

THESIS

EFFICIENCY IMPROVEMENT OF THREE PHASE SQUIRREL CAGE INDUCTION
MOTOR BY CONTROLLING THE APPLIED VOLTAGE TO THE STATOR USING
SIMULINK MODELS

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ABSTRACT

EFFICIENCY IMPROVEMENT OF THREE PHASE SQUIRREL CAGE INDUCTION MOTOR BY CONTROLLING THE APPLIED VOLTAGE TO THE STATOR USING SIMULINK MODELS

Optimizing the efficiency of three phase squirrel cage induction motors (SCIMs) plays a big role in saving electric energy consumption. The purpose of this thesis is to maximize the efficiency of three phase (SCIM) when it runs at speeds greater than the speed at which the efficiency is maximum during normal operation, i.e., rated voltage by decreasing the applied voltage to the stator using MATLAB/SIMULINK. Equivalent circuit and parameter identification of three phase (SCIM) are explained. MATLAB/SIMULINK is employed to identify the motor parameters and to simulate a three phase (SCIM) under different loads. The effect of reducing the voltage on motor characteristics such as the produced torque by the motor, power factor, reactive power, apparent power, output power, rotor speed and magnetizing current is explained.

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DEDICATION

To my father, Mohammed, my mother, Fathea and my brothers. Without your support, I could not have finished this work

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CHAPTER 1

INTRODUCTION

1.1 AC Induction Motors Overview

Induction motors (IMs) are broadly utilized for converting electric energy into mechanical energy. IMs are significant in daily life and available as single and three phase IMs. Centrifugal pumps, washing machines, dryers, mixers, fans, air conditioners, and refrigerators are examples of IM applications [1]. The invention of the IM happened in the last quarter of the nineteenth century by Nikola Tesla [2]. There has been a significant improvement in the IM construction and performance. Using high conductivity materials such as copper as an alternative to standard steel in the squirrel cage rotor decreases motor power losses. In addition, the use of silicon steel sheets that shape the stator core minimizes the hysteresis losses and eddy currents [3].

The speed of three phase IMs can be controlled by varying the applied voltage to the stator, stator frequency, number of stator poles or by connecting external resistor to the rotor circuit (wound rotor type) [4]. Variable frequency drives (VFDs) are commonly used to control the speed of IMs for saving energy. For example, throttles devices, dampers or valves can be used to adjust the output of water pumps to reduce flow rate, but this increase the current drawn by the pump. Therefore, VDFs are employed to control flow by changing motor speed by varying the frequency and voltage applied to the pump instead of adjusting flow via throttling devices. Thus, energy saving is achieved.

Different methods such as star/delta connection, step down auto-transformer and adding resistors in series with rotor (slip ring rotor) or stator windings are used in order to reduce starting current of IM, which is 5 to 7 times its rated current [5].

1.2 Three Phase Induction Motors

Three phase IMs are widely employed for several industrial applications due to their multiple features. These include strong structure, low weight, high efficiency at rated speed, and low maintenance and cheaper in cost [6]. The disadvantages of the three phase IMs, on the other hand, include the following: (i) the rotor speed is difficult to control, (ii) low efficiency and power factor at light load, and (iii) high starting current [6].

1.3 Construction of Three Phase Induction Motors

1.3.1 Stator

The stator core is made of laminated silicon steel sheets which are 0.3 to 0.5 mm thick in order to reduce eddy currents and hysteresis losses [7], [8]. The sheets are then combined together to build the stator core as a cylindrical form. The inner side of the stator is slotted longitudinally. The slots are divided into a suitable number of poles usually 4 poles. Three phase windings are placed in the slots and shifted by 120 electrical degrees from each other and the terminals of these windings can be connected as star or delta connection [8].

1.3.2 Rotor

There are two types of rotor which are slip rings or wound rotor, and squirrel cage rotor. The slip rings rotor is commonly used when high starting torque is required. The slip rings rotor as shown in Fig. 1.1 is similar to the stator structure. It consists of laminated silicon sheets which are assembled together to build the rotor core as a cylindrical form which is fitted on the rotor shaft [9]. The outer side of the wound rotor core is slotted to contain three phase windings, which are then connected as star mode. The wound rotor has a number of poles equal the number of stator poles. The three terminals of wound rotor windings as shown in Fig. 1.1 are connected to three slip rings, which are mounted on the rotor shaft [9]. The purpose of using slip rings is to have an

electric connection between the rotor circuit and external resistors through carbon brushes. This electric connection is used to reduce starting current and control rotor speed [9].

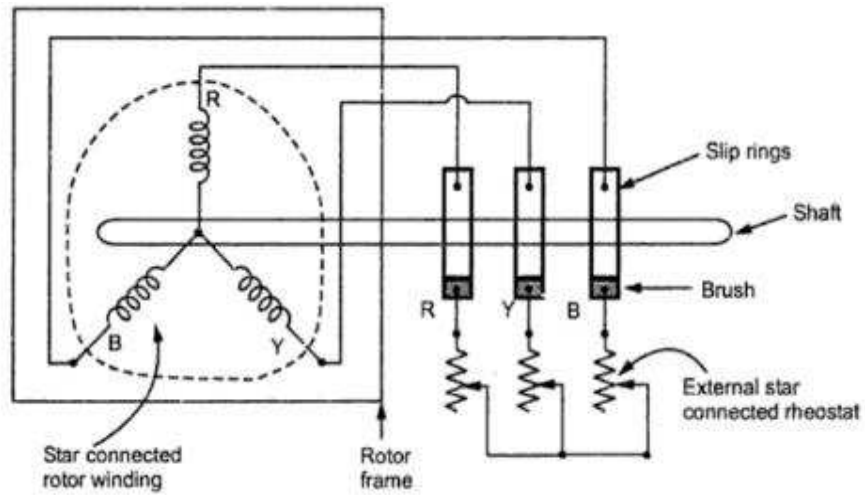


Figure 1-1 Slip rings rotor or wound rotor [9]

The squirrel cage rotor is easier to construct in comparison with the slip rings. It is more commonly used (about 95% of three phase IMs) [9]. The squirrel cage rotor as presented in Fig. 1.2 is constructed of longitudinal bars made of copper or aluminum [9]. These bars are shortened by copper or aluminum rings and the rotor is formed as a cylindrical shape [9]. No carbon brushes are in the squirrel cage rotor as are presented in the slip rings rotor. Therefore, no external resistors can be connected with rotor bars [9]. Hence, no speed control or changing motor operation characteristics can be achieved through the squirrel cage rotor. The bars are not exactly parallel to the rotor shaft axis. They are skewed to reduce the magnetic noise to drive the motor smoothly [9].

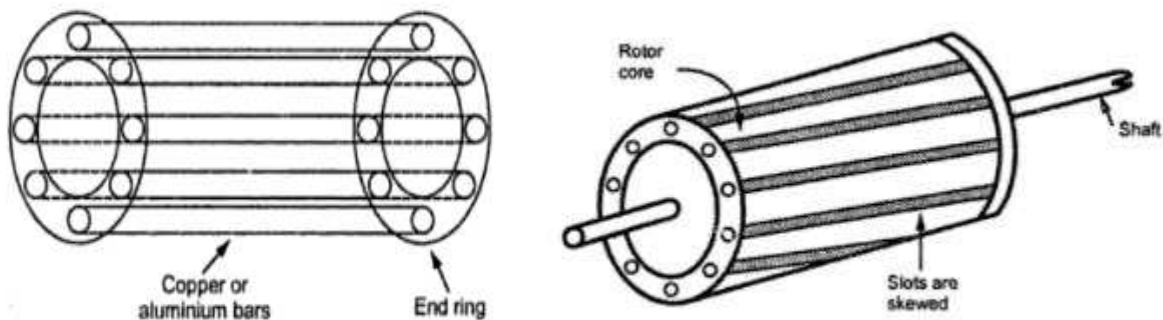


Figure 1-2 Squirrel cage rotor [9]

1.4 Three Phase Induction Motor Operation

Three phase IM can simply be considered as an electric transformer with secondary windings that are free to rotate. The rotor current is induced by induction and its frequency changes when varying the load on the motor. When the stator windings are supplied with a three phase ac voltage, a rotating magnetic field will produce and pass the airgap and induce voltage in the rotor windings [9]. The rotor speed cannot be equal to the synchronous speed (the speed of the rotating magnetic field of the stator). This is because the rotor frequency is directly proportional to the motor slip. When the slip equals zero, the rotor induced voltage becomes zero. This means no currents flow in the rotor windings, hence no motor torque produced [9].

$$S = \frac{N_s - N}{N_s} \quad (1.1)$$

The rotor frequency, current and the electromotive force (emf) induced in the rotor are given by the following equations [9]:

$$F_r = SF \quad (1.2)$$

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} \quad (1.3)$$

$$E_{2r} = SE_2 \quad (1.4)$$

Where [5],

S is motor slip.

N is rotor speed.

N_s is the synchronous speed of rotating magnetic field of the stator.

F is stator frequency.

f_r is rotor frequency (under running conditions).

E_{2r} is rotor induced emf (under running conditions).

E_2 is locked rotor emf (the rotor is in standstill).

I_{2r} is rotor current (under running conditions).

Z_{2r} is rotor impedance (under running conditions).

As the rotating magnetic field of the stator causes voltage in the rotor windings, electric currents will flow in the rotor windings and produce a rotating magnetic field [9]. The interaction of the two magnetic fields in the air gap will produce torque that forces the rotor to rotate [9]. At starting, where rotor speed is zero, a high current will be drawn from the power supply due to the minimum motor impedance. At no load, where the rotor speed is approximately equal to synchronous speed, the rotor emf becomes very small, hence the motor draws low current.

When the motor is loaded, the rotor speed decreases. This results in an increase in rotor current and produced torque. The deceleration continues till a point at which the produced torque by the motor equals the load torque and the motor runs at a constant speed [6].

1.5 Literature Review

Single and three phase IMs represent [10], 80% of electric motors and use up more than 54% of the world electric energy and more than 60% of the total U.S. electric energy [11], [12]. In addition, 60% of the electric power used in industry is consumed by three phase IMs [13]. This large consumption is due to the large amount of reactive power required by IMs, hence high apparent power is drawn from the system and also due to the reduction in IMs efficiency and power factor [14], especially when they operate at light loads. Moreover, the wide spread use of re-wound IMs causes a large decrease in efficiency. Some winders use coils that have a number of turns or conductor cross-sectional area that is less than or greater than the origin ones [15]. These winding deviations may lead to a decrease in motor impedance, which causes an increase in motor temperature.

Improving the efficiency of three phase IMs, which is the purpose of this thesis, plays a significant role in decreasing energy consumption. Different methods have been used for efficiency optimization. The simplest strategy to optimize three phase IM efficiency is to run and maintain the motor in star mode which results in reduction of input power. This simple method is not appropriate for high loads because when the motor runs at high loads with star connection, the motor current increases and the efficiency and power factor decrease [16]. The magnetic material plays a big role in the efficiency enhancement of three phase IMs. In [17], using copper or premium steel rotor cage as an alternative to aluminum and standard steel cage results in improving three phase IMs performance. Also, this substitution lessens the stator coils temperature. Consequently, less cooling effort will be needed.

Internal and external methods are explained in [10], where in the internal method; cooling air passes the air gap between the rotor and stator while passing over frame in the external method. This paper concludes that the effect of using the internal method is better compared to the external method in terms of reducing motor temperature, hence higher efficiency is obtained. The authors in [18] use a method called “Hooke-Jeeves” which is a computer program that finds an appropriate value of motor parameters such as outer and inner stator diameter, slot depth and stack length by adding small incremental changes to motor parameters. A comparison between initial and optimal parameters is explained in [18] where optimal parameters are better than the initial parameters in terms of efficiency and power factor optimization.

Several control methods of three phase IMs have been applied to control motor speed. The scalar control or (v/f control) method that includes open and closed loop control is used in different research papers for the purpose of efficiency improvement.

In research paper [19], a comparison between open and closed loop control found that implementing closed loop gives high efficiency optimization over open loop, where in closed loop; a speed feedback circuit is used to keep rotor frequency constant at a certain value that gives maximum efficiency.

Because of its simplicity [20], MATLAB/SIMULINK has been used to compare between the two methods in [19]. A high efficiency is obtained from the closed loop method [20].

The equivalent circuit of three phase IM represents resistances and reactances of stator and rotor windings. The equivalent circuit parameters of a three phase IM are identified by DC, short circuit and open circuit tests. These tests can also be applied on single or three phase electric transformer as well. In [21], those tests are achieved experimentally while in this thesis, they are carried out using SIMULINK models.

The motivation of doing this work is that a few research papers have taken into consideration all motor characteristics such as apparent power, reactive power, magnetizing current, and rotor current when improving motor efficiency. Furthermore, the proposed method of this thesis is simple and economic and no harmonics are produced in which the efficiency of three phase SCIM is kept constant at its maximum value when the motor runs at speeds greater than the speed at which the efficiency is maximum during normal operation (rated voltage). This will result in reducing electric energy bill significantly. Additionally, the overall power losses reduce. Hence, the motor lifetime increases.

CHAPTER 2

EQUIVALENT CIRCUIT AND PARAMETER IDENTIFICATION OF THREE PHASE INDUCTION MOTORS

2.1 Equivalent Circuit

The equivalent circuit of any electric machine such as induction machines and synchronous machines shows various parameters which represent the resistances and reactances of the machine windings. The equivalent circuit of a three phase IM is similar to that of an electric transformer, but the frequency, reactance, current and induced voltage emf of the rotor windings of the three phase IM are directly proportional to the motor slip as shown in Fig 2.1.

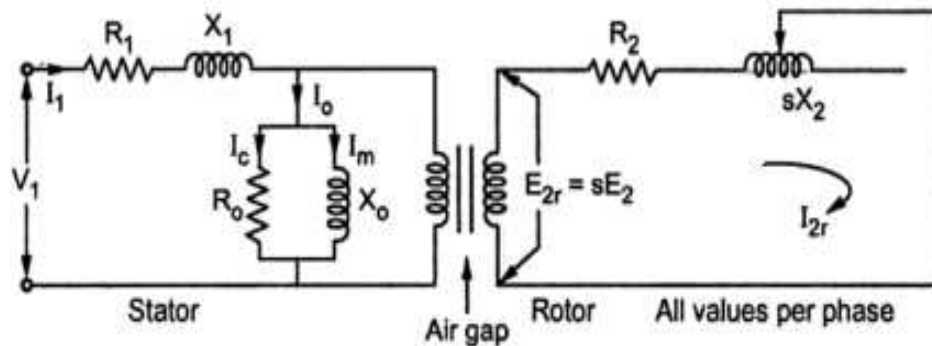


Figure 2-1 Equivalent circuit of a three phase IM per phase [22]

Where [22],

R_1 is stator winding resistance.

X_1 is stator winding reactance.

R_0 is iron losses resistance.

X_0 is magnetizing reactance.

R_2 is rotor winding resistance.

sX_2 is rotor reactance (under running conditions).

X_2 is rotor reactance (the rotor is in standstill).

V_1 is the applied voltage to the stator.

I_1 is stator phase current.

I_0 is No- load current.

I_m is magnetizing current.

I_c is iron losses current.

When the motor is in running conditions (motor is loaded), the rotor current I_{2r} is given by,

$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{S}\right)^2 + (X_2)^2}} \quad (2.1)$$

From equation 2.1, it can be seen that the equivalent circuit of the rotor has a variable resistance R_2/S and fixed induced voltage E_2 , and reactance X_2 . This variable resistance can be divided into two parts, rotor resistance R_2 , which represents rotor copper losses, and $\frac{R_2}{S}(1 - s)$ which represents load resistance (mechanical load on the motor) as follows:

$$\frac{R_2}{S} = \frac{R_2}{S} + R_2 - R_2 \quad (2.2)$$

$$\frac{R_2}{S} = R_2 + R_2\left(\frac{1}{S} - 1\right) \quad (2.3)$$

$$\frac{R_2}{S} = R_2 + \frac{R_2}{S}(1 - s) \quad (2.4)$$

The rotor equivalent circuit is presented in Fig. 2.2.

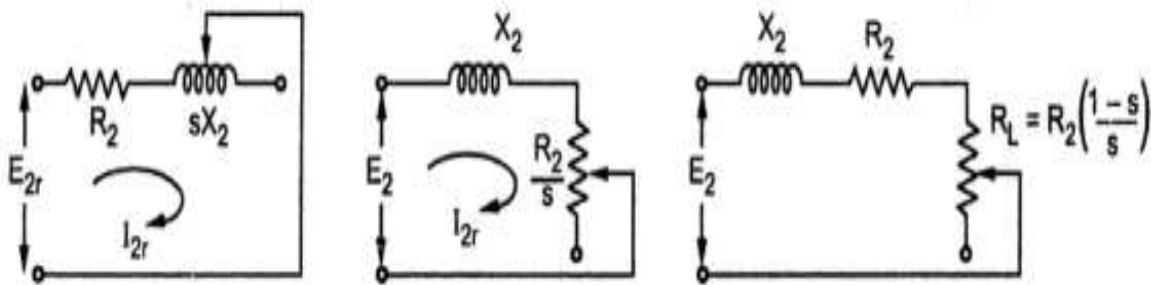


Figure 2-2 Rotor equivalent circuit of a three phase IM per phase [22]

The equivalent circuit 2.1 can be redrawn by referring rotor circuit to the stator circuit called equivalent circuit referred to stator. The two circuits (stator and rotor) of Fig. 2.1 can be replaced with one circuit as shown in Fig. 2.3.

