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Identification of Speed and Torque Characteristics of Induction Motor Using Stator Voltage Parameters

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الآيـــــة

بسم الله الرحمن الرحيم

قال تعالى:

﴿اقرأ باسمِ ربِّكَ الَّذي خلَق(1) خلَقَ الإنسانَ من علَق(2) اقرأ وربُّكَ الأكرم(3) الَّذي علَّمَ بالقلَم(4) علَّم الإنسانَ ما لم يعلم(5)﴾

صدق الله العظيم

سورة العلق

Dedication

We would like to articulate our deep gratitude to our project guide Mr. Abdullah saleh Ali, who has always been our motivation for carrying out the project. His constant inspiration and effort made this project work a great success. We are thankful to him for his contributions in completing this project work. An assemblage of this nature could never have been attempted without reference to and inspiration from the works of others whose details are mentioned in reference section.

Acknowledgments

Before I begin My thanks, I must first pay the highest to the god for given me the strength to complete this thesis.

my deep appreciation to my husband for supporting me. I am greatly indebted to my supervisor, Mr. Abdullah saleh Ali for his guidance and help.

Finally, My sincere thanks to my family my Mother ,my father, my son and my daughter for their prayers and encouragement throughout this work .

Abstract

Stator Voltage parameters are used. To identification speed and torque of induction motor. The rotor speed is varied by changing slip, Also speed can be varied by changing the number of poles and supply frequency.

The torque is proportional to the square of stator voltage. The reduction of stator voltage produces a reduction in speed.

The stator voltage method give a reasonable results.

المستخلص

تم استخدام بارومترات جهد العضو الثابت للتعرف على خصائص السرعة والعزم للمحرك ألحثي

سرعة العضو الدوار يمكن أن تتغير عن طريق ملف الانزلاق وكذلك عن طريق تغيير سرعة العضو الدوار عن طريق تغيير الأقطاب وتردد المصدر.

عزم المحرك ألحثي يتناسب مع مربع جهد العضو الثابت, التقليل في جهد العضو الثابت ينتج عنه نقصان في السرعة.

تم الحصول على نتائج مقبولة بطريقة جهد العضو الثابت.

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List Of Symbols

The Symbol	The Name
IM	Induction Motor
R_s	Stator Resistance per-phase
R_r	Rotor Resistance per-phase
R'_r	Rotor Resistance Referred to Stator side
X_s	Stator Reactance per-phase
X_r	Rotor Reactance per-phase
R'_r	Rotor Reactance Referred to Stator side
X_m	Magnetizing Reactance
R_m	Excitation Resistance
I_s	Stator Current
I_r	Rotor Current
I'_r	Rotor Current referred to Stator side
V_s	Stator Voltage
V_P	Voltage per phase applied to stator winding
Z_S	No. of stator conductors in series per phase
Z_r	No. of rotor conductors in series per phase
Z_i	Input Impedance
E_0	Rotor $e.m.f.$ generated per phase at standstill
K_d	Distribution factor of winding
K_P	Pitch factor of winding
$\emptyset$	Flux per pole
S	Slip
N_r	Number of turns on each rotor phase
ω_m	Angular rotor speed or frequency, Hz
Φ	Relative position of the rotor
θ_m	Angle between I_s and V_s output power

η	Efficiency
E_r	rms value of the induced voltage in the rotor per phase
E_m	peak induced voltage in the rotor per phase
f	Supply Frequency
P	No. of Poles
P_g	Air-gap Power
P_{cu}	Copper loss in the machine
P_m	Mechanical Power output of the machine
P_c	Core loss in the machine
T_s	Starting Torque
T_d	Torque Developed by motor
T_{mm}	Breakdown Torque
T_{mr}	Maximum Regenerative Torque
S_m	Slip at maximum torque
T_{max}	Maximum Torque

CHAPTER ONE

INTRODUCTION

1.1.General View

AC motors exhibit highly coupled, nonlinear, and multivariable structures as opposed to much simpler decoupled structures of separately excited DC motors. The control of AC drives generally requires complex control algorithms that can be performed by microprocessors or microcomputers along with fast-switching power converters. The AC motors have a number of advantages; they are lightweight (20 to 40% lighter than equivalent DC motors), are inexpensive, and have low maintenance compared with DC motors. They require control of frequency, voltage, and current for variable-speed applications. The power converters, inverters, and AC voltage controllers can control the frequency, voltage, or current to meet the drive requirements. These power controllers, which are relatively complex and more expensive, require advanced feedback control techniques such as model reference, adaptive control, sliding mode control, and field-oriented control. However, the advantages of AC drives outweigh the disadvantages[1].

