± 0.80	mA
t_r	Response time[1] @ 90 % of $V_{P\,max}$		40		μs

General data

T_A	Ambient operating temperature	- 40 .. + 85	°C
T_S	Ambient storage temperature	- 50 .. + 90	°C
R_P	Primary coil resistance @ T_A = 85°C	300	Ω
R_S	Secondary coil resistance @ T_A = 85°C	117	Ω
m	Mass	22	g
	Standards	EN 50155	

Note : [1] R_1 = 25 kΩ (L/R constant, produced by the resistance and inductance of the primary circuit).

Features

- Closed loop (compensated) voltage transducer using the Hall effect
- Insulated plastic case recognized according to UL 94-V0.

Special features

- V_d = 4.1 kV (4 kV DC/5 mn)
- T_A = - 40°C .. + 85°C
- Railway equipment.

Principle of use

- For voltage measurements, a current proportional to the measured voltage must be collected through an external resistor R_1 which is selected by the user and installed in series with the primary circuit of the transducer.

Advantages

- Excellent accuracy
- Very good linearity
- Low thermal drift
- Low response time
- High bandwidth
- High immunity to external interference
- Low disturbance in common mode.

Applications

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Power supplies for welding applications.

021206/5

Current Probe Model PR30

The PR30 current probe is based on Hall Effect technology for use in measurement of both DC and AC current. The PR30 may be used in conjunction with oscilloscopes and other suitable recording instruments for accurate non-intrusive current measurement.

Electrical Characteristics

Current Range .... : 20 A AC_{RMS} or DC
Measuring Range.. : +/- 30 A
Output Sensitivity.. : 100 mV / A
Accuracy.. : +/- 1% of reading +/- 2 mA
Resolution.. : +/- 1 mA
Load Impedance.. : > 100 kOhms
Conductor Position Sensitivity.. : +/- 1% relative to centre reading
Frequency Range.. : DC to 100 kHz (- 0.5 dB)
Phase Shift below 1 kHz.. : < 2 degrees
Temperature Coefficient.. : +/- 0.01% of reading / °C
Power Supply.. : 9 V Alkaline, MN1604/PP3
30 Hours, low battery indicator
Working Voltage (see Safety Standards section)............ : 300 V AC_{RMS} or DC

General Characteristics

Maximum Conductor Size.. : 19 mm diameter
Output Connection.. : safety BNC connector
Output Zero.. : Manual adjust via thumbwheel
Cable Length.. : 2 meters
Operating Temperature Range.. : 0 to +50 °C
Storage Temperature Range (with battery removed)..........: -20 to +85 °C
Operating Humidity.. : 15% to 85% (non condensing)
Weight.. : 250 g

APPENDIX I

COMPARISON OF SPEED ESTIMATION METHODS

To verify the speed estimation methods, which are explained in Chapter3, 1.1, 2.2 and 4kW motors are driven with inverter. Measured currents and voltages are logged by Trace program. Speed estimation methods are simulated in Matlab, by using measured data. By this way, any error that may be introduced due to measurements is taken into account these predictions. Speed estimation results are compared with measured speed and motor simulation. Speed estimation results are shown in Table.I.1 to Table.I.24.

When motor is driven with inverter, a dc shift is seen on stator phase currents. This dc shift worsens the estimation of power factor and rms value of stator current, which are explained in Chapter 4. To verify the effect of dc shift on the stator current, 2.2 kW induction motor is driven with line voltage. Speed estimation results are compared with measured speed and motor simulation. Speed estimation results are shown in Table.I.25 and Table.I.26.

Table.I.1 Calculated speed from motor model and estimated speeds at no-load for 1.1 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	199	191.4	3.8	193.8	2.6	190.3	4.4	192.9	3.1	192.2	3.4	194.9	2.0	194.3	2.4
20	399	397.7	0.3	398.0	0.2	397.5	0.4	398.2	0.2	398.0	0.2	398.6	0.1	398.7	0.1
30	599	598.0	0.2	598.1	0.1	597.8	0.2	598.4	0.1	598.3	0.1	598.6	0.1	598.9	0.0
40	799	795.0	0.5	795.2	0.5	794.7	0.5	795.9	0.4	795.7	0.4	796.4	0.3	797.3	0.2
50	999	992.7	0.6	992.8	0.6	992.2	0.7	993.9	0.5	993.6	0.5	994.5	0.4	996.1	0.3
60	1199	1188.8	0.9	1189.7	0.8	1188.0	0.9	1187.4	1.0	1186.9	1.0	1188.6	0.9	1192.2	0.6
70	1398	1386.7	0.8	1390.2	0.6	1385.8	0.9	1379.3	1.3	1378.6	1.4	1381.3	1.2	1387.5	0.7

Table.I.2 Measured speed and estimated speeds at no-load for 1.1 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	199	191.4	3.8	193.8	2.6	190.3	4.4	192.9	3.1	192.2	3.4	194.9	2.0	194.3	2.4
20	398	397.7	0.1	398.0	0.0	397.5	0.1	398.2	-0.1	398.1	0.0	398.6	-0.1	398.7	-0.2
30	597	598.0	-0.2	598.1	-0.2	597.8	-0.1	598.4	-0.2	598.3	-0.2	598.6	-0.3	598.9	-0.3
40	795	795.0	0.0	795.1	0.0	794.6	0.0	795.9	-0.1	795.6	-0.1	796.4	-0.2	797.3	-0.3
50	995	992.7	0.2	992.8	0.2	992.2	0.3	993.9	0.1	993.6	0.1	994.5	0.1	996.1	-0.1
60	1195	1188.8	0.5	1189.6	0.4	1188.0	0.6	1187.4	0.6	1186.8	0.7	1188.6	0.5	1192.2	0.2
70	1397	1386.7	0.7	1390.2	0.5	1385.8	0.8	1379.3	1.3	1378.6	1.3	1381.3	1.1	1387.5	0.7