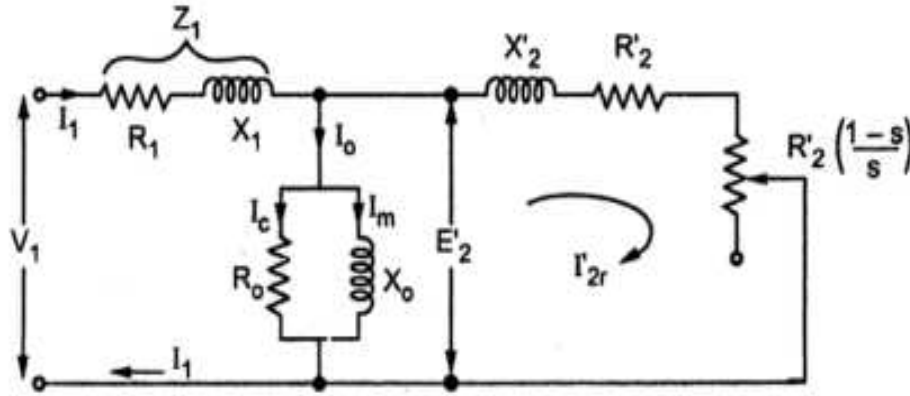


Figure 2-3 Equivalent circuit of a three phase IM per phase referred to stator [22]

Where [22],

X'_2 is rotor reactance referred to stator (the rotor is in standstill).

E'_2 is rotor induced emf referred to stator (the rotor is in standstill).

I'_{2r} is rotor phase current referred to stator (under running conditions).

R'_2 is rotor winding resistance referred to stator.

2.2 Losses in Three Phase Induction Motors

Three phase IMs losses are categorized as constant and variable losses. Constant losses are categorized as core losses and mechanical losses [9]. Core losses create in rotor and stator core which are called iron losses which represent hysteresis losses and eddy current losses [9]. These iron losses can be minimized by specific materials mentioned in Chapter one. Iron losses depend on frequency. In running conditions, the rotor frequency is very small compared to the stator frequency. Thus, iron losses in the rotor are ignored [9]. The mechanical losses comprise frictional losses of bearings and windage losses. Variable losses also called copper losses occur in rotor and

stator coils due to current flowing in the motor coils. When motor speed changes, the slip and motor current change. As the motor current varies, the copper losses in the stator and rotor change. That is why copper losses are called variable losses [9].

2.3 Power Stages in Three Phase Induction Motors

In three phase IMs, we have input power which is electrical power, power losses in rotor and stator cores and windings and output power which is mechanical power. The power flow in a three phase IM is shown in Fig. 2.4.

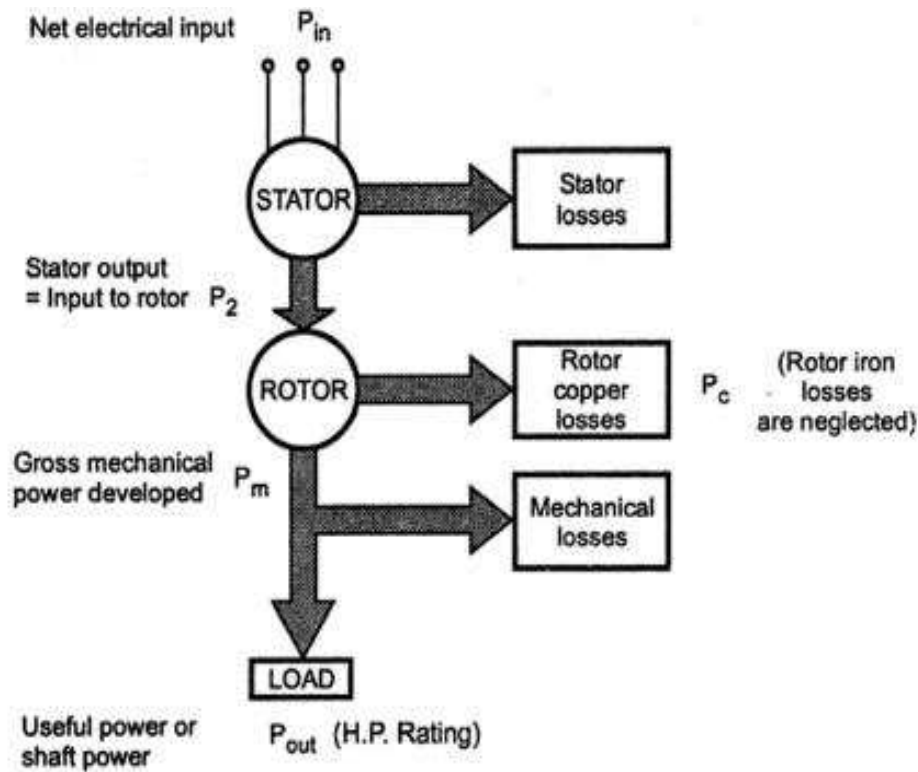


Figure 2-4 Power flow diagram of a three phase IM [9]

The input power of three phase IM is given by the following equation,

$$P_{in} = 3I_1V_1\cos(\theta_{Z_{Total}}) \quad (2.5)$$

Part of the input power is dissipated in the stator winding resistance R_1 , which represents stator copper losses (P_s) and is given by,

$$P_S = 3I_1^2 R_1 \quad (2.6)$$

Another part of the input power is dissipated in the stator core because of the eddy currents and hysteresis losses, called core or iron losses (P_{iron}) which is represented by R_0 in the equivalent circuit 2.3 and is given by,

$$P_{\text{iron}} = \frac{3(E_2')^2}{R_0} \quad (2.7)$$

The remaining part of the input power passes the air gap to the rotor and is given by,

$$P_2 = 3(I_{2r}')^2 \frac{R_2'}{s} \quad (2.8)$$

Part of P_2 is dissipated in the rotor windings resistance, called rotor copper losses (P_R) and is given as follows:

$$P_R = 3(I_{2r}')^2 R_2' \quad (2.9)$$

The remaining part of P_2 transforms into mechanical power (P_m) and is given by,

$$P_m = P_2 - P_{CR} \quad (2.10)$$

or

$$P_m = 3(I_{2r}')^2 \frac{R_2'}{s} (1 - s) \quad (2.11)$$

Part of P_m , will be lost because of the mechanical losses. The remaining part is then called output power (P_{out}) and is given by,

$$P_{\text{out}} = P_m - P_{\text{friction}} \quad (2.12)$$

The three phase IM efficiency is defined as the ratio of output power P_{out} and input power P_{in} and it is given by,

$$\% \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \quad (2.13)$$

2.4 Torque in Three Phase Induction Motors

The produced torque by three phase IMs depends upon three aspects which are rotor current magnitude, flux per stator pole, and the rotor power factor as follows [6]:

$$T \propto I_{2r} \Phi \cos(\Theta_{Z_{2r}}) \quad (2.14)$$

Where [6],

T is the torque produced by three phase IM

Φ is flux per stator pole

$\cos(\Theta_{Z_{2r}})$ is the rotor power factor

Flux per stator pole is proportional to the stator voltage and rotor induced emf on standstill as follows [6]:

$$\Phi \propto V_1 \text{ \& } \Phi \propto E_2 \quad (2.15)$$

The motor torque is then,

$$T \propto I_{2r} E_2 \cos(\Theta_{Z_{2r}}) \quad (2.16)$$

$$T = K I_{2r} E_2 \cos(\Theta_{Z_{2r}}) \quad (2.17)$$

$$K = \frac{3}{2\pi n_s} \quad (2.18)$$

n_s is the synchronous speed of rotating magnetic field of the stator in revolution per second

The current and power factor of the rotor in running conditions are given by,

$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \quad (2.19)$$

$$\cos(\Theta_{Z_{2r}}) = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}} \quad (2.20)$$

By substituting the equations 2.19 and 2.20 in 2.17, the motor torque equation is then,

$$T = \left(\frac{3}{2\pi n_s}\right) \left(\frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}\right) \text{ N-m} \quad (2.21)$$

2.4.1 Starting Torque of Three Phase Induction Motors

The starting torque occurs when the rotor is on standstill. Referring to equation 2.21, the motor slip is equal to one at starting. The starting torque equation is then presented by,

$$T_{st} = \left(\frac{3}{2\pi n_s}\right) \left(\frac{E_2^2 R_2}{R_2^2 + (X_2)^2}\right) \text{ N-m} \quad (2.22)$$

2.4.2 Maximum Torque of Three Phase Induction Motors under Running Conditions

The three phase IM torque under running conditions is presented in the equation 2.21. The condition for maximum torque is obtained by taking the differentiation of equation 2.21 with respect to the motor slip and then equating to zero as follows [6]:

$$\frac{dT}{dS} \left(\left(\frac{3}{2\pi n_s}\right) \left(\frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}\right) \right) = 0 \quad \& \quad K = \frac{3}{2\pi n_s} \quad (2.23)$$

$$\frac{(R_2^2 + S^2 X_2^2)(kE_2^2 R_2) - (KSE_2^2 R_2)(2SX_2^2)}{(R_2^2 + (X_2)^2)^2} = 0 \quad (2.24)$$

$$KR_2^3 E_2^2 + KS^2 X_2^2 E_2^2 R_2 = 2KS^2 X_2^2 E_2^2 R_2 \quad (2.25)$$

$$R_2^2 = S^2 X_2^2 \quad (2.26)$$

$$R_2 = SX_2 \quad (2.27)$$

Hence, the motor under running conditions has maximum torque when rotor reactance in running conditions is equal to rotor winding resistance as shown in equation 2.27. By substituting the equation 2.27 in 2.21, the maximum motor torque is then,

$$T_{max} = \left(\frac{3}{2\pi n_s}\right) \left(\frac{S^2 X_2 E_2^2}{S^2 X_2^2 + S^2 X_2^2}\right) = \left(\frac{3}{2\pi n_s}\right) \left(\frac{E_2^2}{2X_2}\right) \text{ N-m} \quad (2.28)$$

2.5 Three Phase Induction Motor Tests

The purpose of applying motor tests is to identify the equivalent circuit parameters of the motor. These tests include dc, no load (open circuit), and locked (short circuit) tests. In this thesis, the tests are accomplished by SIMULINK models.

2.5.1 Three Phase SCIM Specifications under this Thesis Study

Table 2.1 and 2.2 show the real equivalent circuit parameters and nameplate details of the three phase IM under this thesis study.

Table 2.1 Equivalent Circuit Parameters of Three Phase SCIM

Parameters	Symbols	Values
Stator winding resistance	R_1	3 Ω
Stator winding reactance	X_1	2.25 Ω
Magnetizing reactance	X_0	76.75 Ω
Rotor winding resistance referred to stator	R'_2	1.083 Ω
Rotor winding reactance referred to stator	X'_2	2.25 Ω

Table 2.2 Nameplate of Three Phase SCIM

Parameters	Values
Rated voltage (line to line)	460 V
Rated Current	6.4 A
Rated speed	1750 rpm
Rated output power	5 HP
Stator frequency	60 HZ
Number of poles	4
Stator windings mode	Star

2.5.2 Dc Test

The dc test is applied to identify the stator windings resistance R_1 [23]. Since each winding of the three windings of the stator has two terminals and these three windings are balanced (they

have the same number of turns), a dc voltage is applied to one of them with connecting ammeter and voltmeter, and hence R_1 is obtained as presented in equation 2.32.

$$R_1 = \frac{V_{DC}}{I_{DC}} \quad (2.32)$$

2.5.3 Blocked Rotor Test or Short Circuit Test

In this test, the rotor shaft is locked, i.e., is on standstill. The supply ac voltage is increased gradually till the current flows in the stator windings reaches its rated value [23]. This is because when the rotor is locked, and the applied voltage is at its rated value, a high current will be drawn by the motor and may burn the motor windings. When the rotor is on standstill, the slip is equal to one which means that the slip and the rotor emf are at maximum values. In this test, the applied voltage is about 10 to 15% of rated motor voltage. Therefore, the No- load current I_0 becomes very small which is neglected in this test. Since the slip equals 1, the resistance $R_2'(\frac{1-s}{s})$ in Fig 2.3 is equal to zero. This means that the equivalent circuit 2.3 is short circuited at the rotor circuit as presented in Fig 2.5. The equivalent circuit parameters R_2' , X_1 and X_2' in Fig. 2.5 can be determined by the following equations:

$$R_{Total} = R_1 + R_2' \quad (2.33)$$

$$X_{Total} = X_1 + X_2' \quad (2.34)$$

$$R_{Total} = \frac{P_{sc}}{I_1^2} \quad (2.35)$$

$$R_2' = R_{Total} - R_1 \quad (2.36)$$

$$Z_{Total} = \frac{V_1}{I_1} \quad (2.37)$$

$$X_{Total} = \sqrt{Z_{Total}^2 - R_{Total}^2} \quad (2.38)$$

$$X_1 = X'_2 = \frac{X_{\text{Total}}}{2} \quad (2.39)$$

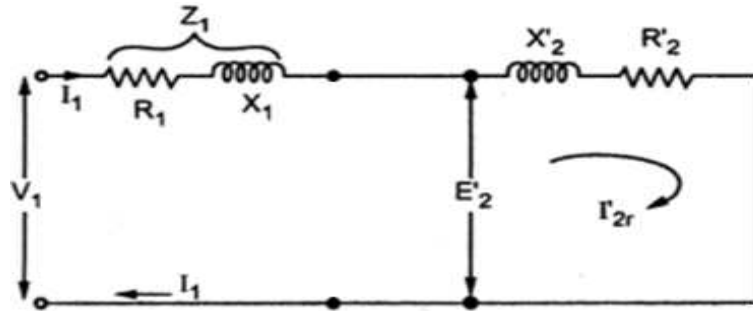


Figure 2-5 Short circuit test (equivalent circuit) [9]

2.5.4 No-Load Test (Open Circuit Test)

In this test, the motor is kept driving without any load and the applied voltage to the stator is at its rated value, i.e., its rotor speed is almost equal to the synchronous speed. This means that the motor slip is approximately equal to zero. The resistance $R'_2(\frac{1-s}{s})$ in Fig 2.3 becomes infinity, hence the rotor current referred to stator is equal to zero. The equivalent circuit then becomes an open circuit at the rotor circuit as shown in Fig. 2.6. The equivalent circuit parameters R_0 and X_0 in Fig 2.6 can be determined by the following equations:

$$\cos(\theta_1) = \frac{P_{o.c}}{V_1 I_1} \quad (2.40)$$

$$I_C = I_1 \cos(\theta_1) \quad (2.41)$$

$$I_m = I_1 \sin(\theta_1) \quad (2.42)$$

$$R_0 = \frac{V_1 - I_1 Z_1}{I_C} \quad (2.43)$$

$$X_0 = \frac{V_1 - I_1 Z_1}{I_m} \quad (2.44)$$

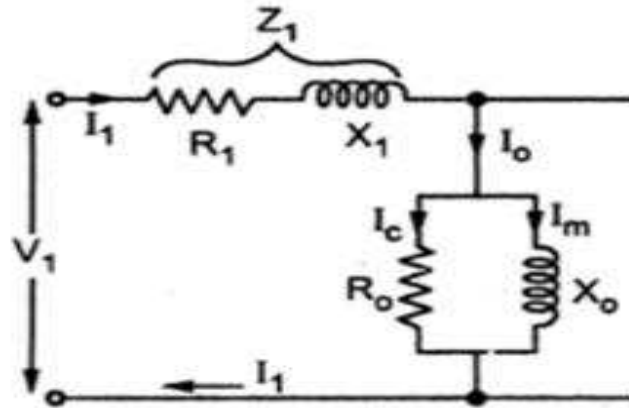


Figure 2-6 Open circuit test (equivalent circuit) [9]

2.6 Simulink Model of DC Test

The model shown in Fig. 2.7 is built to identify the stator winding resistance R_1 of a three phase SCIM. The motor in this model is connected as star mode. A dc voltage source is applied to two phases of the motor (phases A and B) or (phases A and C). The resistance R_1 can then be obtained by the following equation:

$$R_{1(A)} + R_{1(C)} = \frac{V_{dc}}{I_{dc}} \quad (2.45)$$

$$R_{1(A)} = R_{1(B)} = R_{1(C)} = R_1 \quad (2.46)$$

$$R_{1(A)} = 0.5 \frac{V_{dc}}{I_{dc}} = R_1 \quad (2.47)$$

In this model, blocks are used to measure the current, voltage, and resistance values. The dc voltage applied to the two phases is adjusted to a specific value at which the current flowing through the two phases reaches its rated value.

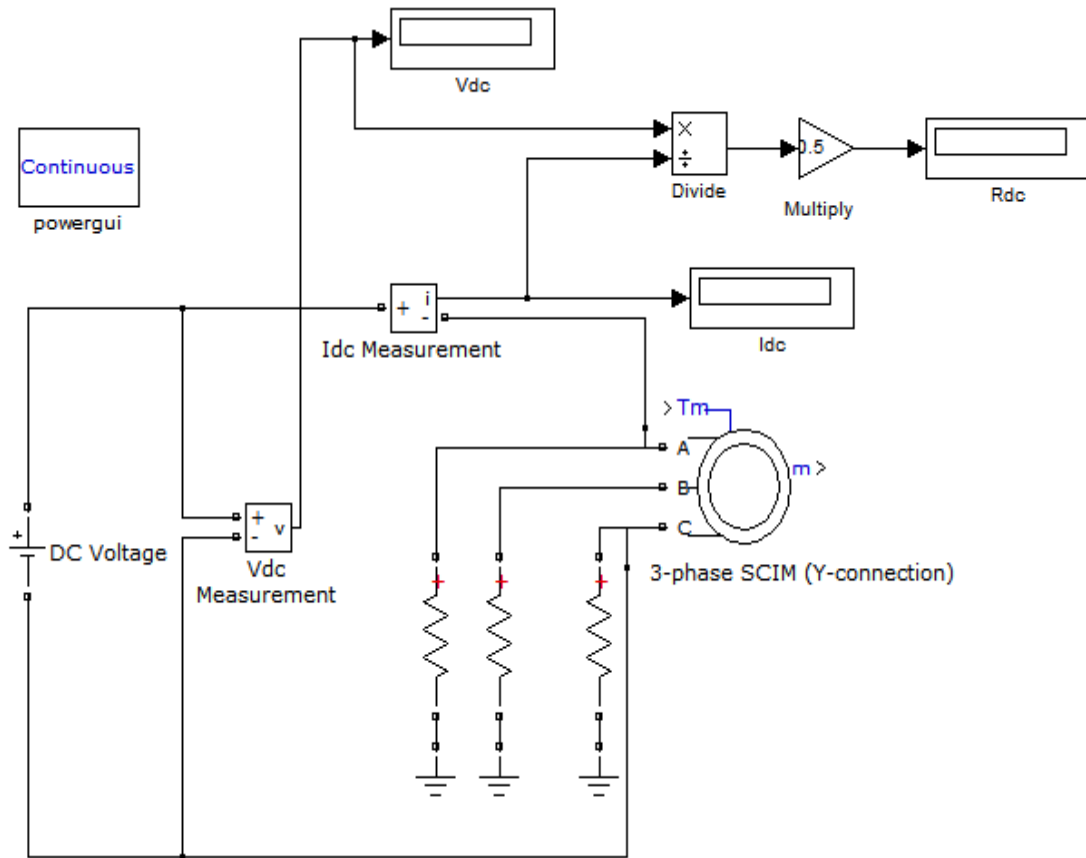


Figure 2-7 Simulink model for Dc test

2.7 Simulink Model of Blocked Rotor Test (Short Circuit Test)

The model shown in Fig. 2.8 is built to determine the rotor winding resistance referred to stator R'_2 , the stator reactance X_1 , and the rotor reactance referred to stator X'_2 of a three phase SCIM. The applied three phase balanced ac voltage to the stator terminals is adjusted to a certain value at which the motor draws its rated current. In this model, the inertia of the motor is set to a high value in order to drive the motor at approximately zero speed. Several blocks are used in the model to measure motor current, voltage, input power, rotor speed and others.