1.2. Problem Statement

Characteristics usually of stator task and help in the development of an appropriate ruling. Recognize these characteristics are a number of ways, including using the measurement software packages. and use of MATLAB, so that they are more accurate and Usefulness .

1.3.Objectives

The objectives of the thesis are to:

Derive the mathematical model.

Determine Torque and Speed characteristic.

Developed Torque Speed characteristic duty cycle.

1.4. Methodology

The MATLAB is used to simulate the characteristics of an induction motor (speed and torque).

1.5. Thesis Layout

This thesis consists of five chapters. In the first chapter, this chapter discusses the overall idea of this project including the Problem statement, Objectives, and Methodology of project, and summary of this thesis.

Chapter two discussed more on theory and literature review that have been done. It is well discusses about the analysis of various methods for speed control of induction motor.

Chapter three described briefly the methodology of the data extraction, parameters tables and extra information are aided into this chapter to be the benchmark thesis in development related to this project and simulation development for this project.

Chapter four included the results of the simulation and presents a discussion of the implementation, and analysis of the whole project.

Chapter five provides the conclusions of the project. There are also several suggestions that can be used for future implementation or upgrading for this project.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction:

A novel stator voltage oriented voltage/frequency (V/F) control method for induction motor is presented in this paper to improve the low speed performance and stability of open-loop system. The control scheme adopts a novel stator resistor voltage drop compensation method to ensure the rated stator flux constant over a wide range of operating speeds. And through deeply research of the instability under light load condition, a stabilizing control method is proposed. Under very low speed condition, the performance has greatly improved by boosting the torque and compensating the motor slip frequency. Different from vector control methods, all the compensation and regulation are based on stator voltage oriented synchronous rotation frame transformation, which avoid complicated vector calculation and are simple to implement. The experimental results showed that, by adopting the proposed method, the speed can be accurately controlled down to 0.1 Hz with rated load torque [2].

Amitpal Singh, The Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives.

Out of the several methods of speed control of an induction such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/f control, slip recovery method etc., the closed loop constant V/f speed control method is most widely used. In this method, the V/f ratio is kept constant which in turn maintains the magnetizing flux constant so that the maximum torque remains unchanged. Thus, the motor is completely utilized in this method.

During starting of an induction motor, the stator resistance and the motor inductance (both rotor and stator) must be kept low to reduce the steady state time and also to reduce the jerks during starting. On the other hand, higher value of rotor resistance leads to lesser jerks while having no effect on the steady state time. The vector control analysis of an induction motor allows the decoupled analysis where the torque and the flux components can be independently controlled (just as in dc motor). This makes the analysis easier than the per phase equivalent circuit[3].

ALNASIR, Z.A, Induction motors are currently used in many industrial applications. Thus, their control techniques have received a lot of interest. An efficient method of induction motor control is the direct torque control (DTC). In this project, a DTC model has been developed and tested using a MATLAB/SIMULINK package. A 6 kW three phase induction motor has been used in order to run and evaluate the developed model. Simulation results have shown the validity and high accuracy of the proposed model. The independence of torque and stator flux control has been confirmed. However, further work should be done in order to limit the significant variation in the starting up stator current caused by any small variation in the stator flux in the developed DTC model. *Index Terms*….Induction motor, state feedback and estimator[4].

T. MUNI PRAKASH This letter proposes a rotor flux amplitude reference generation strategy for doubly fed induction machine based wind turbines. It is specially designed to address perturbations, such as voltage dips, keeping controlled the torque of the wind turbine, and considerably reducing the stator and rotor over currents during faults. In addition, a direct torque control strategy that provides fast dynamic response accompanies the overall control of the wind turbine. Despite the fact that the proposed control does not totally eliminate the necessity of the typical crowbar protection for this kind of turbines, it eliminates the activation of this protection during low voltage dips[5].