Table.I.3 Calculated speed from motor model and estimated speeds at ¼ load for 1.1 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	180	174.3	3.2	182.4	-1.4	168.8	6.2	175.7	2.4	173.8	3.4	185.7	-3.2	184.1	-2.3
20	381	377.4	0.9	380.1	0.2	374.3	1.8	380.1	0.2	378.7	0.6	385.5	-1.2	387.1	-1.6
30	581	580.9	0.0	581.9	-0.1	578.7	0.4	583.5	-0.4	582.4	-0.2	586.6	-1.0	589.3	-1.4
40	782	783.9	-0.2	784.3	-0.3	782.3	0.0	786.3	-0.6	785.6	-0.5	788.2	-0.8	791.2	-1.2
50	982	984.9	-0.3	985.0	-0.3	983.4	-0.1	987.3	-0.5	986.7	-0.5	988.6	-0.7	991.9	-1.0
60	1175	1188.9	-1.2	1189.8	-1.3	1187.9	-1.1	1187.3	-1.0	1186.8	-1.0	1188.4	-1.1	1192.0	-1.4
70	1365	1391.8	-2.0	1394.0	-2.1	1391.1	-1.9	1387.2	-1.6	1386.8	-1.6	1388.1	-1.7	1391.9	-2.0

Table.I.4 Measured speed and estimated speeds at ¼ load for 1.1 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	172	174.5	-1.4	182.6	-6.2	169.0	1.7	176.0	-2.3	174.1	-1.2	185.8	-8.0	184.2	-7.1
20	376	377.5	-0.4	380.2	-1.1	374.4	0.4	380.2	-1.1	378.8	-0.7	385.6	-2.5	387.1	-3.0
30	577	580.9	-0.7	581.9	-0.8	578.8	-0.3	583.5	-1.1	582.5	-0.9	586.6	-1.7	589.3	-2.1
40	776	784.0	-1.0	784.3	-1.1	782.3	-0.8	786.4	-1.3	785.7	-1.2	788.2	-1.6	791.2	-2.0
50	974	984.9	-1.1	985.1	-1.1	983.5	-1.0	987.4	-1.4	986.8	-1.3	988.6	-1.5	991.9	-1.8
60	1170	1189.0	-1.6	1189.8	-1.7	1188.0	-1.5	1187.4	-1.5	1186.8	-1.4	1188.4	-1.6	1192.0	-1.9
70	1361	1391.8	-2.3	1394.0	-2.4	1391.1	-2.2	1387.3	-1.9	1386.8	-1.9	1388.1	-2.0	1391.9	-2.3

Table.I.5 Calculated speed from motor model and estimated speeds
at ½ load for 1.1 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	160	156.0	2.5	172.2	-7.6	142.9	10.7	151.9	5.1	148.9	6.9	173.5	-8.4	169.1	-5.7
20	359	360.2	-0.3	364.4	-1.5	353.3	1.6	358.4	0.2	355.8	0.9	371.6	-3.5	373.8	-4.1
30	560	561.1	-0.2	563.0	-0.5	555.8	0.7	561.1	-0.2	558.9	0.2	569.9	-1.8	575.4	-2.8
40	761	763.2	-0.3	764.1	-0.4	758.9	0.3	764.2	-0.4	762.4	-0.2	770.1	-1.2	777.2	-2.1
50	964	964.7	-0.1	964.7	-0.1	960.8	0.3	968.2	-0.4	966.8	-0.3	972.0	-0.8	979.5	-1.6
60	1147	1168.7	-1.9	1171.0	-2.1	1165.5	-1.6	1159.6	-1.1	1158.1	-1.0	1163.9	-1.5	1174.1	-2.4
70	1328	1371.2	-3.3	1378.4	-3.8	1368.4	-3.0	1350.9	-1.7	1349.4	-1.6	1354.8	-2.0	1367.7	-3.0

Table.I.6 Measured speed and estimated speeds at ½ load for 1.1 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	136	156.6	-15.1	172.6	-26.9	143.7	-5.7	153.1	-12.5	150.1	-10.4	173.9	-27.9	169.6	-24.7
20	348	360.3	-3.5	364.6	-4.8	353.5	-1.6	358.6	-3.1	356.0	-2.3	371.7	-6.8	373.9	-7.4
30	550	561.2	-2.0	563.1	-2.4	555.9	-1.1	561.2	-2.0	559.0	-1.6	570.0	-3.6	575.5	-4.6
40	750	763.3	-1.8	764.2	-1.9	758.9	-1.2	764.3	-1.9	762.5	-1.7	770.2	-2.7	777.3	-3.6
50	954	964.7	-1.1	964.8	-1.1	960.9	-0.7	968.2	-1.5	966.8	-1.3	972.1	-1.9	979.5	-2.7
60	1138	1168.7	-2.7	1171.1	-2.9	1165.6	-2.4	1159.7	-1.9	1158.2	-1.8	1163.9	-2.3	1174.2	-3.2
70	1314	1371.2	-4.4	1378.5	-4.9	1368.5	-4.1	1351.0	-2.8	1349.6	-2.7	1354.9	-3.1	1367.7	-4.1