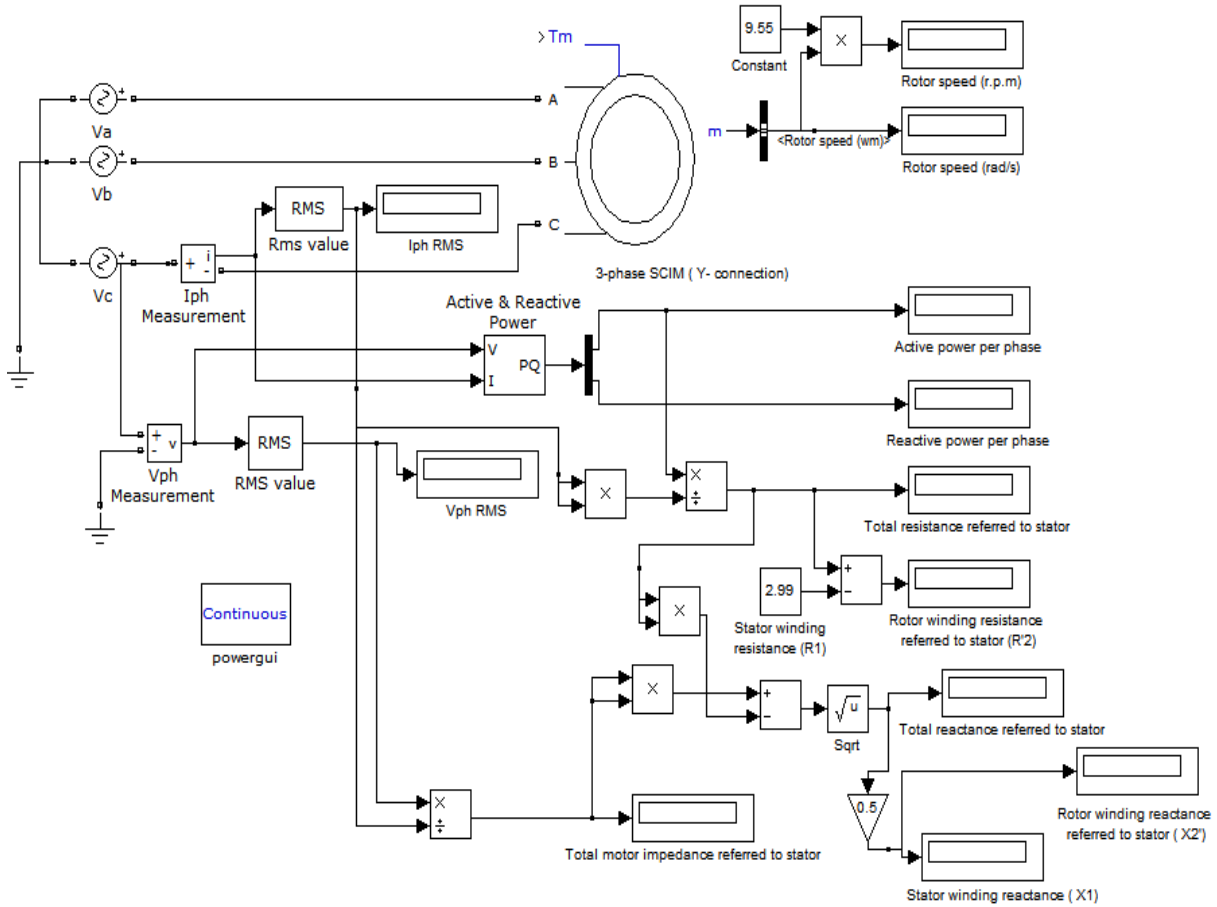


Figure 2-8 Simulink model for blocked rotor test

2.8 Simulink Model of No Load Test (Open Circuit Test)

Fig. 2.9 presents the Simulink model of No-load test. The Core losses resistance R_0 is neglected because of its high value, thus in this test, only the magnetizing reactance X_0 is determined as follows:

$$Z_{\text{Total}} = \frac{V_1}{I_1} \quad (2.48)$$

$$X_{\text{Total}} = X'_1 + X_0 = \sqrt{Z_{\text{Total}}^2 - R_1^2} \quad (2.49)$$

$$X_0 = \sqrt{Z_{\text{Total}}^2 - R_1^2} - X'_1 \quad (2.50)$$

This model is similar to that of short circuit test with the exception that the torque block in the model (T_m) is set to a very small value in order to simulate the motor at a rotor speed that is approximately equal to synchronous speed.

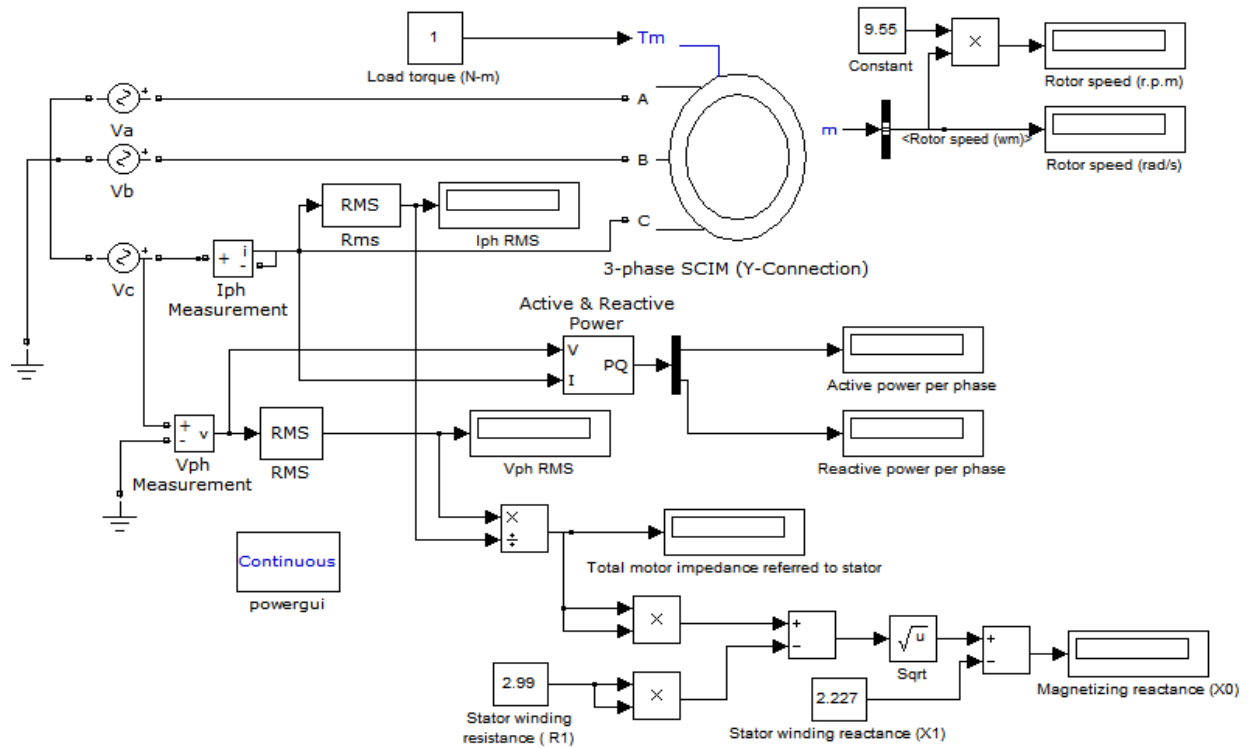


Figure 2-9 Simulink model for No load test

CHAPTER 3
STUDY THE EFFECT OF REDUCING STATOR VOLTAGE ON MOTOR
CHARACTERISTICS

3.1 Introduction

Since the proposed method of this thesis depends on varying the applied voltage to the motor to maximize its efficiency when the motor runs at speeds greater than the speed at which the efficiency is maximum during normal operation (rated voltage), it is important to study the effect of voltage change on motor characteristics. In this chapter, the curves of motor characteristics are obtained based on the mathematical representation and equivalent circuit parameters of the three phase IM explained in chapter 2.

3.2 Variation of Three Phase SCIM Characteristics with Rotor Speed

Fig. 3.1 shows the relationship between produced torque and rotor speed. From this figure, it can be seen that when the motor operates at light load, i.e., the rotor speed approximately equals to the synchronous speed, the produced torque becomes smaller because of the decrease in the rotor emf and current. As rotor speed decreases, i.e., increasing the load on motor, the motor torque increases till reaches its maximum value (T_{max}), where in this case, the motor operates in the stable region. Beyond the point of T_{max} , the motor will start operating in the unstable region where the load torque is always greater than motor torque. Thus, the motor starts slowing down and stops at a point at which the torque is called starting torque (T_{st}). At starting, the motor torque decreases if the applied voltage decreases. Therefore, it is important to consider the value of the applied voltage to ensure that the starting torque is able to accelerate the load. At starting, the stator windings are preferred to be connected as star connection in order to reduce starting current where the voltage

across each winding is reduced by a factor of $1/\sqrt{3}$. The motor torque will also decrease, hence, the load on the motor must not be greater than starting torque of star connection. Delta connection is then applied when the motor runs in the normal operation. During operation region, decreasing the applied voltage results in a decrease in motor torque and the motor decelerates until a point at which the load torque is equal to the motor torque and the motor runs at a constant speed. When we increase the voltage, the motor torque increases and the motor accelerates until a point at which the load torque equals motor torque where the motor runs at a new constant speed.

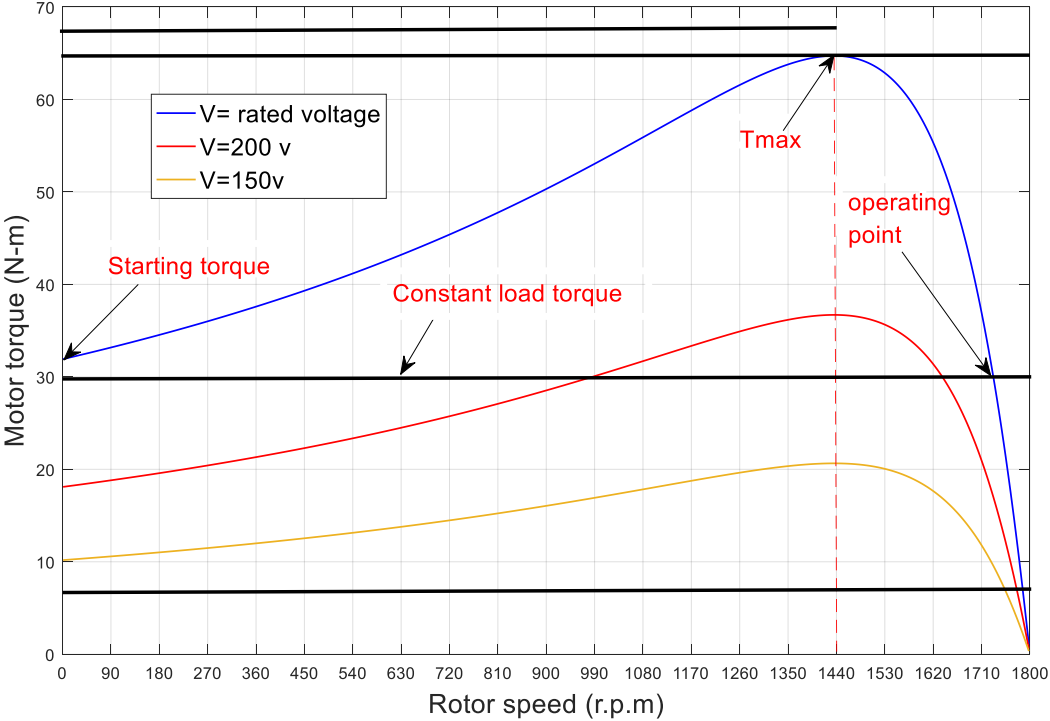


Figure 3-1 Speed-torque curve

Fig. 3.2 shows the relationship between stator phase current and rotor speed. The stator current is inversely proportional to the rotor speed in both regions stable region BC and unstable region AB. The stator current reaches its maximum value at starting (slip equals unity). As the rotor speed increases, the rotor current decreases until becomes nearly zero. Therefore, the stator current is approximately equal to no- load current. Fig. 3.3 shows the relationship between rotor

current referred to stator and rotor speed. It can be seen that it is similar to stator current-speed curve, i.e., rotor current decreases when increasing speed. At the same speed, the motor currents decrease when reducing the stator voltage.

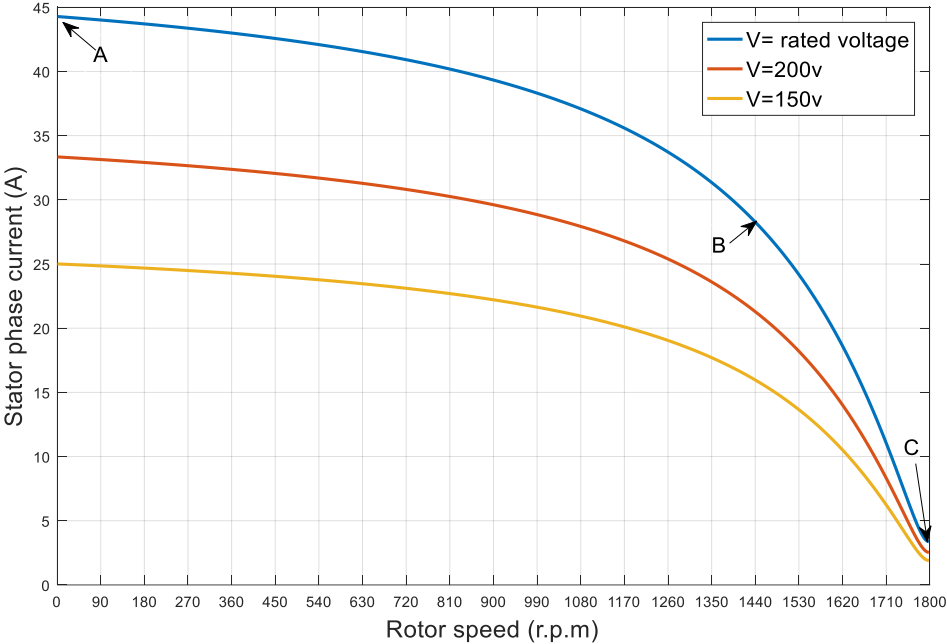


Figure 3-2 Stator current-speed curve

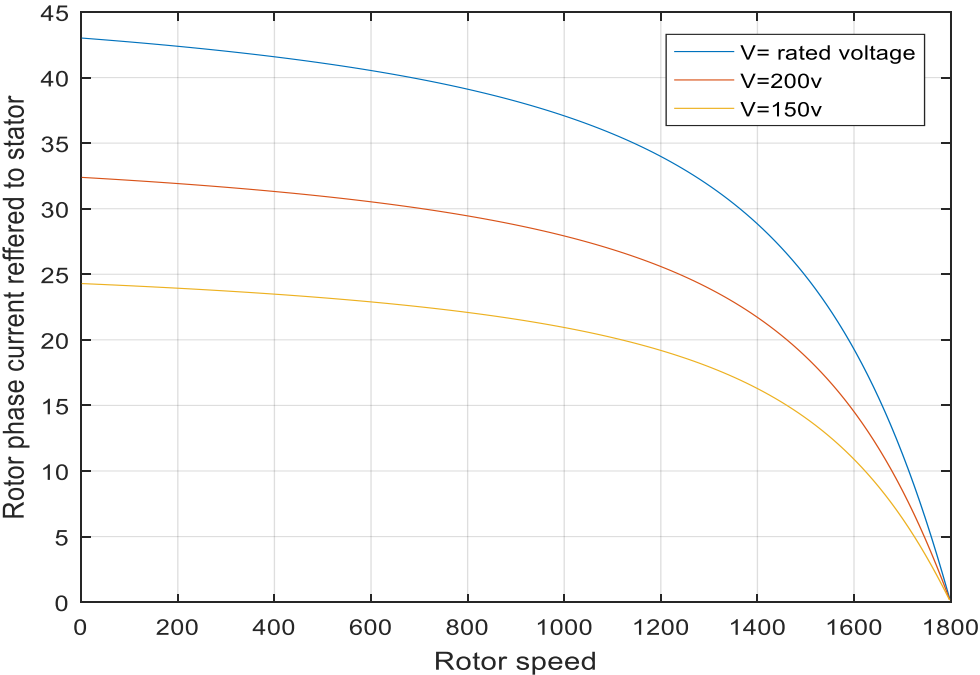


Figure 3-3 Rotor current referred to stator-speed curve

Fig. 3.4 shows the variation of magnetizing current with rotor speed. As the load of the motor increases, the rotor speed decreases and the voltage drop of stator impedance increases. Thus, the magnetizing current decreases. At light loads, the voltage drop of stator impedance decreases. Hence, magnetizing current increases. The decrease and the increase in magnetizing current is small. Therefore, we can assume that the magnetizing current is independent of rotor speed, i.e., it is constant at any rotor speed.