2.2Control System

A control system is a collection of components working together under the direction of some machine intelligence. In most cases, electronic circuits provide the intelligence, and electromechanical components such as sensors and motors provide the interface to the physical world. A good example is the modern automobile. Various sensors supply the on-board computer with information about the engine's condition. The computer then calculates the precise amount of fuel to be injected into the engine and adjusts the ignition timing. The mechanical parts of the system include the engine, transmission, wheels, and so on. To design, diagnose, or repair these sophisticated systems, you must understand the electronics, mechanics, and control system principles.

In past days, so-called automatic machines or processes were controlled either by analog electronic circuits, or circuits using switches, relays, and timers. Since the advent of the inexpensive microprocessor, more and more devices and systems are being redesigned to incorporate a microprocessor controller. Examples include copying machines, soft-drink machines, robots, and industrial process controllers. Many of these machines are taking advantage of the increased processing power that comes with the microprocessor and, as a consequence, are becoming more sophisticated and are including new features. Taking again the modern automobile as an example, the original motivation for the on-board computer was to replace the mechanical and vacuum-driven subsystems used in the distributor and carburetor. Once a computer was in the design, however, making the system more sophisticated and relatively easy-for example, self adjusting fuel/air ratio for changes in altitude. Also, features such as computer-assisted engine diagnostics could be had without much additional cost. This trend toward computerized control will no doubt continue in the future. In a modern control system, electronic intelligence controls some physical process. Control systems are the "automatic" in such things as automatic pilot and automatic washer. Because the machine itself is making the routine decisions, the human operator is freed to do other things. In many cases, machine intelligence is better than direct human control because it can react faster or slower (keep track of long-term slow changes), respond more precisely, and maintain an accurate log of the system's performance. Control systems can be classified in several ways. A regulator system follow-up system An event control system [6].

2.3.Construction Of Induction Motor

The induction motor is the electric motor type most used industry. The certain excellent features of the induction motor such as for the user this low cost and high reliability, good efficiency and low maintenance.

The induction motors are asynchronous induction machines whose speed depends upon applied frequency, pole pair number, and load torque. This market need and growing at a healthy rate as users of operating motors at variable speeds [7].

There are two types of AC drives:

- Induction motor drives.
- Synchronous motor drives.

AC drives are replacing DC drives and are used in many industrial and domestic applications[1].

Induction machine is the most used in industry because of its high robustness, reliability, low cost, high efficiency and good self-starting capability [8,9,10,11]. The induction motor, particularly with a squirrel cage rotor, is the most widely used source of mechanical power fed from an AC power system. Its low sensitivity to disturbances during operation make this squirrel cage motor the first choice when selecting a motor for a particular application [12].

An induction motor consists essentially of two main parts; stator and rotor

2.3.1.A stator

The stator of induction motor is, in principle, the same as that of a synchronous motor or generator. It is made up of number of stamp lings, which are slotted to receive the windings. The stator carries a 3-phase winding and is fed from A 3-Phase supply. It is wound for a definite number of poles, the exact number of poles being determine by the requirements of speed. Greater the number of poles, lesser the speed and vice versa. The stator windings, when supplied with 3- phase currents, produce a magnetic flux, which is of constant magnitude but which revolves (or rotates) at synchronous speed N_s. This revolving magnetic flux induces an $e.m.f.$ in the rotor by mutual induction. And it is calculated from equation:

$$N_s = \frac{120f}{p}$$

2.3.2.A rotor

(1) Squirrel –cage motor: motors employing this type of rotor are known as squirrel –cage induction motors

(2) Phase –wound or wound rotor: motors employing this type of rotor are variously known as "phase –wound" motors or 'wound' motors or as "slip –ring" motors.

2.4. Squirrel –Cage Rotor

Almost 90 per cent of induction motors are squirrel –cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminum or alloys. One bar is placed in each slot, rather the bars are inserted from the end when semi –closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short –circuiting end –rings, thus giving us, what is so picturesquely called, a squirrel –case construction .

It should be noted that the rotor bars are permanently short –circuited on themselves, hence it is not possible to add any external resistance in series with the rotor circuit for starting purposes.

The rotor slots are usually not quite parallel to the shaft but are purposely given a slight skew. This is useful in two ways:

- It helps to make the motor run quietly by reducing the magnetic hum.
- It helps in reducing the locking tendency of the rotor i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

In small motors, another method of construction is used. It consist of placing the entire rotor core in a mould and casting all the bars and end –rings in one piece. The metal commonly used is an aluminum alloy.