Table.I.7 Calculated speed from motor model and estimated speeds at full-load for 1.1 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	134	119.0	11.2	119.9	10.5	84.0	37.3	121.7	9.2	118.3	11.7	155.0	-15.7	147.2	-9.8
20	322	316.9	1.6	317.3	1.5	298.0	7.5	319.6	0.7	315.7	1.9	346.0	-7.5	349.3	-8.5
30	518	515.7	0.4	515.9	0.4	502.4	3.0	517.9	0.0	514.5	0.7	537.9	-3.8	548.2	-5.8
40	718	718.3	0.0	718.2	0.0	708.2	1.4	722.8	-0.7	719.8	-0.3	736.9	-2.6	750.5	-4.5
50	910	920.8	-1.2	920.8	-1.2	912.6	-0.3	919.8	-1.1	917.0	-0.8	931.4	-2.4	947.8	-4.2
60	1053	1123.7	-6.7	1126.1	-6.9	1116.7	-6.0	1080.5	-2.6	1077.7	-2.3	1093.7	-3.9	1116.7	-6.1
70	1256	1348.0	-7.3	1359.9	-8.3	1343.0	-6.9	1294.6	-3.1	1292.1	-2.9	1302.5	-3.7	1323.9	-5.4

Table.I.8 Measured speed and estimated speeds at full-load for 1.1 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	91	120.0	-31.9	120.9	-32.8	85.6	5.9	124.1	-36.4	120.8	-32.7	155.7	-71.1	148.0	-62.7
20	305	317.2	-4.0	317.5	-4.1	298.3	2.2	320.0	-4.9	316.2	-3.7	346.2	-13.5	349.5	-14.6
30	501	515.9	-3.0	516.1	-3.0	502.6	-0.3	518.1	-3.4	514.7	-2.7	538.1	-7.4	548.3	-9.4
40	704	718.4	-2.0	718.4	-2.0	708.4	-0.6	722.9	-2.7	720.0	-2.3	737.0	-4.7	750.6	-6.6
50	899	920.9	-2.4	920.9	-2.4	912.7	-1.5	919.8	-2.3	917.1	-2.0	931.5	-3.6	947.9	-5.4
60	1034	1123.8	-8.7	1126.2	-8.9	1116.8	-8.0	1080.8	-4.5	1078.0	-4.3	1093.9	-5.8	1116.9	-8.0
70	1229	1348.1	-9.7	1360.1	-10.7	1343.2	-9.3	1295.0	-5.4	1292.5	-5.2	1302.8	-6.0	1324.2	-7.7

Table.I.9 Calculated speed from motor model and estimated speeds at no-load for 2.2 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	299	293.3	1.9	296.2	1.0	292.9	2.0	292.1	2.3	291.8	2.4	294.6	1.5	294.6	1.5
20	599	597.8	0.2	598.0	0.2	597.7	0.2	597.3	0.3	597.2	0.3	597.9	0.2	598.2	0.1
30	899	899.7	-0.1	899.7	-0.1	899.7	-0.1	899.6	-0.1	899.6	-0.1	899.7	-0.1	899.8	-0.1
40	1199	1197.8	0.1	1197.9	0.1	1197.7	0.1	1197.3	0.1	1197.2	0.1	1197.6	0.1	1198.3	0.1
50	1499	1496.1	0.2	1496.2	0.2	1496.0	0.2	1494.8	0.3	1494.7	0.3	1495.4	0.2	1496.7	0.2
60	1798	1795.1	0.2	1795.6	0.1	1795.0	0.2	1791.6	0.4	1791.5	0.4	1792.4	0.3	1794.7	0.2
70	2098	2094.6	0.2	2095.8	0.1	2094.4	0.2	2087.3	0.5	2087.1	0.5	2088.4	0.5	2092.1	0.3

Table.I.10 Measured speed and estimated speeds at no-load for 2.2 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	299	293.3	1.9	296.2	1.0	292.9	2.0	292.1	2.3	291.8	2.4	294.6	1.5	294.6	1.5
20	598	597.8	0.0	598.0	0.0	597.7	0.1	597.3	0.1	597.2	0.1	597.9	0.0	598.2	0.0
30	897	899.7	-0.3	899.7	-0.3	899.7	-0.3	899.6	-0.3	899.6	-0.3	899.7	-0.3	899.8	-0.3
40	1194	1197.8	-0.3	1197.9	-0.3	1197.7	-0.3	1197.3	-0.3	1197.2	-0.3	1197.6	-0.3	1198.2	-0.4
50	1492	1496.1	-0.3	1496.2	-0.3	1495.9	-0.3	1494.8	-0.2	1494.7	-0.2	1495.3	-0.2	1496.7	-0.3
60	1795	1795.1	0.0	1795.6	0.0	1795.0	0.0	1791.6	0.2	1791.5	0.2	1792.4	0.1	1794.7	0.0
70	2097	2094.6	0.1	2095.8	0.1	2094.4	0.1	2087.3	0.5	2087.1	0.5	2088.4	0.4	2092.1	0.2

Table.I.11 Calculated speed from motor model and estimated speeds at ¼ load for 2.2 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	281	275.1	2.1	282.1	-0.4	272.1	3.2	269.4	4.1	268.2	4.5	281.8	-0.3	281.9	-0.3
20	581	578.6	0.4	580.1	0.2	577.0	0.7	574.6	1.1	573.7	1.3	581.6	-0.1	584.3	-0.6
30	880	881.2	-0.1	881.9	-0.2	880.1	0.0	877.6	0.3	876.9	0.4	882.0	-0.2	885.9	-0.7
40	1180	1182.3	-0.2	1182.8	-0.2	1181.4	-0.1	1178.3	0.1	1177.8	0.2	1181.6	-0.1	1186.3	-0.5
50	1479	1484.2	-0.4	1484.6	-0.4	1483.4	-0.3	1479.8	-0.1	1479.3	0.0	1482.1	-0.2	1487.1	-0.5
60	1769	1785.8	-1.0	1787.1	-1.0	1785.2	-0.9	1774.1	-0.3	1773.6	-0.3	1776.7	-0.4	1783.6	-0.8
70	2057	2086.2	-1.4	2089.2	-1.6	2085.5	-1.4	2065.3	-0.4	2064.8	-0.4	2068.3	-0.5	2077.8	-1.0