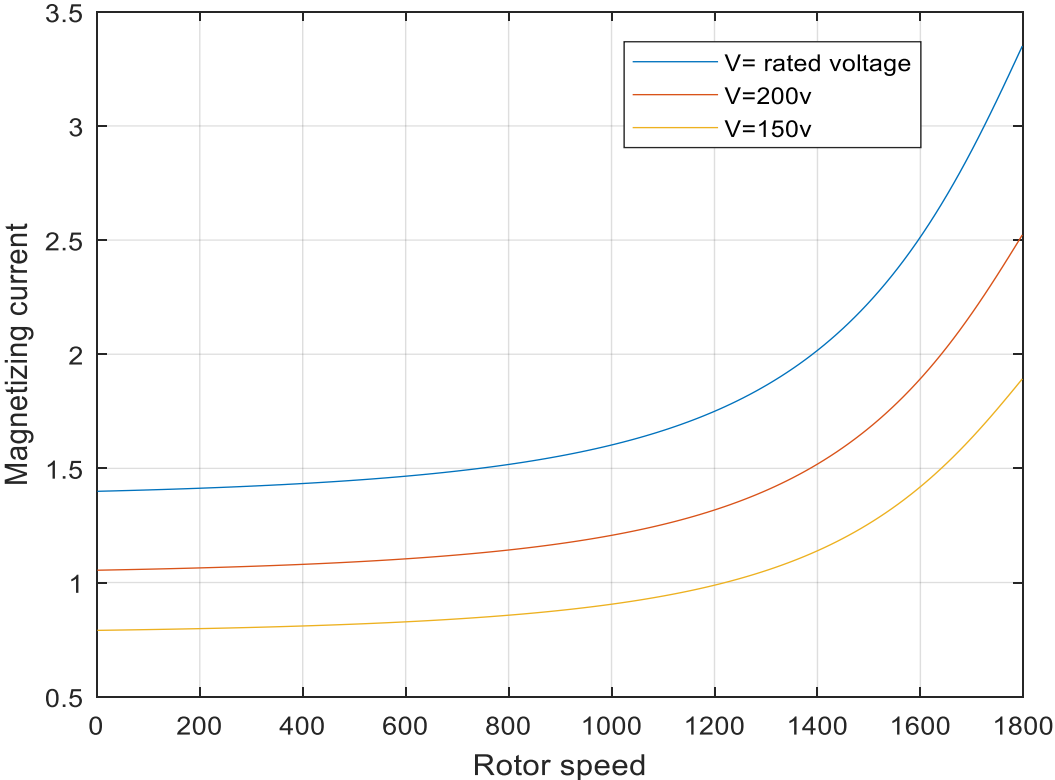


Figure 3-4 Magnetizing current-rotor speed

Fig. 3.5 and Fig. 3.6 show the variations of reactive power and apparent power with rotor speed. These characteristics are a function of stator current. Therefore, in stable region BC and unstable region AB, they decrease when rotor speed increases as the stator current decreases. At the same speed, these characteristics decrease if applied voltage reduces.

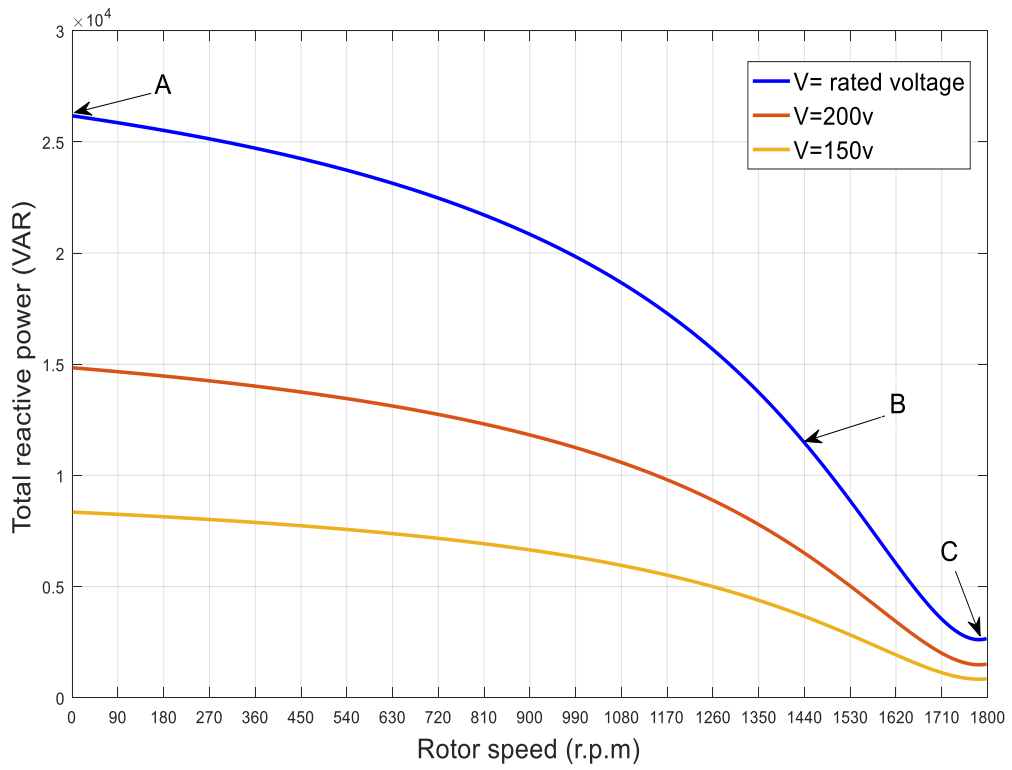


Figure 3-5 Reactive power-speed curve

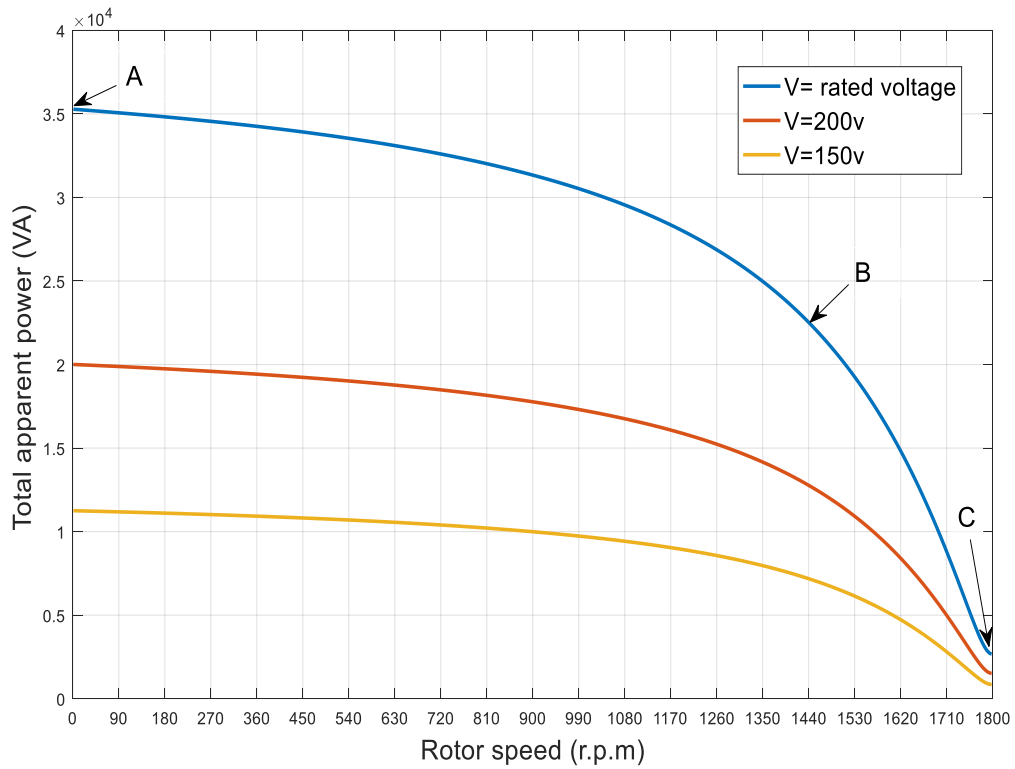


Figure 3-6 Apparent power-speed curve

The variation of motor efficiency and power factor with rotor speed is shown in Fig. 3.7 and Fig. 3.8, respectively. Power factor is poor when the motor operates at light loads. This is due to the fact that the circuit is highly inductive, i.e., the reactive power is very high compared to input power at light loads. As mechanical load increases, the slip increases, thus power factor improves. The motor efficiency is low when the motor runs at light loads. The motor runs at maximum efficiency when constant losses are equal to variable losses. Beyond the point of maximum efficiency, any increase in load results in an increase in power losses, hence the efficiency decreases. This decrease of efficiency continues during the unstable region AB until the efficiency becomes zero because of zero output power.

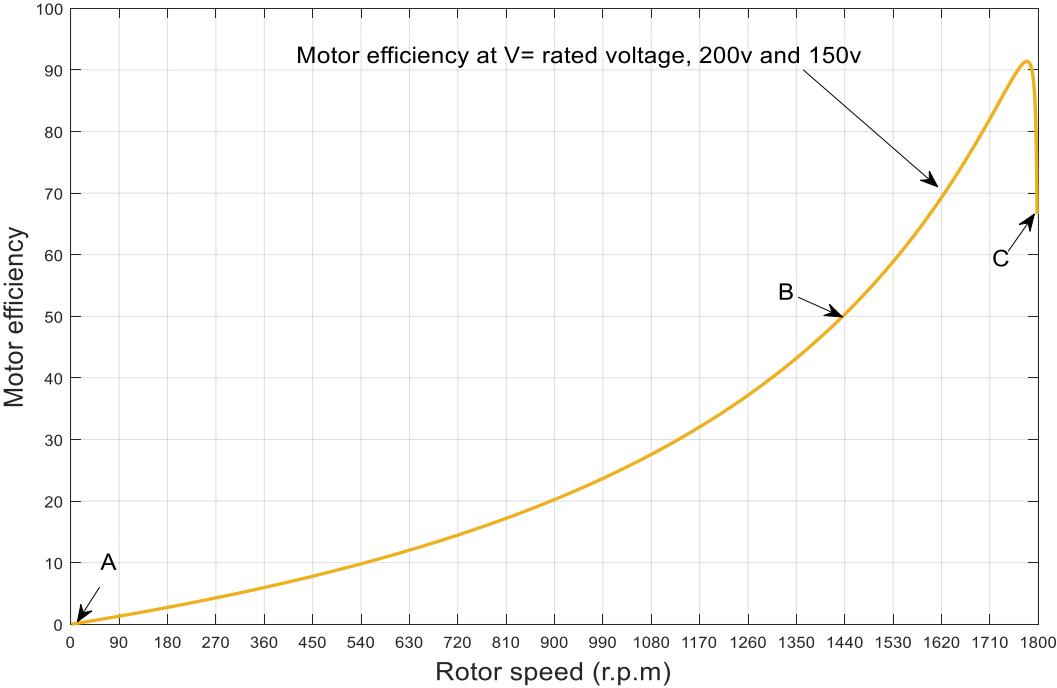


Figure 3-7 Efficiency-speed curve

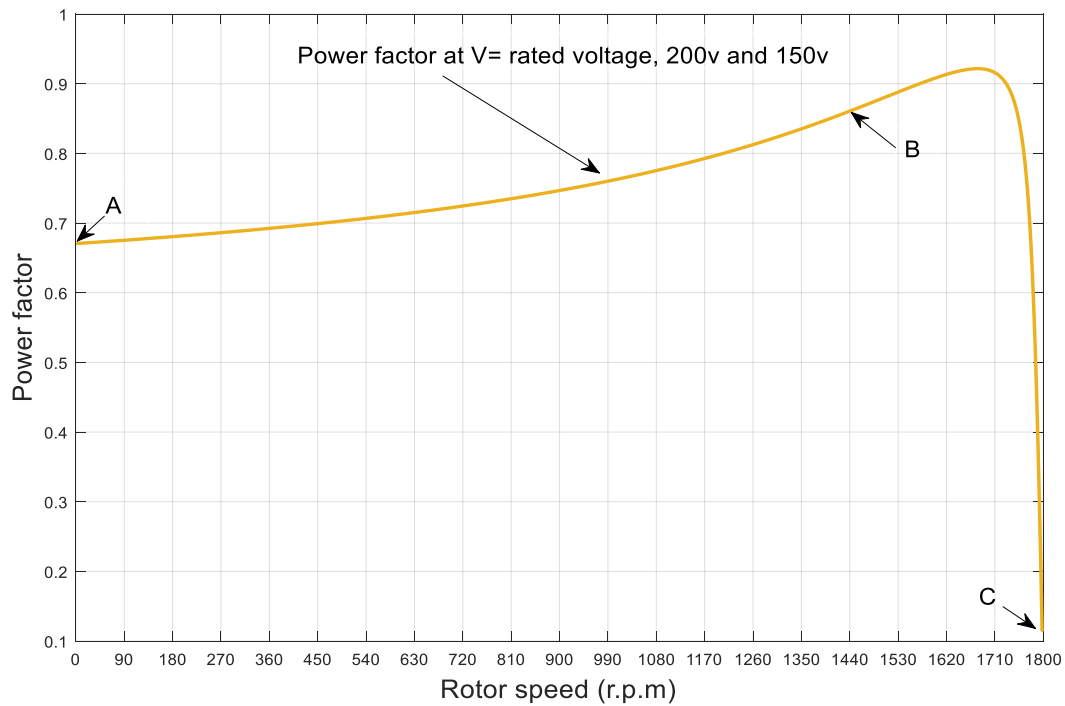


Figure 3-8 Power factor-speed curve

Fig. 3.9 shows the relationship between output power and rotor speed. In stable region BC, as the load on motor increases, the motor torque increases more than the reduction in rotor speed, thus output power increases until reaches its maximum value. Beyond the point of maximum output power, any decrease in motor load results in a decrease in output power. This decrease of output power continues during the unstable region AB as well. The output power equals zero when motor is in standstill because of zero speed. In addition, the output power almost becomes zero due do the low torque at high rotor speeds. When motor is operated at the same speed, the output power decreases with decreasing the applied voltage.

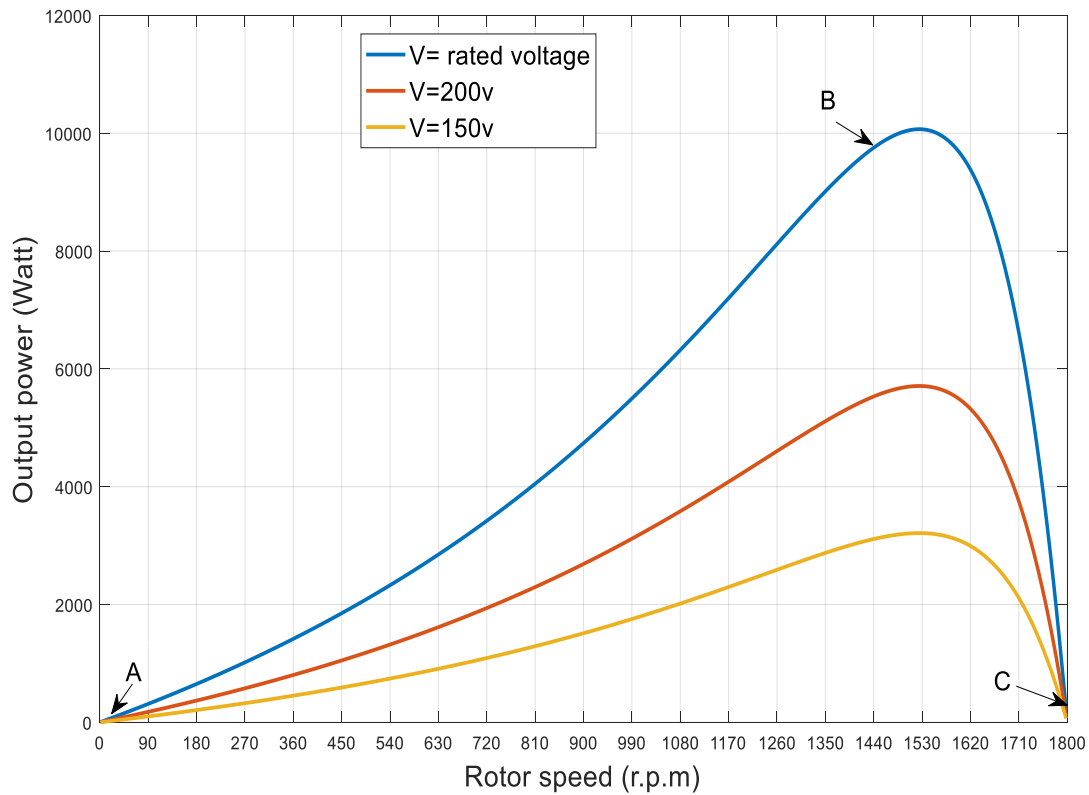


Figure 3-9 Output power-speed curve

Fig. 3.10, Fig. 3.11, Fig. 3.12, and Fig. 3.13 show the variation of stator phase current, reactive power, and apparent power and magnetizing current with motor torque. A direct correlation is in the stable region BC where these characteristics increase with increasing motor torque as load on motor increases. An inverse relationship occurs in the unstable region AB, where these characteristics increase when motor torque decreases as speed decreases.