Another form of rotor consists of a solid cylinder of steel without any conductors or slots at all. The motor operation depends upon the production of eddy current in the steel rotor.

2.4.1.Phase –Wound Rotor

This type of rotor is provided with 3 –phase, double –layer, distributed winding consisting of coils as used in alternators. The rotor is wound for as many poles as the number of stator poles and is always wound 3 –phase even when the stator is wound two –phase.

The three phases are starred internally. The other three winding terminals are brought out and connected to three insulated slip –rings mounted on the shaft with brushes resting on them. These three brushes are further externally connected to a 3 –phase star –connected rheostat. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor and for changing its speed –torque/current characteristics. When running under normal conditions, the slip –rings are automatically short –circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip –rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short –circuited on itself just like the squirrel –case rotor[13].

2.5 The Principle Of Action

The stator of an induction motor is similar to that of a synchronous machine; and in the case of a machine supplied with three-phase currents, The rotor core is laminated and the conductors often consist of insulated copper or aluminum bars in semi-enclosed slots, the bars being short-circuited at each end by rings or plates to which the bars are brazed or welded. In motors below about 50 kW the aluminum rotor bars and end-rings are often cast in one operation. This type is known as the cage or short-circuited rotor. The air gap between the rotor and the stator is uniform and made as small as is mechanically possible. For simplicity the stator slots and winding have been omitted in figure2.1.

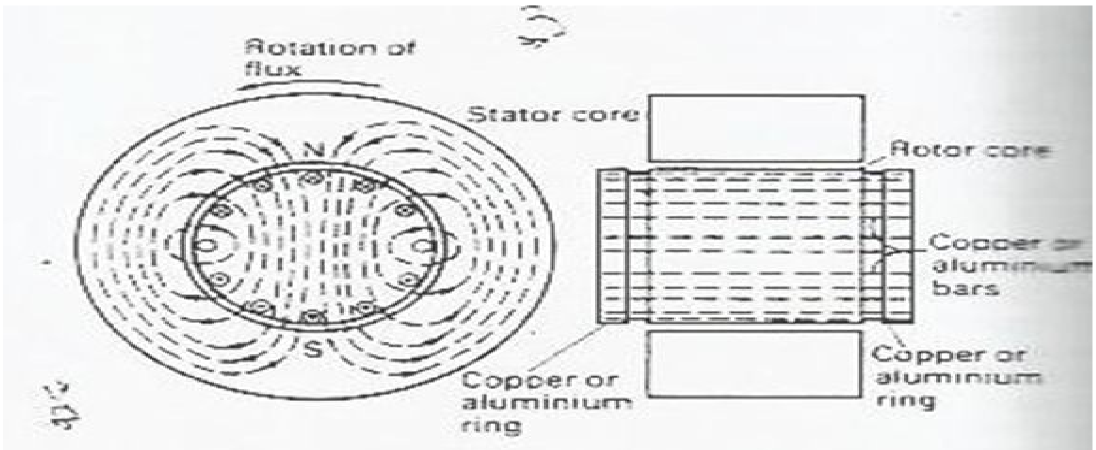

Figure2.1. induction motor with cage rotor

If the stator is wound for two poles. the distribution of the magnetic flux due to the stator currents at a particular instant is shown in fig.2.1. The $e.m.f.$ generated in a rotor conductor is a maximum in the region of maximum flux density and if the flux be assumed to rotate anticlockwise. The directions of the $e.mf.s.$ generated in the stationary rotor conductors can be determined by the right-hand rule and are indicated by the crosses fig. The $e.m.f$.generated in the rotor conductor shown in figure2.2 circulate a current the effect of which is to strengthen the flux density