Table.I.12 Measured speed and estimated speeds at ¼ load for 2.2 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	274	275.2	-0.4	282.1	-3.0	272.1	0.7	269.5	1.6	268.3	2.1	281.8	-2.8	282.0	-2.9
20	577	578.6	-0.3	580.1	-0.5	577.0	0.0	574.6	0.4	573.7	0.6	581.6	-0.8	584.3	-1.3
30	877	881.2	-0.5	881.9	-0.6	880.1	-0.3	877.6	-0.1	876.9	0.0	882.0	-0.6	885.9	-1.0
40	1173	1182.3	-0.8	1182.8	-0.8	1181.4	-0.7	1178.4	-0.5	1177.8	-0.4	1181.6	-0.7	1186.3	-1.1
50	1471	1484.2	-0.9	1484.6	-0.9	1483.5	-0.8	1479.8	-0.6	1479.4	-0.6	1482.1	-0.8	1487.1	-1.1
60	1764	1785.8	-1.2	1787.1	-1.3	1785.2	-1.2	1774.1	-0.6	1773.6	-0.5	1776.7	-0.7	1783.6	-1.1
70	2054	2086.2	-1.6	2089.2	-1.7	2085.5	-1.5	2065.3	-0.6	2064.8	-0.5	2068.3	-0.7	2077.8	-1.2

Table.I.13 Calculated speed from motor model and estimated speeds at ½ load for 2.2 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	261	256.2	1.8	261.3	-0.1	248.4	4.8	245.1	6.1	243.3	6.8	268.3	-2.8	268.5	-2.9
20	559	559.3	-0.1	560.9	-0.3	555.3	0.7	552.3	1.2	550.8	1.5	566.4	-1.3	571.1	-2.2
30	859	861.0	-0.2	861.7	-0.3	858.0	0.1	855.1	0.5	853.9	0.6	864.6	-0.7	872.1	-1.5
40	1159	1163.7	-0.4	1164.1	-0.4	1161.4	-0.2	1158.7	0.0	1157.7	0.1	1165.2	-0.5	1173.9	-1.3
50	1452	1465.4	-0.9	1466.0	-1.0	1463.4	-0.8	1454.2	-0.2	1453.3	-0.1	1460.1	-0.6	1470.9	-1.3
60	1729	1766.5	-2.2	1769.0	-2.3	1764.7	-2.1	1735.2	-0.4	1734.1	-0.3	1742.2	-0.8	1758.1	-1.7
70	1999	2066.6	-3.4	2073.2	-3.7	2065.0	-3.3	2010.1	-0.6	2009.0	-0.5	2018.1	-1.0	2039.5	-2.0

Table.I.14 Measured speed and estimated speeds at ½ load for 2.2 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	247	256.3	-3.8	261.4	-5.8	248.5	-0.6	245.3	0.7	243.5	1.4	268.4	-8.7	268.6	-8.7
20	556	559.4	-0.6	560.9	-0.9	555.3	0.1	552.3	0.7	550.8	0.9	566.4	-1.9	571.1	-2.7
30	857	861.0	-0.5	861.7	-0.5	858.0	-0.1	855.1	0.2	853.9	0.4	864.6	-0.9	872.1	-1.8
40	1156	1163.7	-0.7	1164.1	-0.7	1161.4	-0.5	1158.7	-0.2	1157.7	-0.1	1165.2	-0.8	1173.9	-1.5
50	1446	1465.4	-1.3	1466.1	-1.4	1463.4	-1.2	1454.3	-0.6	1453.3	-0.5	1460.1	-1.0	1470.9	-1.7
60	1727	1766.5	-2.3	1769.0	-2.4	1764.7	-2.2	1735.2	-0.5	1734.1	-0.4	1742.2	-0.9	1758.1	-1.8
70	1998	2066.6	-3.4	2073.2	-3.8	2065.0	-3.4	2010.1	-0.6	2009.0	-0.5	2018.1	-1.0	2039.5	-2.1

Table.I.15 Calculated speed from motor model and estimated speeds at full-load for 2.2 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	219	227.0	-3.7	228.0	-4.1	208.7	4.7	203.8	6.9	201.5	8.0	242.6	-10.8	241.8	-10.4
20	508	521.3	-2.6	521.4	-2.6	510.8	-0.6	496.0	2.4	493.4	2.9	528.5	-4.0	536.5	-5.6
30	807	823.6	-2.1	823.8	-2.1	816.9	-1.2	804.1	0.4	801.9	0.6	826.1	-2.4	839.6	-4.0
40	1104	1125.9	-2.0	1126.0	-2.0	1120.9	-1.5	1105.9	-0.2	1104.0	0.0	1122.6	-1.7	1139.3	-3.2
50	1362	1428.3	-4.9	1428.7	-4.9	1424.3	-4.6	1381.9	-1.5	1379.9	-1.3	1399.3	-2.7	1422.1	-4.4
60	1591	1727.3	-8.6	1728.8	-8.7	1723.8	-8.3	1606.8	-1.0	1604.6	-0.9	1630.0	-2.5	1662.4	-4.5
70	1958	2057.0	-5.1	2065.0	-5.5	2054.9	-4.9	1970.8	-0.7	1969.3	-0.6	1982.8	-1.3	2009.9	-2.7