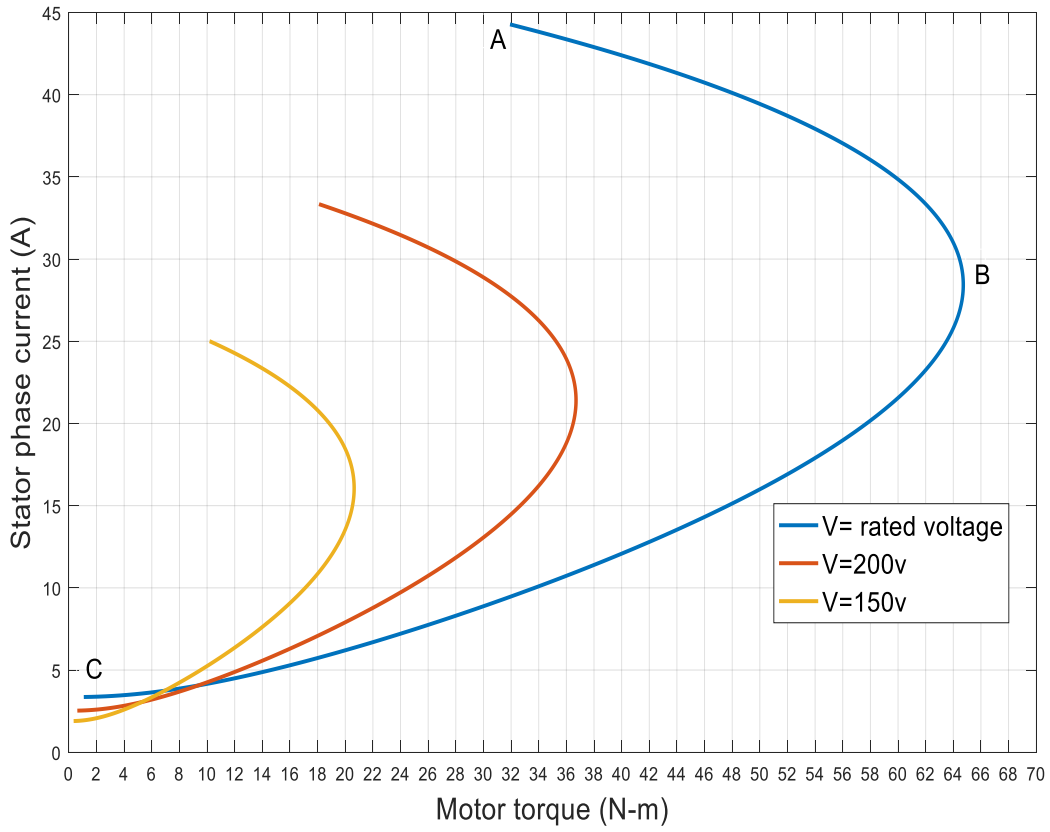


Figure 3-10 Stator current-torque curve

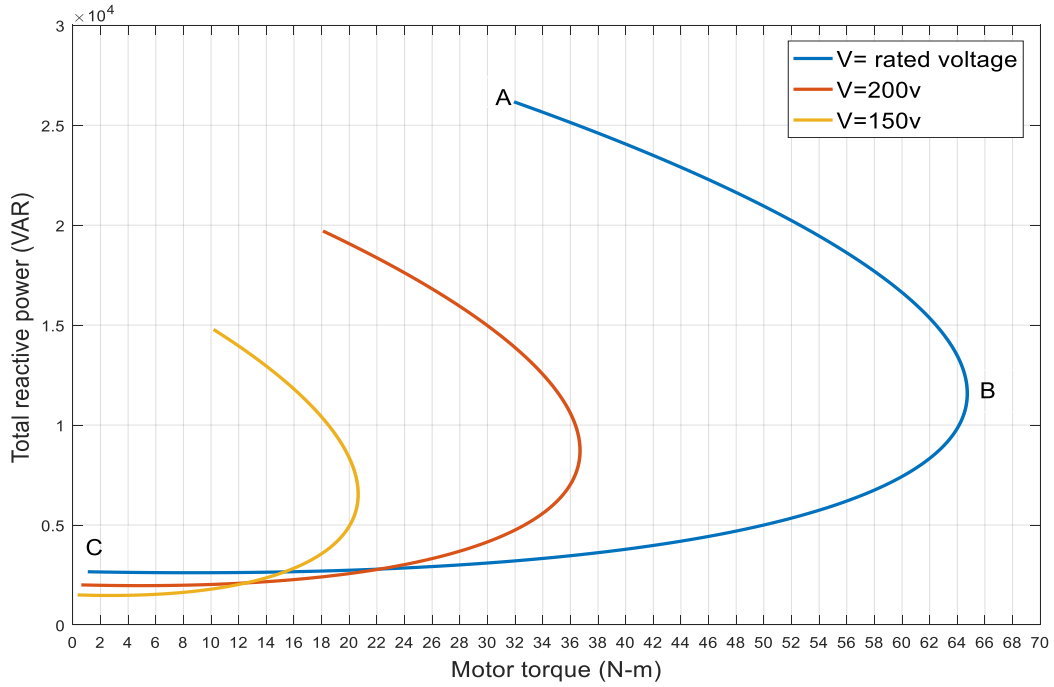


Figure 3-11 Reactive power-torque curve

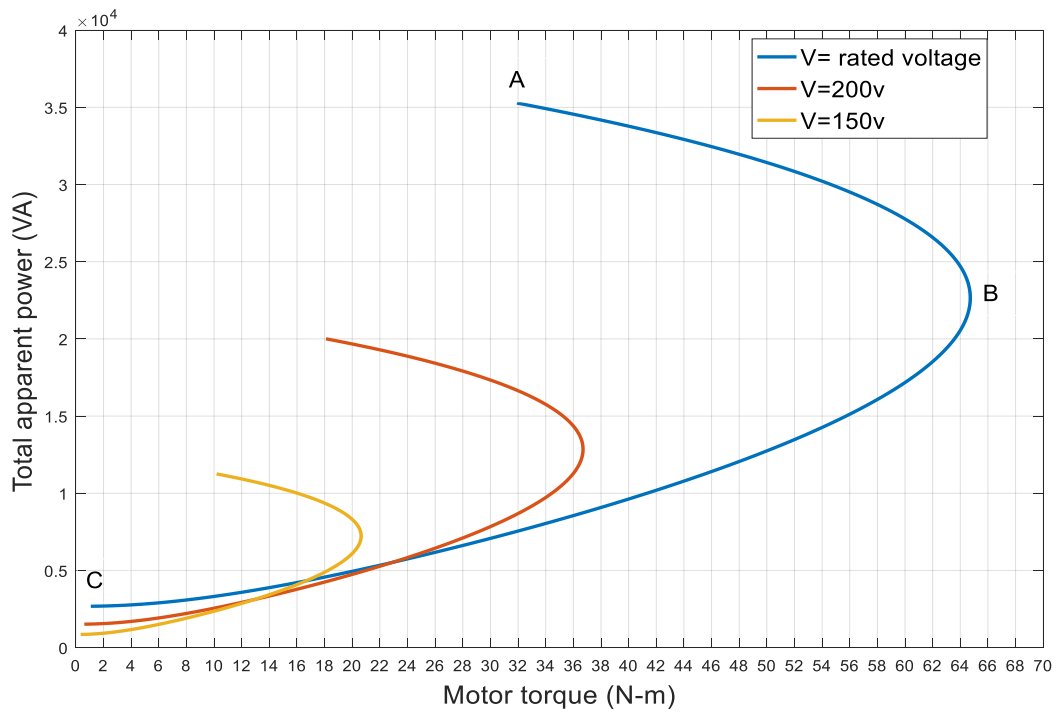


Figure 3-12 Apparent power-torque curve

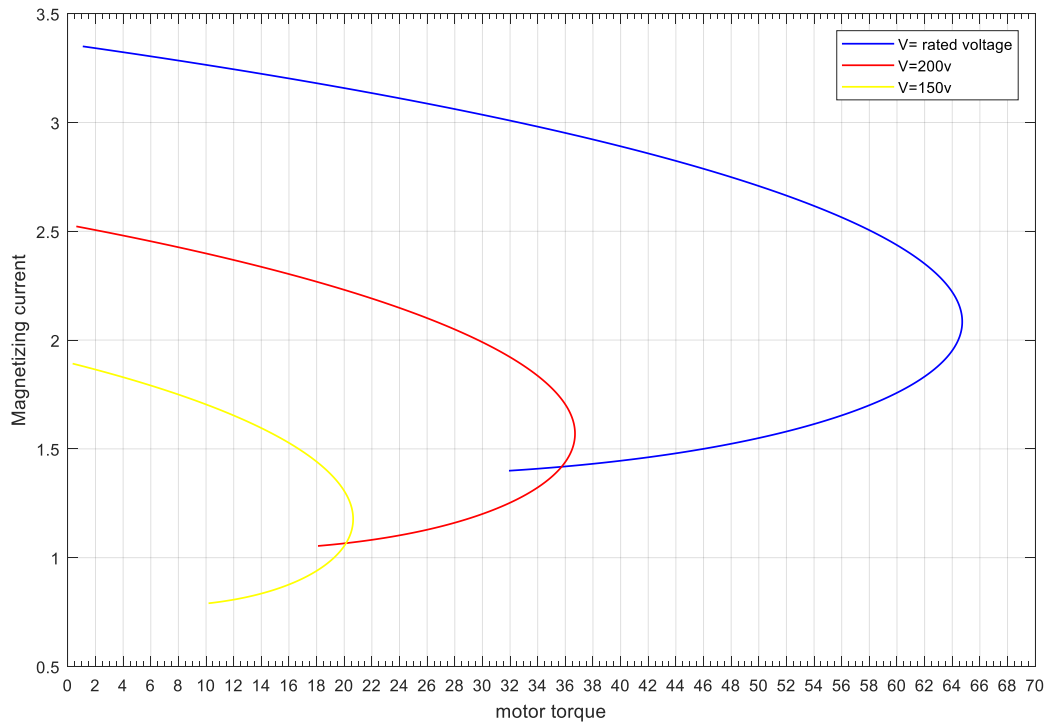


Figure 3-13 Magnetizing current-torque curve

3.3 Simulink Model of Variation of Motor Characteristics with Slip

The Simulink model shown in Fig. 3.14 is built to show the variation of motor characteristics with slip in stable region with taking the rated current of the motor into consideration.

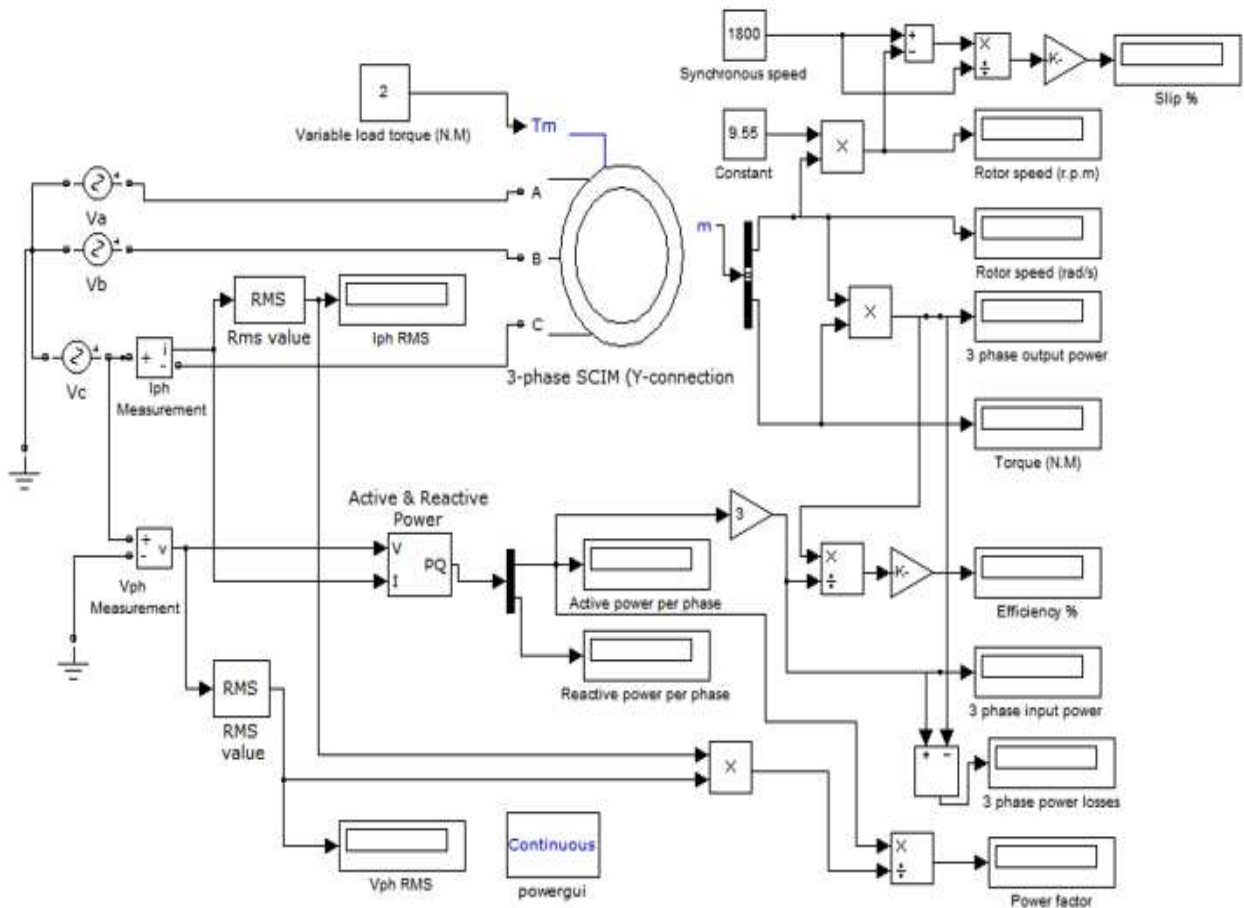


Figure 3-14 Simulink model of variation of motor characteristics with slip

3.4 Simulink Model of Three Phase Induction Motor under Different Loads

The Simulink model shown in Fig. 3.15 is built to make a comparison between normal operation and the proposed method of a three phase SCIM. The model consists of a three phase SCIM whose stator winding are connected as Y connection. A dc generator (separately excited dc generator) is used as load to the motor where its rotor shaft is directly connected with the rotor of dc generator. In Simulink, a negative torque signal indicates that a DC or AC machine operates

as a generator, and a positive torque signal indicates that the machine runs as a motor. Hence, in our model, the applied load torque to the motor must be positive, i.e., 1 multiplies the torque of the dc generator. The dc generator is loaded by variable resistive load. In normal operation, the applied voltage to the motor is set to its rated value and the load on the motor is changed at different values by varying the resistive load. In proposed method, the applied voltage to the motor is changed to operate the motor with maximum efficiency when the motor runs at speeds that are greater than the speed at which the efficiency is maximum during normal operation (rated voltage). Several blocks are used in the model to measure, current, voltage, active and reactive power, efficiency, power factor, output power, apparent power, rotor speed and others.

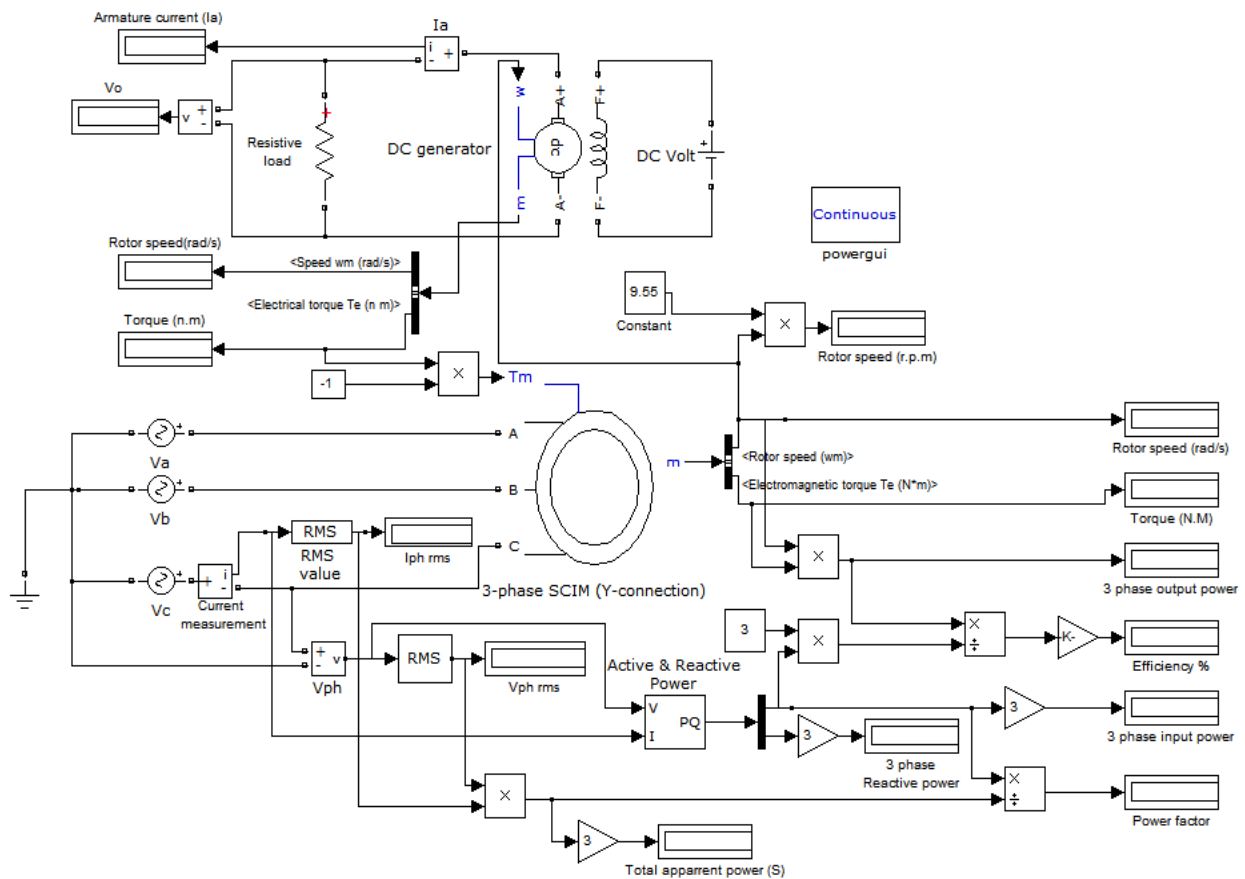


Figure 3-15 Simulink Model of Three Phase SCIM under Different Load

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

4.1 Simulation Result of DC Test

The block diagram of Simulink model of DC test after simulation is shown in Fig. 4.1. The stator winding resistance R_1 after running the model is 2.99Ω . The actual value of R_1 as presented in table 2.1 is 3Ω .