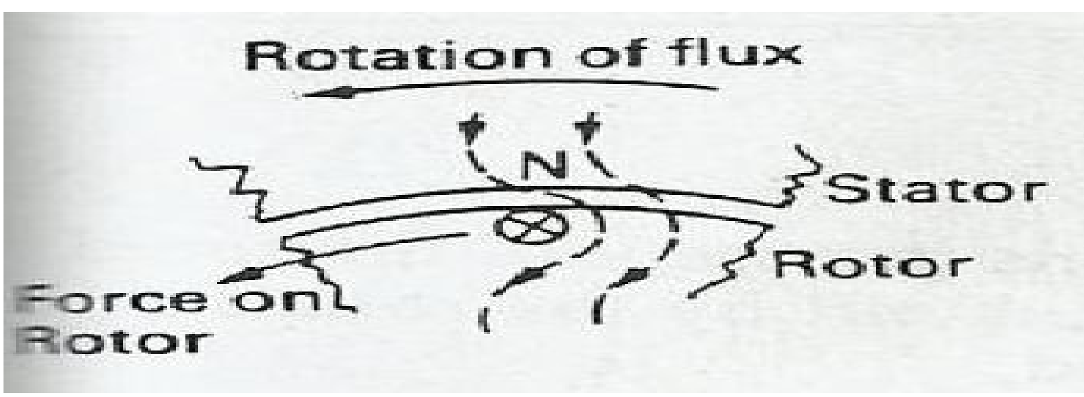

Figure 2.2 force on rotor

on the right hand side and weaken that on the left hand side; i.e. the flux in the gap is distorted as indicated by the dotted lines in figure2.2. Consequently, a force is exerted on the rotor tending to drag it in the direction of the rotating flux . The higher the speed of the rotor, the lower is the speed of f the rotating field relative to the rotor winding and the smaller is the $e.m.f.$ generated in the latter. Should the speed of rotor attain the synchronous value, the rotor conductors would be stationary in relation to the rotating flux. There would therefore be no $e.m.f.$ and no current in the rotor conductors and consequently no torque on the rotor. Hence the latter could not continue rotating at synchronous speed. As the rotor speed falls more and more below the synchronous speed the values of the rotor $e.m.f$ and current and therefore of the torque continue to increase until the latter is equal to that required by the rotor losses and by any load there may be on the motor. The speed of the rotor relative to that of the rotating flux synchronous is termed the slip; thus for a torque OA in fig. 2.3. the rotor need speed is AC and the slip is AD. Where

$$AD = AB - AC = CB.$$

For torques varying between zero and the full-load value, the slip is practically proportional to the torque. It is usual to express the slip either as a per-unit or fractional value or as a percentage of the synchronous speed;

$$per\ unit\ slip = \frac{slip\ in\ r/min}{synchronous\ speed\ in\ r/min} = \frac{AD}{AB}$$

$$= \frac{synchronous\ speed - rotor\ speed}{synchronous\ speed}$$

$$= \frac{n_1 - n_r}{n_1}$$

$$percentage\ slip = per\ unit\ or\ fraction\ slip\ \times 100 = \frac{AD}{AB} \times 100$$

The value of the slip at full load varies from about 6 percent, for small motors to about 2 per cent for large machines. The induction motor may therefore be regarded as practically a constant-speed machine; and the difficulty of varying its speed economically constitutes one of its main disadvantages.

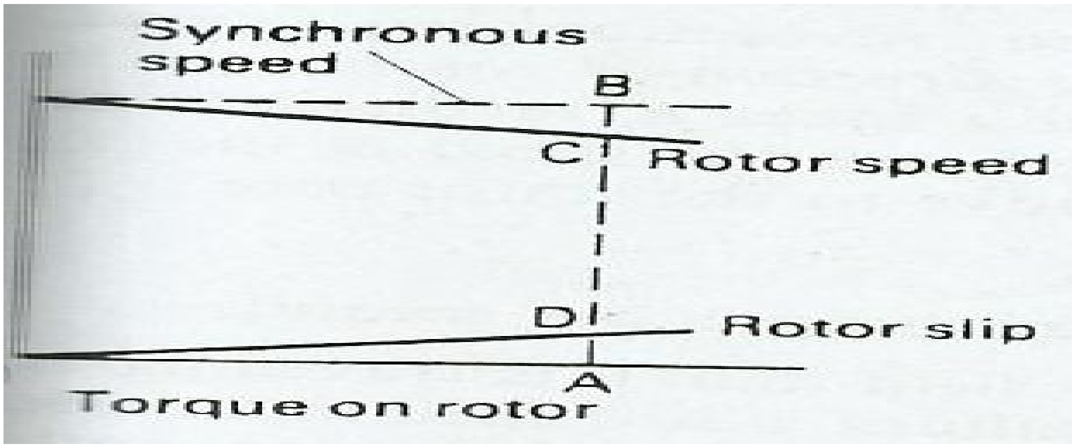

Figure2.3. slip and rotor speed of an induction motor

2.6 Frequency of rotor $e.m.f.$ and current

The three- phase winding with p pairs of poles supplied at a frequency of $f$hertz the speed of rotating flux is given by n_1 revolutions per second.