Table.I.16 Measured speed and estimated speeds at full-load for 2.2 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	209	227.1	-8.7	228.1	-9.1	208.8	0.1	204.0	2.4	201.7	3.5	242.6	-16.1	241.9	-15.7
20	502	521.3	-3.8	521.4	-3.9	510.9	-1.8	496.0	1.2	493.4	1.7	528.5	-5.3	536.5	-6.9
30	809	823.6	-1.8	823.7	-1.8	816.8	-1.0	804.1	0.6	801.9	0.9	826.1	-2.1	839.6	-3.8
40	1109	1125.9	-1.5	1126.0	-1.5	1120.8	-1.1	1105.9	0.3	1104.0	0.5	1122.5	-1.2	1139.3	-2.7
50	1385	1428.2	-3.1	1428.7	-3.2	1424.2	-2.8	1381.8	0.2	1379.8	0.4	1399.3	-1.0	1422.0	-2.7
60	1607	1727.3	-7.5	1728.8	-7.6	1723.8	-7.3	1606.7	0.0	1604.5	0.2	1629.9	-1.4	1662.4	-3.4
70	1958	2057.0	-5.1	2065.0	-5.5	2054.9	-4.9	1970.8	-0.7	1969.3	-0.6	1982.8	-1.3	2009.9	-2.7

Table.I.17 Calculated speed from motor model and estimated speeds at no-load for 4 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	299	294.1	1.6	295.9	1.0	293.8	1.7	294.3	1.6	294.1	1.6	295.3	1.2	299.5	-0.2
20	599	598.1	0.1	598.2	0.1	598.0	0.2	598.2	0.1	598.2	0.1	598.3	0.1	599.4	-0.1
30	899	899.3	0.0	899.3	0.0	899.3	0.0	899.3	0.0	899.3	0.0	899.3	0.0	899.4	0.0
40	1199	1196.7	0.2	1197.1	0.2	1196.6	0.2	1194.8	0.4	1194.7	0.4	1194.8	0.4	1199.4	0.0
50	1499	1496.1	0.2	1496.2	0.2	1496.0	0.2	1495.8	0.2	1495.7	0.2	1495.7	0.2	1499.4	0.0
60	1799	1794.6	0.2	1794.9	0.2	1794.4	0.3	1792.5	0.4	1792.4	0.4	1792.4	0.4	1799.4	0.0
70	2099	2093.4	0.3	2094.3	0.2	2093.2	0.3	2087.5	0.5	2087.3	0.6	2087.4	0.6	2099.4	0.0

Table.I.18 Measured speed and estimated speeds at no-load for 4 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	299	294.1	1.6	295.9	1.0	293.8	1.7	294.3	1.6	294.1	1.6	295.3	1.2	299.5	-0.2
20	599	598.1	0.1	598.2	0.1	598.0	0.2	598.2	0.1	598.2	0.1	598.3	0.1	599.4	-0.1
30	898	899.3	-0.1	899.3	-0.1	899.3	-0.1	899.3	-0.1	899.3	-0.1	899.3	-0.1	898.8	-0.1
40	1195	1196.7	-0.1	1197.1	-0.2	1196.6	-0.1	1194.8	0.0	1194.6	0.0	1194.8	0.0	1196.9	-0.2
50	1492	1496.1	-0.3	1496.2	-0.3	1496.0	-0.3	1495.8	-0.3	1495.7	-0.2	1495.7	-0.2	1495.1	-0.2
60	1795	1794.6	0.0	1794.9	0.0	1794.4	0.0	1792.5	0.1	1792.4	0.1	1792.4	0.1	1796.9	-0.1
70	2097	2093.4	0.2	2094.3	0.1	2093.2	0.2	2087.5	0.5	2087.3	0.5	2087.4	0.5	2098.1	-0.1

Table.I.19 Calculated speed from motor model and estimated speeds at ¼ load for 4 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	277	278.1	-0.4	287.6	-3.8	275.8	0.4	272.3	1.7	271.3	2.1	278.9	-0.7	287.4	-3.8
20	580	579.0	0.2	580.5	-0.1	577.7	0.4	577.3	0.5	576.6	0.6	579.3	0.1	588.3	-1.4
30	881	880.2	0.1	880.8	0.0	879.2	0.2	879.7	0.1	879.2	0.2	880.3	0.1	888.5	-0.9
40	1180	1182.3	-0.2	1182.7	-0.2	1181.5	-0.1	1181.7	-0.1	1181.3	-0.1	1181.7	-0.1	1187.8	-0.7
50	1480	1485.2	-0.4	1485.5	-0.4	1484.7	-0.3	1484.5	-0.3	1484.2	-0.3	1484.2	-0.3	1487.7	-0.5
60	1771	1785.7	-0.8	1786.7	-0.9	1785.2	-0.8	1778.4	-0.4	1778.0	-0.4	1778.1	-0.4	1782.0	-0.6
70	2059	2087.8	-1.4	2089.9	-1.5	2087.3	-1.4	2074.6	-0.8	2074.3	-0.7	2074.1	-0.7	2074.5	-0.8

Table.I.20 Measured speed and estimated speeds at ¼ load for 4 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	277	278.1	-0.4	287.6	-3.8	275.8	0.4	272.3	1.7	271.3	2.1	278.9	-0.7	287.4	-3.8
20	580	579.0	0.2	580.5	-0.1	577.7	0.4	577.3	0.5	576.6	0.6	579.3	0.1	588.3	-1.4
30	880	880.2	0.0	880.8	-0.1	879.2	0.1	879.7	0.0	879.2	0.1	880.3	0.0	887.9	-0.9
40	1178	1182.3	-0.4	1182.7	-0.4	1181.5	-0.3	1181.7	-0.3	1181.3	-0.3	1181.7	-0.3	1186.5	-0.7
50	1475	1485.3	-0.7	1485.5	-0.7	1484.7	-0.7	1484.5	-0.6	1484.2	-0.6	1484.2	-0.6	1484.6	-0.6
60	1772	1785.7	-0.8	1786.7	-0.8	1785.2	-0.7	1778.4	-0.4	1778.0	-0.3	1778.0	-0.3	1782.7	-0.6
70	2062	2087.8	-1.2	2089.9	-1.4	2087.3	-1.2	2074.6	-0.6	2074.2	-0.6	2074.1	-0.6	2076.4	-0.7