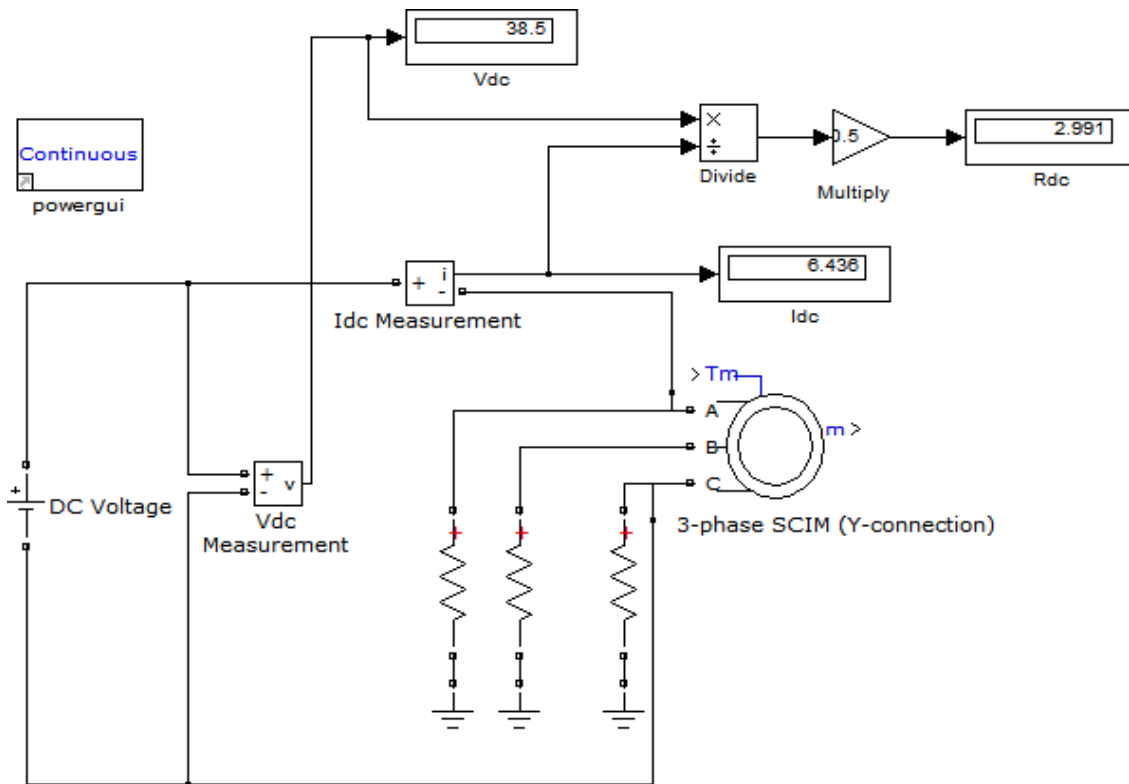


Figure 4-1 Simulation result of dc test

4.2 Simulation Result of Blocked Rotor Test

The block diagram of Simulink model of blocked rotor test (short circuit test) after simulation is presented in Fig .4.2. The value of the rotor winding resistance referred to the stator R'_2 , the stator reactance X_1 , and the rotor reactance referred to stator X'_2 after simulation are 1.08

Ω , 2.227Ω and 2.227Ω , respectively. The actual values of R'_2 , X_1 and X'_2 as mentioned in table 2.1 are 1.083Ω , 2.25Ω and 2.25Ω respectively.

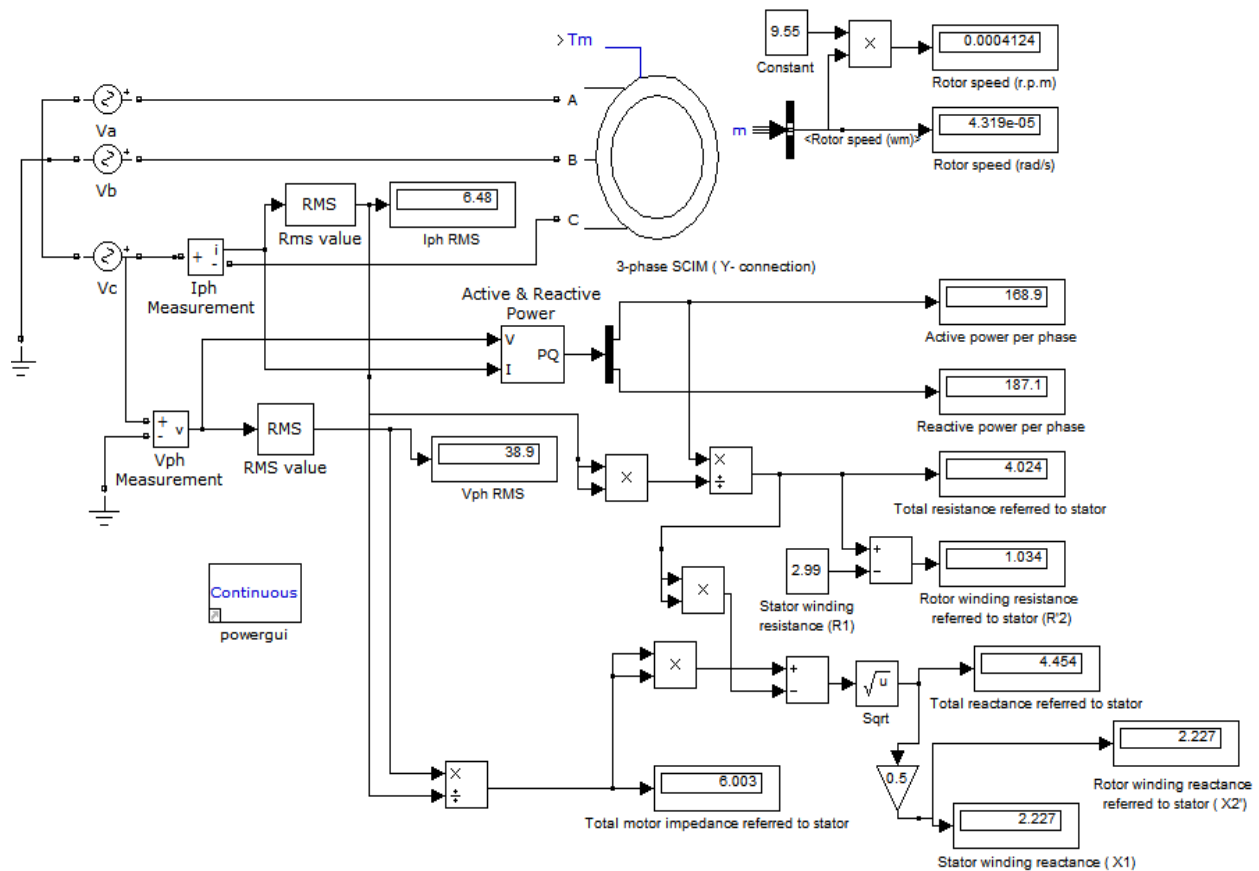


Figure 4-2 Simulation result of blocked test

4.3 Simulation Result of No-Load Test

Fig .4.3 shows the simulation result of Simulink model of No-load test. The value of magnetizing reactance X_0 obtained after running the model is 76.8Ω . The actual value of X_0 as shown in table 2.1 is 76.75Ω .

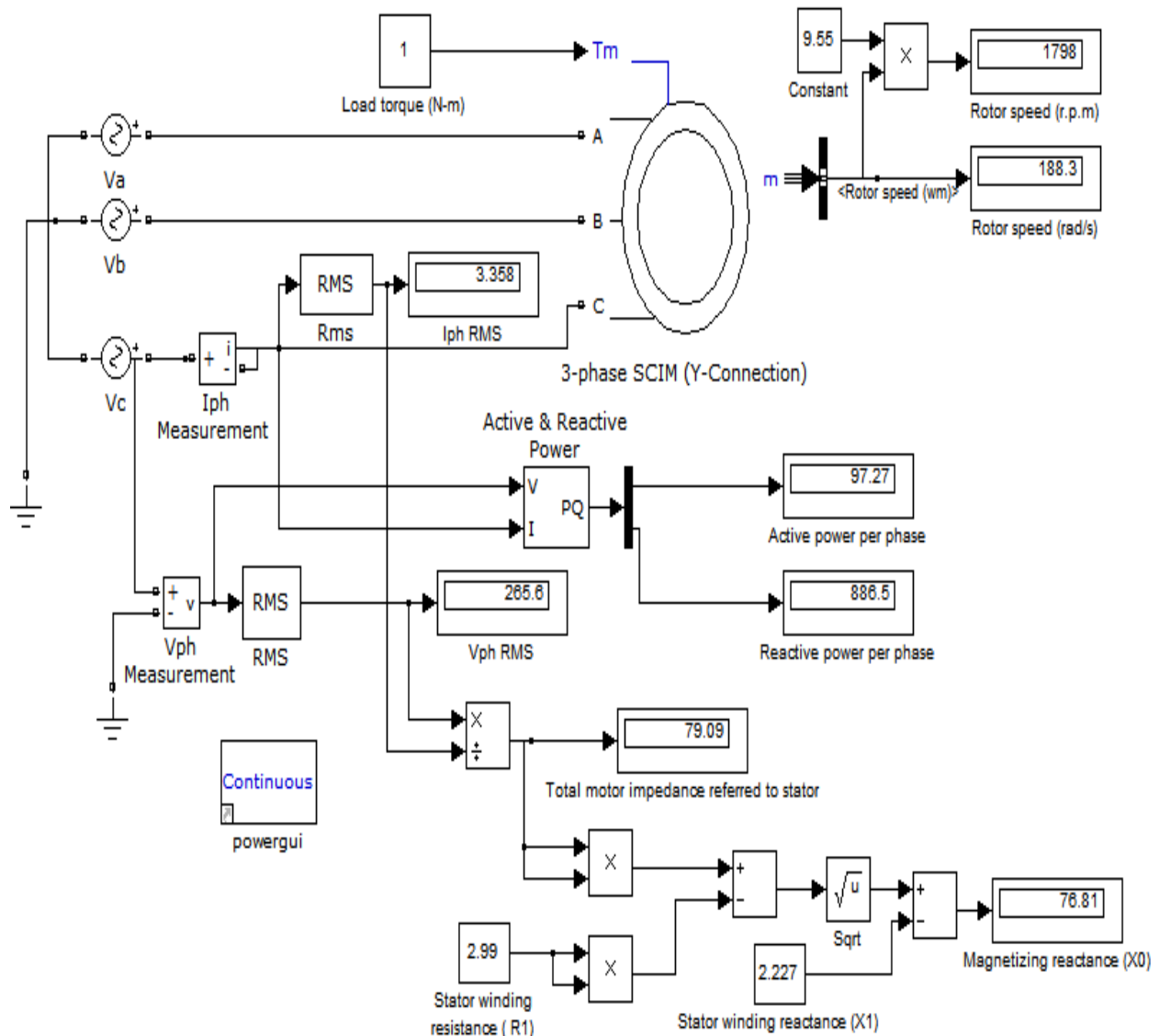


Figure 4-3 simulation result of no load test

4.4 Percentage Errors for the Equivalent Circuit Parameters.

Table 4.1 presents the equivalent circuit parameters (actual and simulated values) and the percentage error for these parameters. The percentage error formula used is given by the following equation:

$$\% \text{ Error} = (\text{actual} - \text{resultant})/\text{actual}$$

Table 4.1 Equivalent Circuit Parameters (Actual and Resultant Values)

Parameter	Actual values	Simulation results	Error
Stator winding resistance R_1	3 Ω	2.99 Ω	0.3%
Stator winding reactance X_1	2.25 Ω	2.227 Ω	1%
Magnetizing reactance X_0	76.75 Ω	76.81 Ω	0.078%
Rotor winding resistance referred to stator R'_2	1.083 Ω	1.034 Ω	4.2%
Rotor winding reactance referred to stator X'_2	2.25 Ω	2.227 Ω	1 %

Based on the comparison between actual and simulated values, we can notice that the percentage errors are small. Therefore, Simulink models of motor tests explained in chapter 2 can be used to identify the equivalent circuit parameters of three phase IM.

4.5 Simulation Result of Variation of Motor Characteristics with Slip

Figures 4 to 8 show the variation of motor characteristics with motor slip in stable region with taking the rated current of the motor into consideration. These figures are plotted based on the simulation results of Simulink model of variation of motor characteristics with slip. From figures 4 to 8, we can notice that the motor characteristics are directly proportional with the slip

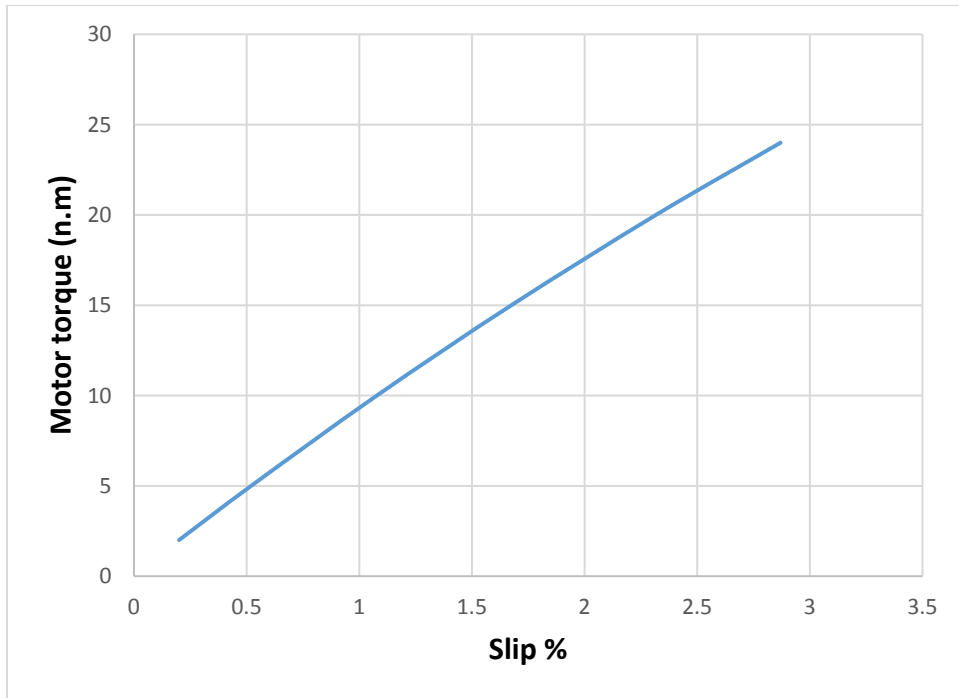


Figure 4-4 Variation of motor torque with slip (simulation result)

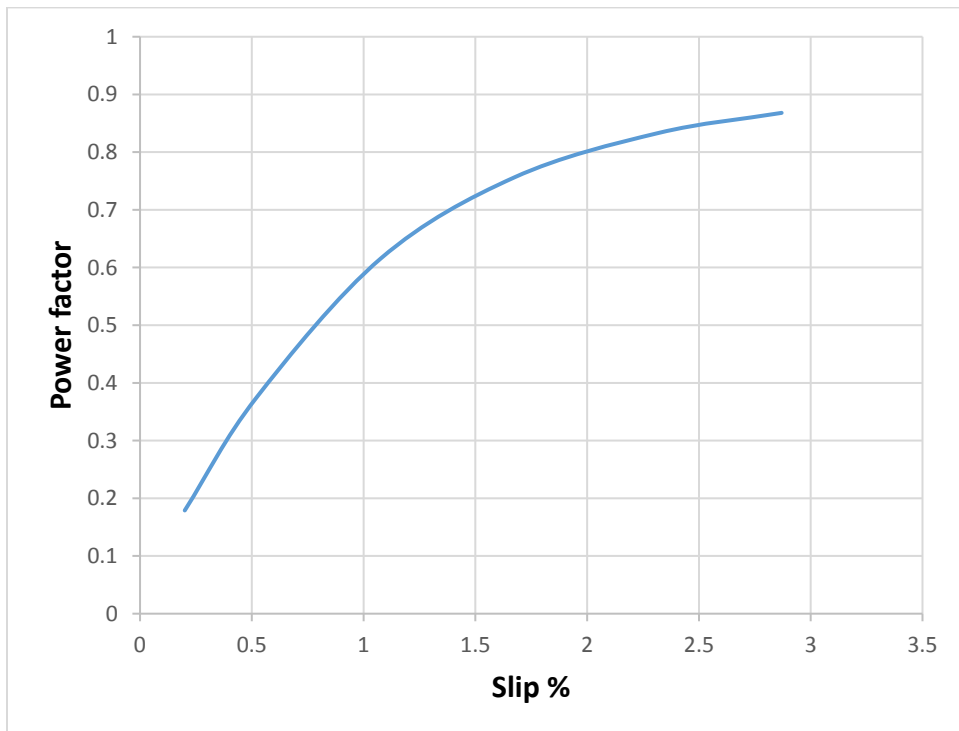


Figure 4-5 Variation of power factor with slip (simulation result)

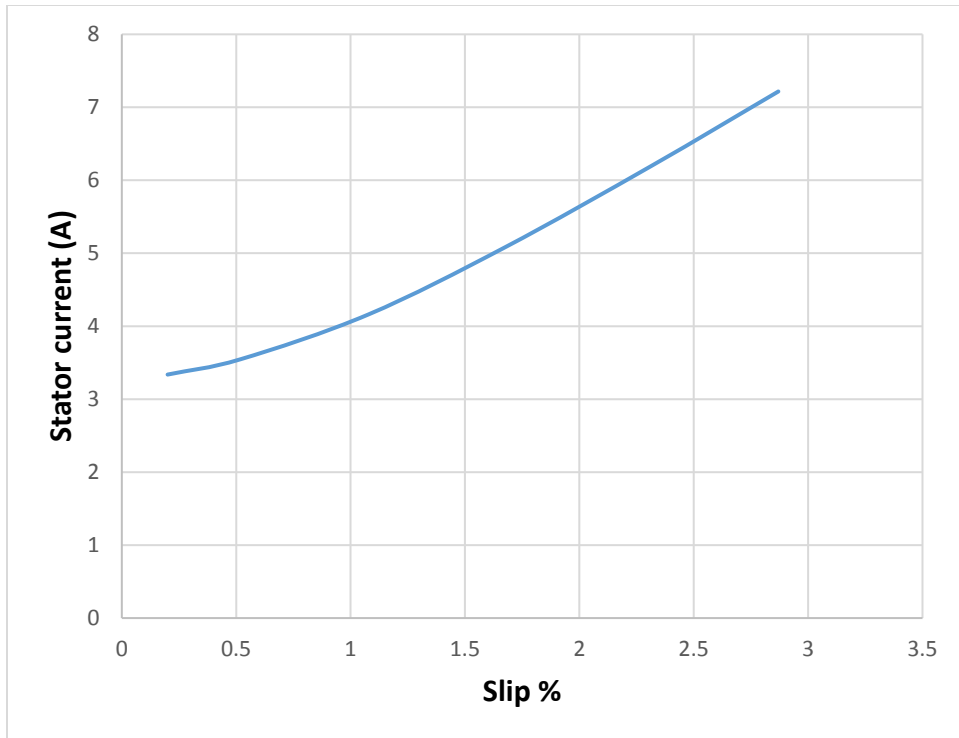


Figure 4-6 Variation of stator current with slip (simulation result)

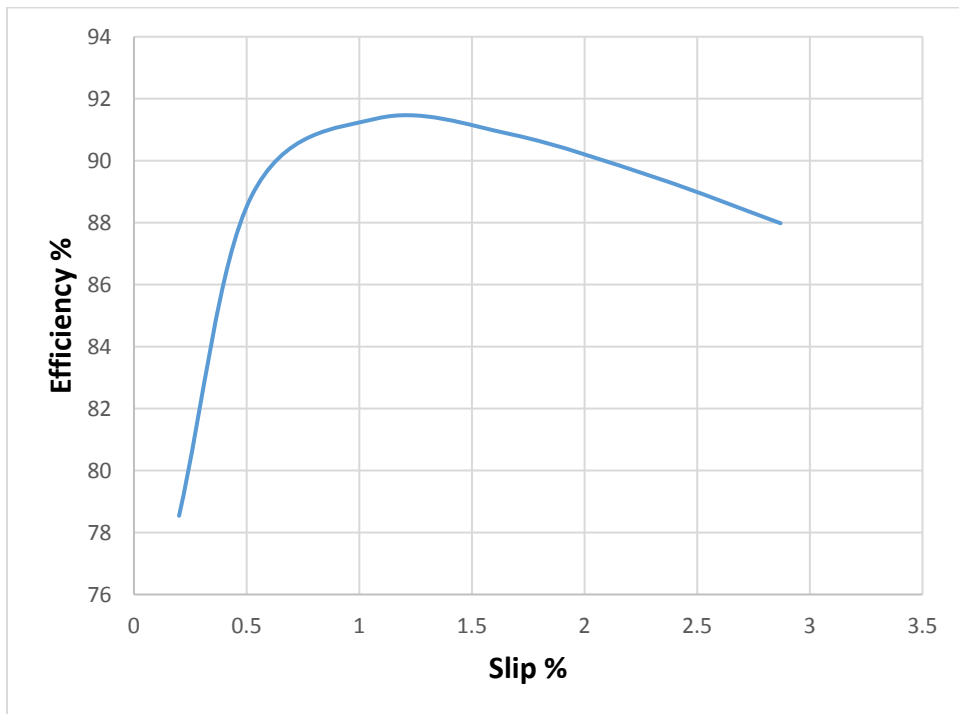


Figure 4-7 Variation of motor efficiency with slip (simulation result)

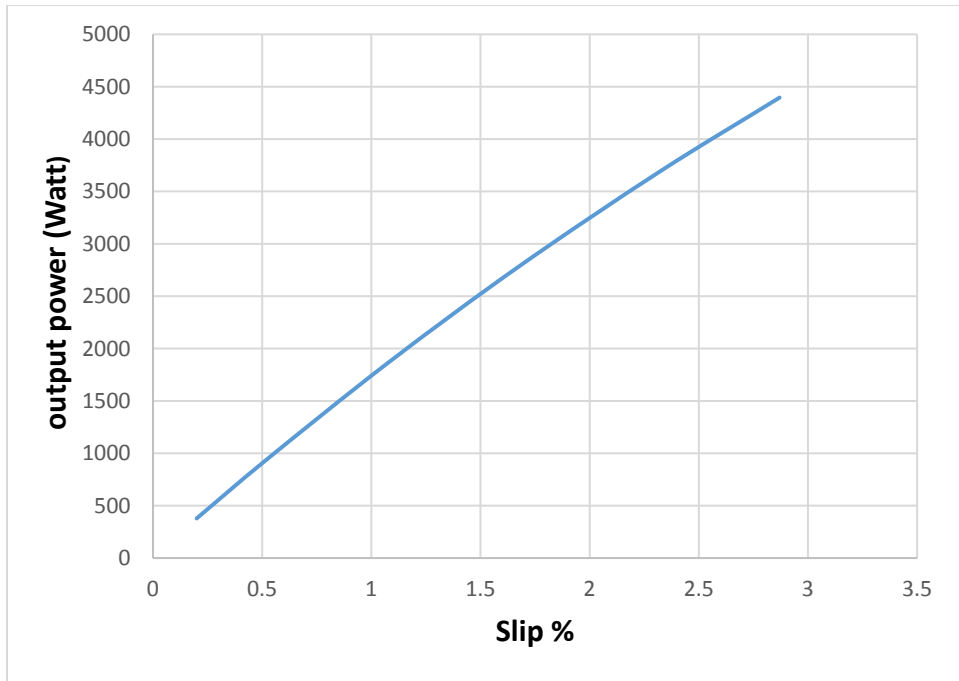


Figure 4-8 Variation of output power with slip (simulation result)

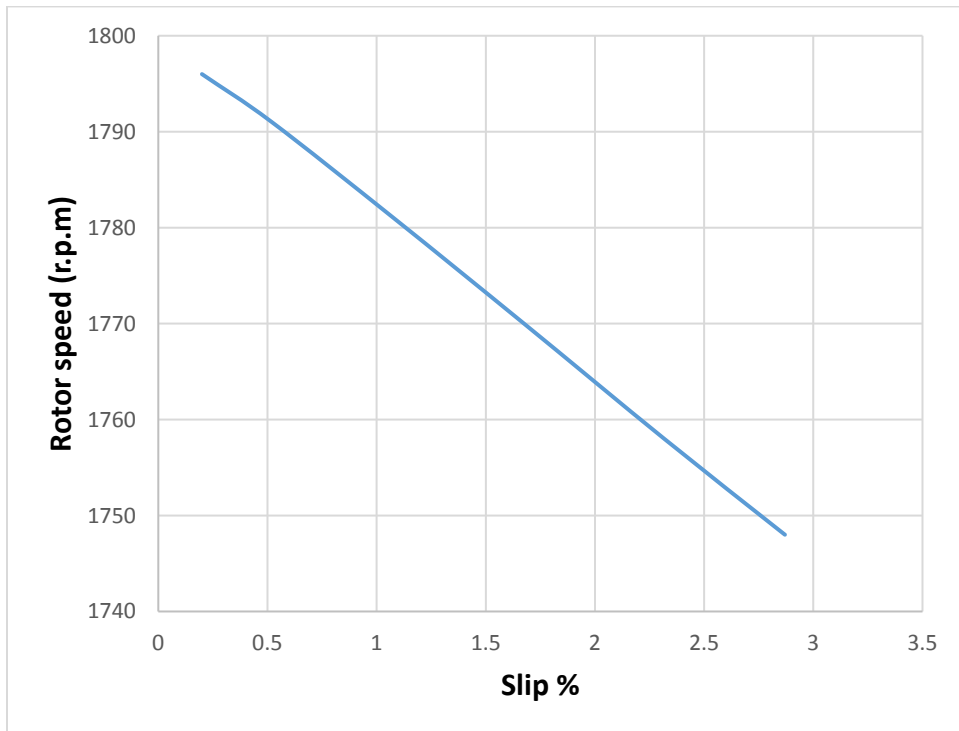


Figure 4-9 Variation of rotor speed with slip (simulation result)

4.6 Simulation Result of Three Phase Induction Motor under Different Loads

After running the Simulink model of three phase SCIM under different loads, various characteristics are presented to show their variation with motor torque in normal operation and proposed method. These different characteristics include motor efficiency, power factor, output power, apparent power, stator current, and rotor speed.

Fig .4.10 shows the variation of stator phase current with motor torque. We can notice that the stator phase current when motor operates with maximum efficiency is lower than the stator phase current of the normal operation at light loads where the applied voltage to the motor is lower than the rated voltage. We can also observe that when motor runs at motor torques greater than the motor torque at which the efficiency is maximum during normal operation, reducing the applied voltage increases the stator current and decreases motor efficiency. Therefore, the applied voltage to the motor is kept at its rated value.

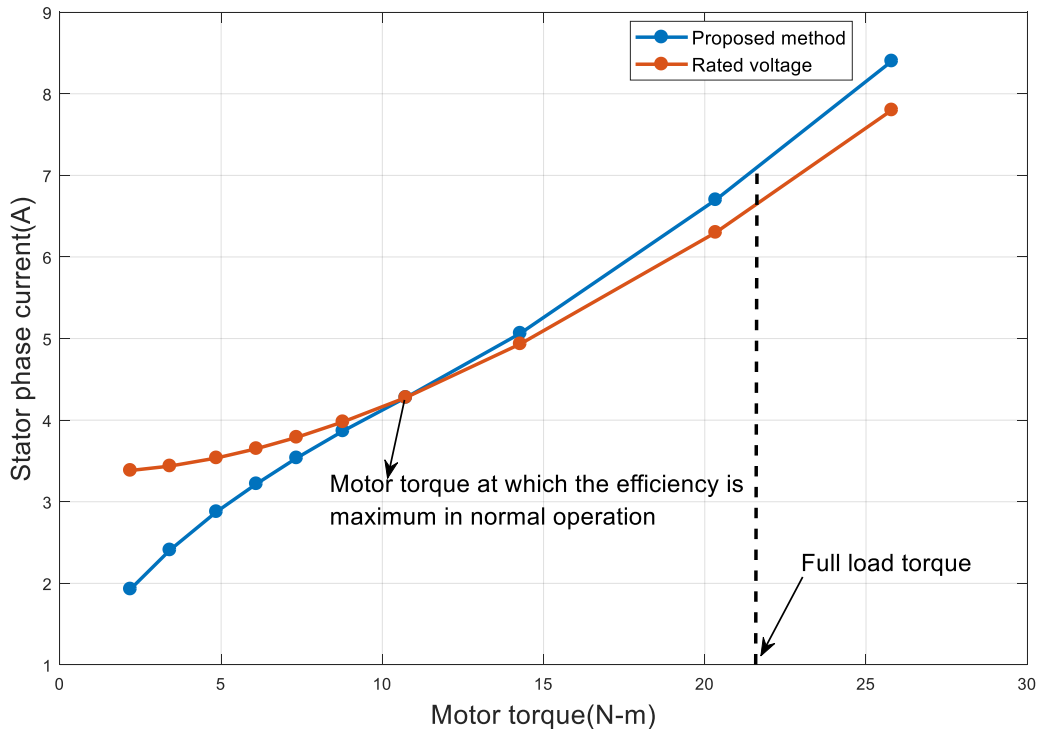


Figure 4-10 Stator current versus torque (simulation result)

Fig .4.11 shows the variation of motor efficiency with motor torque. As shown from this figure, the applied voltage varies at different values below rated value to keep the motor efficiency constant at maximum efficiency from light loads to a certain load at which the motor operates at maximum efficiency in normal operation (rated voltage). We can also see that at motor torques greater than the motor torque at which the efficiency is maximum in normal operation, reducing the applied voltage leads to a decrease in efficiency. Hence, the applied voltage must be kept at its rated voltage.

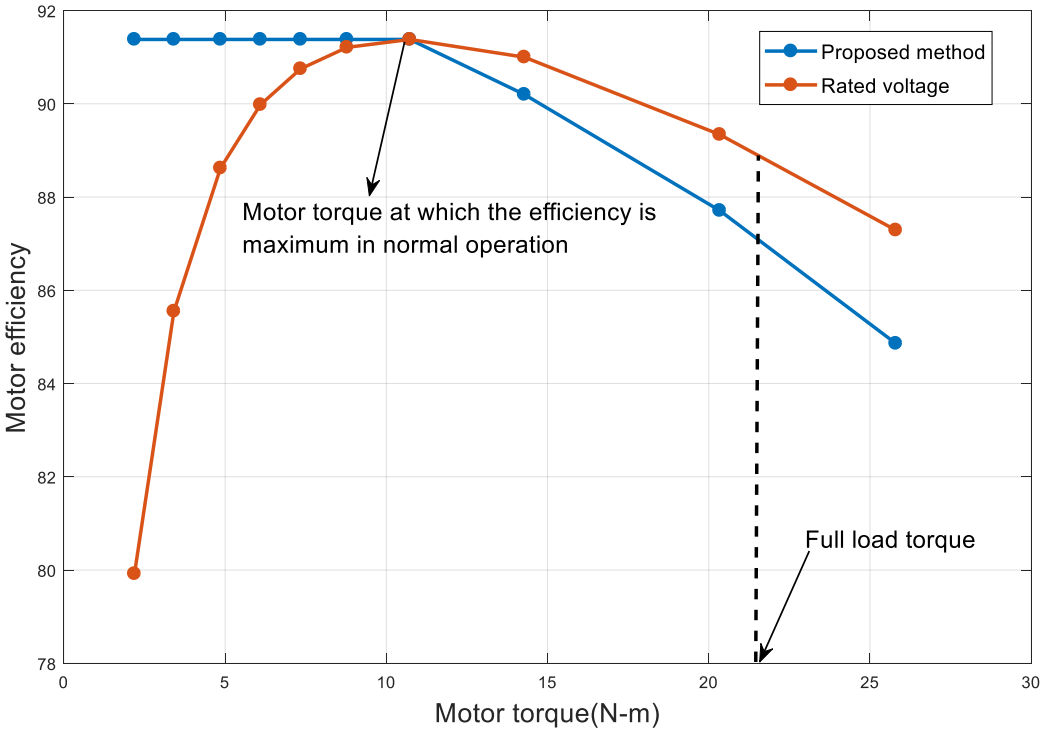


Figure 4-11 Efficiency versus torque (simulation result)

Fig .4.12 shows the variation of rotor speed with motor torque. At light loads, the motor is driven at a constant speed that gives maximum efficiency by decreasing the applied voltage. From this figure, we can observe that any decrease in applied voltage to run the motor at maximum efficiency causes a decrease in rotor speed. Thus, we must ensure that this decrease in rotor speed

is still suitable to the driven load condition. For instance, it is important to ensure that the speed reduction in a centrifugal pump does not cause inadequate fluid flow when operating at maximum efficiency.

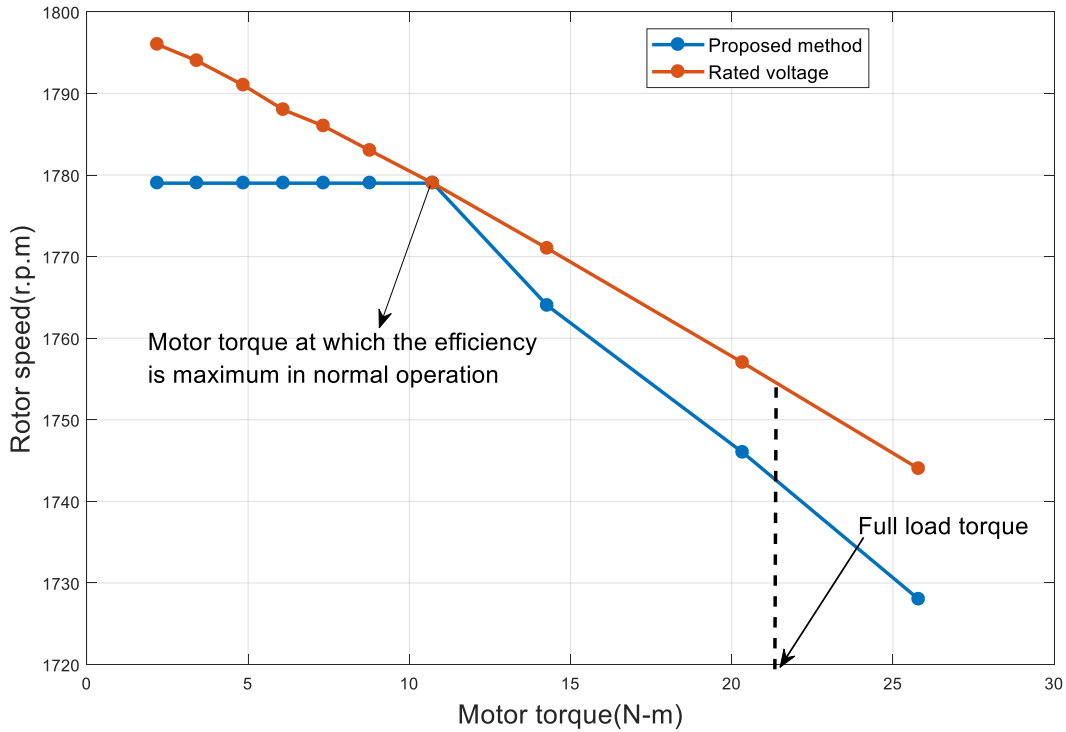


Figure 4-12 rotor speed versus torque (simulation result)

Fig. 4.13 and Fig. 4.14 show the variation of apparent power and reactive power with motor torque respectively. At light loads, we can see that apparent power and reactive power in the proposed method are lower than those of normal operation. We can see that the apparent power and reactive power are still decreasing at the loads at which the current increases. This is because the degree of voltage decrease is greater than the degree of current increase, hence apparent power decreases. Although the decrease of apparent power and reactive power at loads at which the current increases, the applied voltage must be at its rated to avoid flowing current greater than rated current and also to avoid a decrease in motor efficiency.