Table.I.21 Calculated speed from motor model and estimated speeds at ½ load for 4 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	247	262.7	-6.4	275.3	-11.4	257.1	-4.1	244.8	0.9	243.2	1.5	258.7	-4.7	270.9	-9.7
20	554	562.8	-1.6	565.2	-2.0	559.6	-1.0	554.5	-0.1	553.2	0.1	559.2	-0.9	573.0	-3.4
30	859	862.2	-0.4	863.3	-0.5	859.8	-0.1	858.7	0.0	857.7	0.2	860.3	-0.1	875.2	-1.9
40	1157	1164.9	-0.7	1165.7	-0.8	1163.1	-0.5	1161.0	-0.3	1160.2	-0.3	1161.2	-0.4	1173.6	-1.4
50	1458	1467.1	-0.6	1467.5	-0.7	1465.6	-0.5	1464.4	-0.4	1463.8	-0.4	1464.1	-0.4	1474.1	-1.1
60	1737	1768.1	-1.8	1770.0	-1.9	1766.7	-1.7	1748.0	-0.6	1747.3	-0.6	1747.4	-0.6	1760.9	-1.4
70	2013	2068.8	-2.8	2073.2	-3.0	2067.6	-2.7	2031.3	-0.9	2030.4	-0.9	2030.0	-0.8	2045.8	-1.6

Table.I.22 Measured speed and estimated speeds at ½ load for 4 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	250	262.7	-5.1	275.2	-10.1	257.1	-2.8	244.8	2.1	243.2	2.7	258.7	-3.5	272.6	-9.0
20	558	562.8	-0.9	565.2	-1.3	559.6	-0.3	554.5	0.6	553.2	0.9	559.2	-0.2	575.3	-3.1
30	861	862.2	-0.1	863.3	-0.3	859.8	0.1	858.7	0.3	857.7	0.4	860.3	0.1	876.4	-1.8
40	1158	1164.9	-0.6	1165.7	-0.7	1163.1	-0.4	1161.0	-0.3	1160.2	-0.2	1161.2	-0.3	1174.3	-1.4
50	1459	1467.1	-0.6	1467.5	-0.6	1465.5	-0.4	1464.4	-0.4	1463.8	-0.3	1464.1	-0.4	1474.7	-1.1
60	1746	1768.1	-1.3	1770.0	-1.4	1766.7	-1.2	1748.0	-0.1	1747.2	-0.1	1747.4	-0.1	1766.5	-1.2
70	2026	2068.8	-2.1	2073.2	-2.3	2067.5	-2.0	2031.2	-0.3	2030.4	-0.2	2030.0	-0.2	2054.0	-1.4

Table.I.23 Calculated speed from motor model and estimated speeds
at full-load for 4 kW induction motor

f (Hz)	Reference speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	212	231.7	-9.3	233.6	-10.2	215.7	-1.7	207.6	2.1	205.5	3.1	229.2	-8.1	251.3	-18.5
20	518	527.2	-1.8	527.6	-1.9	518.2	0.0	515.6	0.5	513.6	0.8	524.8	-1.3	551.8	-6.5
30	821	827.0	-0.7	827.2	-0.8	821.0	0.0	820.9	0.0	819.3	0.2	824.1	-0.4	852.2	-3.8
40	1117	1134.2	-1.5	1134.5	-1.6	1130.1	-1.2	1128.0	-1.0	1126.7	-0.9	1128.7	-1.1	1149.0	-2.9
50	1407	1432.8	-1.8	1433.1	-1.9	1429.3	-1.6	1417.9	-0.8	1416.6	-0.7	1417.6	-0.8	1442.5	-2.5
60	1664	1733.9	-4.2	1735.2	-4.3	1731.0	-4.0	1685.4	-1.3	1684.0	-1.2	1683.2	-1.2	1715.0	-3.1
70	1949	2047.1	-5.0	2051.5	-5.3	2044.9	-4.9	1977.6	-1.5	1976.4	-1.4	1973.9	-1.3	2005.1	-2.9

Table.I.24 Measured speed and estimated speeds at full-load for 4 kW induction motor

f (Hz)	Measured speed (rpm)	M1		M2		M3		M4		M5		M6		M7	
		rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
10	218	231.6	-6.2	233.6	-7.1	215.6	1.1	207.4	4.9	205.4	5.8	229.1	-5.1	254.8	-16.9
20	525	527.1	-0.4	527.6	-0.5	518.1	1.3	515.5	1.8	513.5	2.2	524.8	0.0	556.0	-5.9
30	829	827.0	0.2	827.2	0.2	820.9	1.0	820.9	1.0	819.3	1.2	824.0	0.6	857.0	-3.4
40	1129	1134.1	-0.5	1134.4	-0.5	1130.0	-0.1	1127.9	0.1	1126.6	0.2	1128.7	0.0	1156.4	-2.4
50	1424	1432.7	-0.6	1433.1	-0.6	1429.3	-0.4	1417.8	0.4	1416.6	0.5	1417.6	0.5	1453.1	-2.0
60	1689	1733.8	-2.7	1735.1	-2.7	1730.9	-2.5	1685.2	0.2	1683.9	0.3	1683.1	0.4	1730.9	-2.5
70	1970	2047.0	-3.9	2051.5	-4.1	2044.9	-3.8	1977.5	-0.4	1976.3	-0.3	1973.8	-0.2	2018.6	-2.5

Table.I.25 Calculated speed from motor model and estimated speeds
when 2.2 kW induction motor is driven with line voltage

f	Referans	Measured	M1		M2		M3		M4		M5		M6		M7	
(Hz)	speed (rpm)	torque (Nm)	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
50	1488	1.8	1491.9	-0.3	1492.1	-0.3	1491.5	-0.2	1489.3	-0.1	1489.0	-0.1	1489.0	-0.1	1493.2	-0.3
50	1477	3.4	1481.9	-0.3	1482.3	-0.4	1480.9	-0.3	1475.4	0.1	1474.8	0.1	1475.1	0.1	1484.4	-0.5
50	1454	6.6	1466.1	-0.8	1466.9	-0.9	1464.2	-0.7	1452.2	0.1	1451.3	0.2	1452.2	0.1	1469.8	-1.1
50	1442	8.2	1457.6	-1.1	1458.4	-1.1	1455.2	-0.9	1439.0	0.2	1437.8	0.3	1439.3	0.2	1461.4	-1.3
50	1417	11.4	1442.7	-1.8	1443.5	-1.9	1439.3	-1.6	1413.7	0.2	1412.1	0.3	1414.2	0.2	1444.7	-2.0
50	1403	13	1435.9	-2.3	1436.5	-2.4	1432.2	-2.1	1401.5	0.1	1399.9	0.2	1401.8	0.1	1436.1	-2.4
50	1388	14.6	1424.2	-2.6	1424.5	-2.6	1420.1	-2.3	1378.8	0.7	1376.9	0.8	1379.2	0.6	1420.7	-2.4

Table.I.26 Measured speed and estimated speeds
when 2.2 kW induction motor is driven with line voltage

f	Measured	Measured	M1		M2		M3		M4		M5		M6		M7	
(Hz)	speed (rpm)	torque (Nm)	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.	rpm	%err.
50	1486	1.8	1491.9	-0.4	1492.1	-0.4	1491.5	-0.4	1489.3	-0.2	1489.0	-0.2	1489.0	-0.2	1493.2	-0.5
50	1478	3.4	1481.9	-0.3	1482.3	-0.3	1480.9	-0.2	1475.4	0.2	1474.8	0.2	1475.1	0.2	1484.4	-0.4
50	1457	6.6	1466.1	-0.6	1466.8	-0.7	1464.2	-0.5	1452.2	0.3	1451.3	0.4	1452.2	0.3	1469.8	-0.9
50	1445	8.2	1457.6	-0.9	1458.4	-0.9	1455.1	-0.7	1439.0	0.4	1437.8	0.5	1439.3	0.4	1461.4	-1.1
50	1424	11.4	1442.7	-1.3	1443.5	-1.4	1439.3	-1.1	1413.7	0.7	1412.1	0.8	1414.2	0.7	1444.7	-1.5
50	1411	13	1435.9	-1.8	1436.5	-1.8	1432.2	-1.5	1401.5	0.7	1399.8	0.8	1401.8	0.7	1436.1	-1.8
50	1396	14.6	1424.2	-2.0	1424.5	-2.0	1420.1	-1.7	1378.8	1.2	1376.9	1.4	1379.2	1.2	1420.7	-1.8

APPENDIX J

CALCULATION OF INVERTER LOSSES

Inverter losses can be calculated by adding conduction losses and switching losses. To calculate conduction loss, voltage drop on the switch is found from datasheet of IPM. Conduction loss is calculated as in equation (J.1).

$$P_{con} = V_{CE} * I_C * duty * phasenumbe\,r \qquad \text{(J.1)}$$

Switching losses is calculated as follows.

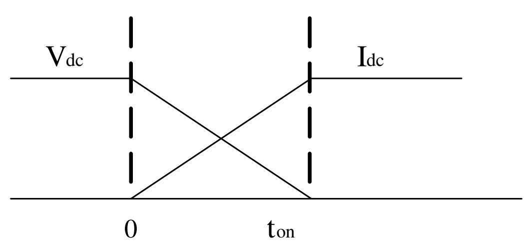


Figure.J.1 Voltage and current on the switch at turn-on of the switch

$$P_{swon} = \frac{1}{T}.\int_0^{t_{on}} V(t).I(t).dt \qquad \text{(J.2)}$$

$$P_{swoff} = \frac{1}{T}.\int_0^{t_{off}} V(t).I(t).dt \qquad \text{(J.3)}$$

$$P_{swon} = \frac{V_{dc}.I_{dc}.t_{on}}{6.T} \qquad \text{(J.4)}$$

$$P_{swoff} = \frac{V_{dc}.I_{dc}.t_{off}}{6.T} \quad (J.5)$$

$$P_{sw} = numberofph\,ases * (P_{swon} + P_{swoff}) \quad (J.6)$$

Switching times of IPM can be found from Fig.J.2. an example of calculation of witching losses is shown in Table.J.1.