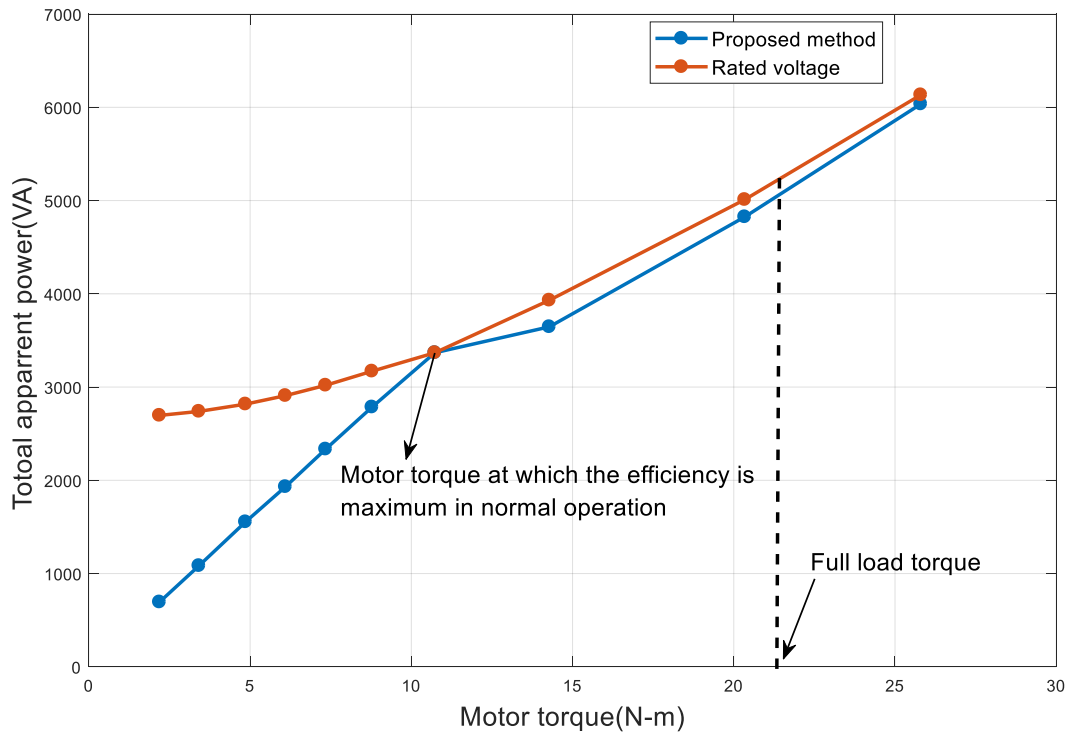


Figure 4-13 apparent power versus torque (simulation result)

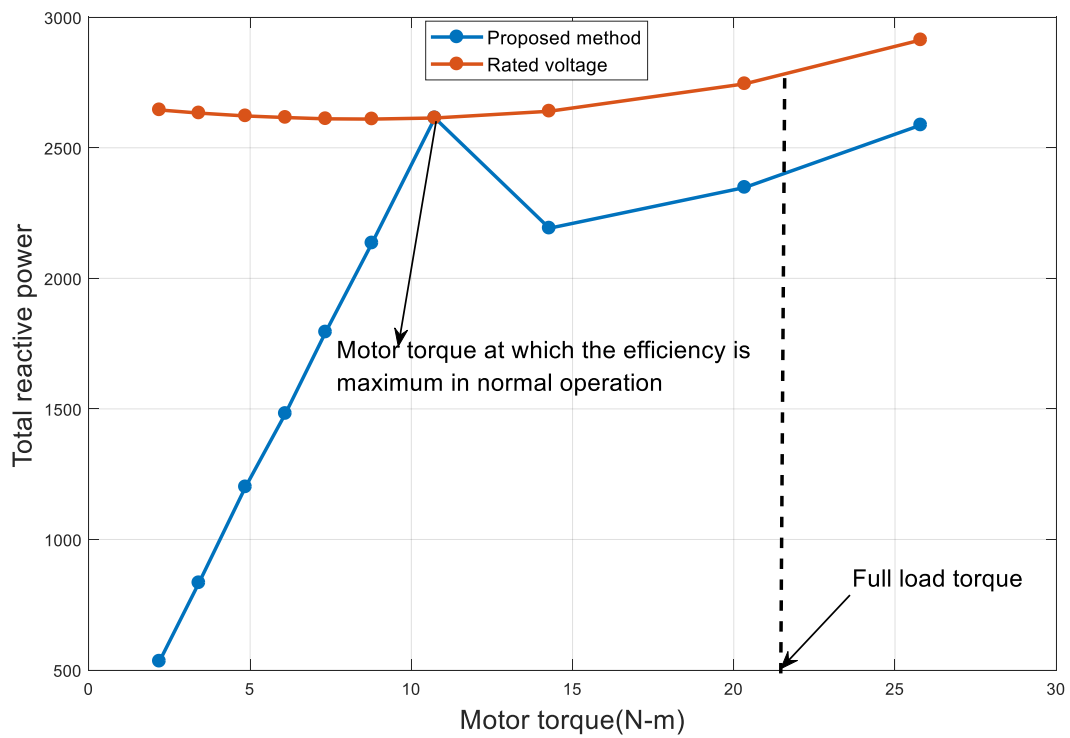


Figure 4-14 Reactive power versus torque (simulation result)

Fig .4.15 shows the variation of power factor with motor torque. We can see that, at light loads, power factor in the proposed method is high and constant while it is poor in the normal operation.

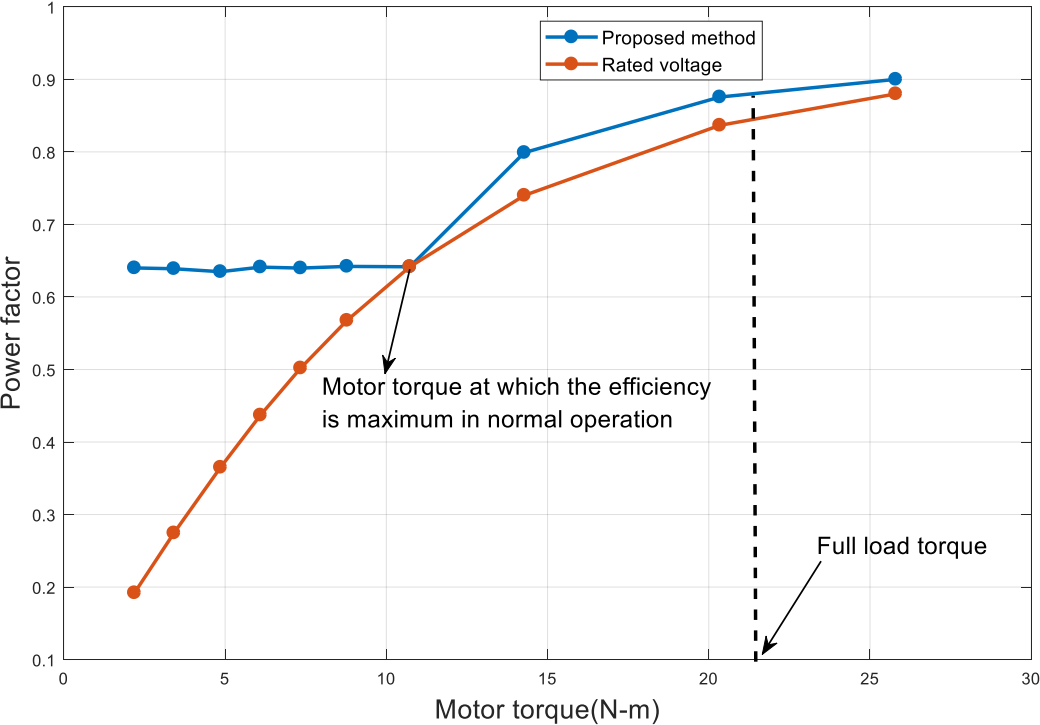


Figure 4-15 power factor versus torque (simulation result)

Fig .4.16 shows the variation of output power and motor torque. We can notice that, at light and high loads, the output power in the proposed method is lower than that of rated voltage. This is because of the reduction in rotor speed in both cases, light and high load operation due to reducing the applied voltage below its rated value.

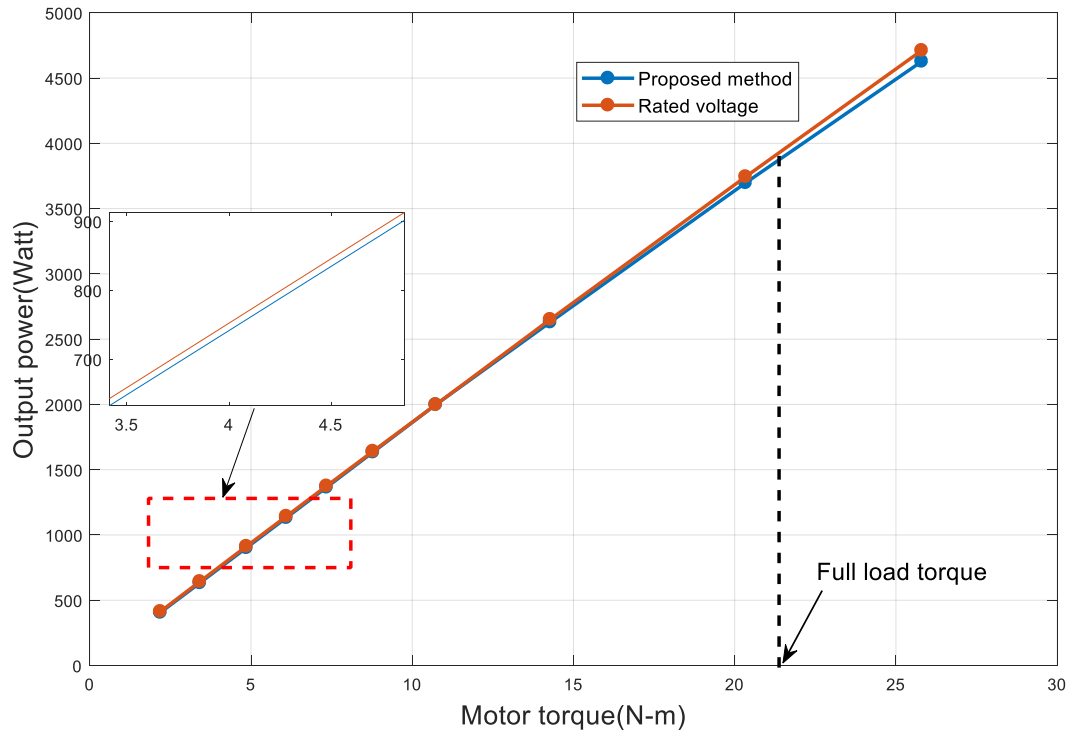


Figure 4-16 output power versus torque (simulation result)

From figures 4.10 to 4.16, we can summarize what we observed as follows:

1. When the motor runs at light loads, the motor efficiency can reach its maximum value and power factor can be improved and kept constant by reducing the applied voltage.
2. Stator current, and apparent power can be decreased by decreasing the applied voltage at light load. This plays a big role in saving electric energy consumption and increasing the motor lifetime.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

Three phase IMs are widely utilized to convert electrical energy into mechanical energy. Most of electric power utilized in industry is consumed by three phase IMs. These motors have poor efficiency and power factor when they run at light loads. Therefore, it is important to run these motors with high power factor and efficiency to save the electric energy consumption. This is can be achieved by applying the proposed method used in this thesis which depends on reducing the applied voltage to the motor below rated voltage to run it with high power factor and efficiency at low loads. We consider the effect of the proposed method on motor characteristics such as stator current, output power, reactive power, rotor speed and others when optimizing the efficiency at light loads. We also explain the equivalent circuit and mathematical analysis of the three phase IM in more detailed and we use SIMULINK models to determine its equivalent circuit parameters. From this study, we see that the motor efficiency and power factor is constant at different voltages if the motor is driven at the same rotor speed and they are low at light load and increase when increasing the load on motor. In addition, we also observe that the motor can be run with maximum efficiency at different load torques below the load of maximum efficiency of normal operation (rated voltage) by keeping the motor running at a constant speed that gives maximum efficiency by reducing the applied voltage.

Important notes when applying the proposed method include that the efficiency improvement and power factor are effective at light loads. For example, from Fig. 4.11, at motor torque 2 N-m, the efficiency is 80 % when the motor voltage is rated. The motor efficiency

becomes 91.35 % if the motor voltage reduces. The power factor is improved when applying the proposed method. For example, from Fig. 4.15, the power factor is 0.2 when the motor voltage is rated at motor torque 2 N-m. The power factor becomes 0.64 if the motor voltage decreases.

Other notes include that the stator current and apparent power decrease when employing the proposed method compared to the normal operation. This essentially reduce electrical energy bill. Additionally, as the motor efficiency increases, the motor overall losses reduce, hence the motor lifetime increases.

5.2 Future Work

Experimental study for maximizing the efficiency of three phase IMs when they run at speeds greater than the speed at which the efficiency is maximum at rated voltage should be done as future work of this topic to verify if the characteristics behavior of modeling motor using MATLAB/SIMULINK match the characteristics behavior of the motor experimentally. In addition, future work of this topic should apply on single phase IMS as they are widely used for domestic, commercial and industrial purpose and as their power factor and efficiency are low as compared to three phase IMs.

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APPENDIX A

MATLAB code for three phase squirrel cage induction motor characteristics

```

% 1) At rated phase voltage ( 265.6 v)
n=1:1:1798; % Rotor speed
ns=1800; % Stator magnetic field speed(synchronous speed)
s=(ns-n)./ns; % Slip
vi=265.6; % Rated phase voltage
xm=76.75; % magnetizing reactance
R1=3; % Stator winding resistance
x1=2.25; % stator winding leakage reactance
R2=1.083; % Rotor winding resistance referred to stator
x2=2.25; % Rotor leakage reactance referred to stator
z1= R1+j*x1; % Stator impedance
z2=(R2./s)+j*x2; % Rotor impedance referred to stator
z3=(j*xm.*z2)./(j*xm+z2);
z4=z1+z3; % Total impedance
iph=vi./(z4);iph_m= abs(iph); % Stator phase current
i2=(iph.*j*xm)./(j*xm+((R2./s)+j*x2));i2_m= abs(i2); % Rotor phase current
referred to stator
pf=cos(angle(z4)); % Power factor
po=3.*((i2_m.*i2_m.*(R2./s))-(i2_m.*i2_m.*R2)); % Output power
eff=(po./pi).*100; % Motor efficiency
t=(9.554.*po)./n; % Motor torque
Q= 3.*vi.*iph_m.*sin(angle(z4)); % Total reactive power
S=3.*iph_m*vi; % Total apparent power
% 2) At 200 phase voltage
vil=200;
iph1=vil./(z4);iph1_m= abs(iph1); % Stator phase current
i22=(iph1.*j*xm)./(j*xm+((R2./s)+j*x2));i22_m= abs(i22); % Rotor phase
current referred to stator
pol=3.*((i22_m.*i22_m.*(R2./s))-(i22_m.*i22_m.*R2)); % Output power
eff1=(pol./pi1).*100; % Motor efficiency
t1=(9.554.*pol)./n; % Motor torque
Q1= 3.*vil.*iph1_m.*sin(angle(z4)); % Total reactive power
S1=3.*iph1_m.*vil; % Total apparent power
% 3) At 150 phase voltage
vil1=150;
iph11=vil1./(z4);iph11_m= abs(iph11); % Stator phase current
i222=(iph11.*j*xm)./(j*xm+((R2./s)+j*x2));i222_m= abs(i222); % Rotor phase
current referred to stator
pol1=3.*((i222_m.*i222_m.*(R2./s))-(i222_m.*i222_m.*R2)); % Output power
eff11=(pol1./pi11).*100; % Motor efficiency
t11=(9.554.*pol1)./n; % Motor torque
Q11= 3.*vil1.*iph11_m.*sin(angle(z4)); % Total reactive power
S2=3.*iph11_m.*vil1; % Total apparent power
plot(n,t,n,t1,n,t11)
xlabel('Rotor speed')
ylabel('Motor torque')
grid on
legend('V= rated voltage','V=200 v','V=150v')

```

```

figure
plot(n,iph_m,n,iph1_m,n,iph11_m)
xlabel('Rotor speed')
ylabel('Stator phase current')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(n,Q,n,Q1,n,Q11)
xlabel('Rotor speed')
ylabel('Total reactive power')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(n,S,n,S1,n,S2)
xlabel('Rotor speed')
ylabel('Total apparent power')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(n,pf,n,pf,n,pf)
xlabel('Rotor speed')
ylabel('Power factor')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(n,eff,n,eff1,n,eff11)
xlabel('Rotor speed')
ylabel('Motor efficiency')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(n,po,n,po1,n,po11)
xlabel('Rotor speed')
ylabel('Output power')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(t,iph_m,t1,iph1_m,t11,iph11_m)
xlabel('Motor torque')
ylabel('Stator phase current')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(t,Q,t1,Q1,t11,Q11)
xlabel('Motor torque')
ylabel('Total reactive power')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(t,S,t1,S1,t11,S2)
xlabel('Motor torque')
ylabel('Total apparent power')
grid on
legend('V= rated voltage','V=200v','V=150v')
figure
plot(t,pf,t1,pf,t11,pf)
xlabel('Motor torque')

```

```
ylabel('Power factor')
grid on
legend('V= rated voltage', 'V=200v', 'V=150v')
figure
plot(t, eff, t1, eff1, t11, eff11)
xlabel('Motor torque')
ylabel('Motor efficiency')
grid on
legend('V= rated voltage', 'V=200v', 'V=150v')
figure
plot(t, po, t1, pol, t11, pol1)
xlabel('Motor torque')
ylabel('Output power')
grid on
legend('V= rated voltage', 'V=200v', 'V=150v')
figure
```