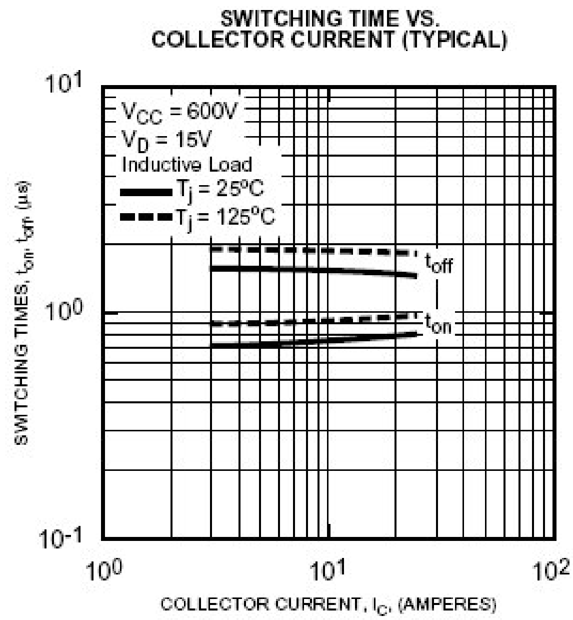


Figure.J.2 Switching times of IPM versus current

Table.J.1 Switching losses of IPM

Current (A)	Conduction losses (W)	Switching losses (W)
5	2	30
2.9	1	18

APPENDIX K

EFFECT OF DC-LINK OSCILATIONS ON STATOR PHASE CURRENTS

That oscillations on the dc-link worsen the stator phase currents as discussed in Chapter 4 is shown in Fig.K.1 and Fig.K.2.

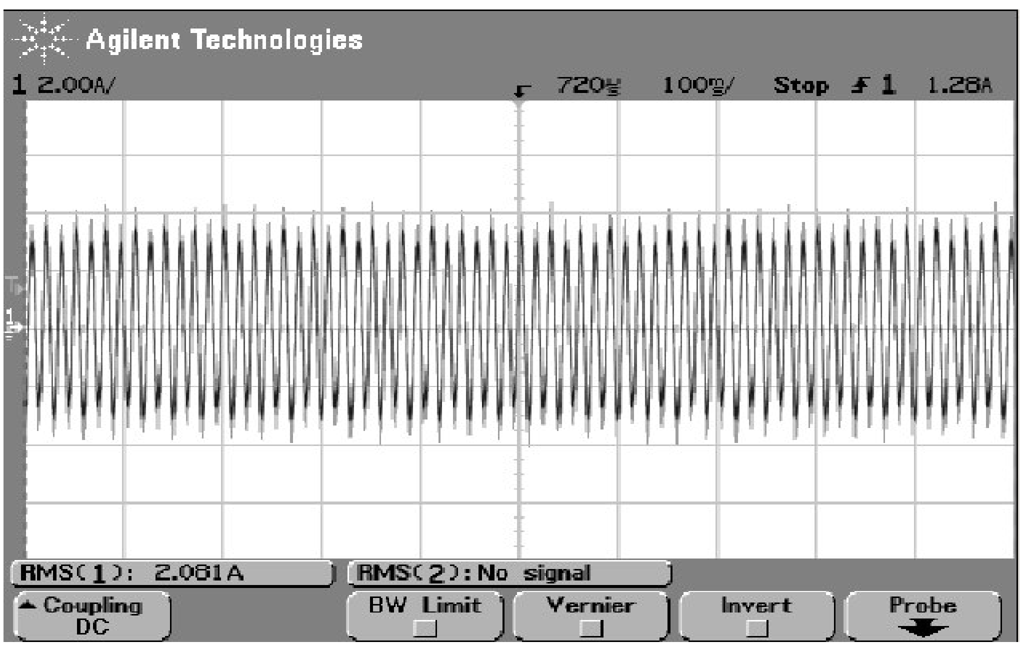


Fig.K.1 Stator phase current at 70 Hz

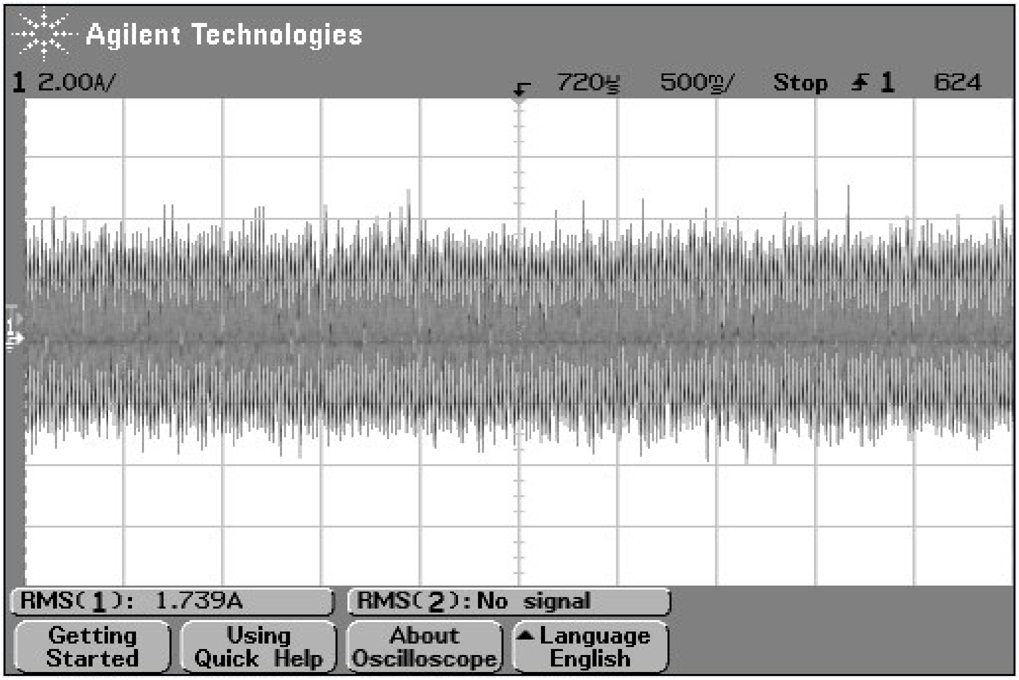


Fig.K.2 Stator phase current at 50 Hz