If n_r is the rotor speed in revolutions per second, the speed at the which the rotor conductors are being cut by the rotating flux is $(n_1 - n_r)$revolutions per second,

$$frequency\ of\ rotor\ e.m.f. = f_r = (n_1 - n_r)p$$

If s =per-unit or fractional slip= $(n_1 - n_r)/n_1$

Then $n_1 - n_r = sn_1$

And $f_r = sn_1 p = sf$

Polyphase currents in the stator winding produce a resultant magnetic field. The axis of which rotates at synchronous speed,n_1 revolution per second. Relative to the stator. Similarly the polyphase current in the rotor winding produce a resultant magnetic field, the axis of which rotates by expression (2.2) at a speed sn_1revolution per second relative to the rotor surface, in the direction of rotation of the rotor. But the rotor is revolution per second relative to the stator core; hence the speed of the resultant rotor magnetic field relative to the stator core

$= sn_1$

$- n_r$ (2.2)

$= (n_1 - n_r) + n_r = n_1$ Revolutions per second.

i.e. the axis of the resultant rotor field $m.m.f$ is traveling at the same speed as that of the resultant stator filed $m.m.f.$, so that they are stationary relative to each other . Consequently the polyphase induction motor can be regarded as being equivalent to a transformer having an air gap separating the steel portions of the magnetic circuit carrying the primary and secondary windings.

Owing to this gap, the magnetizing current and the magnetic leakage for an induction motor are large compared with the corresponding values for a transformer of the same apparent power rating. Also the friction and winding losses contribute towards making the efficiency of the induction motor less than that of the corresponding transformer. On the other hand, the stator field $m.m.f.$ has to balance the rotor field $m.m.f.$ and also provide the magnetizing and no-load loss components of the stator current, as in a transformer. Hence, an increase of slip due to increase of load is accompanied by an increase of rotor currents and therefore by a corresponding increase of the stator currents.

2.7 Rotor e. m. f. and Current

Let $V_{P=}$ voltage per phase applied to stator winding,

Z_S= no. of stator conductors in series per phase,

$K_{d=}$ Distribution factor of winding,

K_P= Pitch factor of winding,

= 1.0 for full-Pitch coils,

and $\emptyset$= flux per pole, i.e. total flux entering or leaving the stator over one pole pitch, namely the distance between 2 adjacent points of zero flux density.

Since the back e. m. f. generated in the stator winding is approximately equal to the applied voltage we have:

$V_P \approx 2.22 K_d K_P Z_S f \emptyset$

(2.3)

When the rotor is at stand still, the rotating flux $\emptyset$ cuts the rotor at the name speed as it cuts the stator winding, so that the frequency of the rotor $e.m.f.$ is then the same as the supply frequency, namely f hertz hence:

If E_0=rotor $e.m.f.$ generated per phase at standstill,

And Z_r=no. of rotor conductors in series per phase, Then $E_0=2.22k_d K_P Z_r f\emptyset$

(2.4)

Assuming the distribution and pitch factors to be the same for the stator and rotor windings, we have from (2.3) and (2.4) :

$E_0 \approx V_P * \frac{Z_r}{Z_S}$

(2.5)

IF E_r is the rotor e.m.f. generated per phase when the per-unit slip is s and the rotor frequency is $f_r = sf_s$

$E_r = 2.22K_d K_P Z_r f_r \emptyset$

(2.6)

$=SE_0$

(2.7)

IF R = resistance per phase of the rotor winding,

And X_0 = leakage reactanceper phase of the rotor winding at standstill,

$= 2\pi f \times$leakage reactance per phase of the rotor winding,

Then for per-unit or fractional slip S,

Corresponding reactance per phase = $X_r = SX_0$

And Corresponding impedance per phase

$=Z_r = \sqrt{(R^2 + (SX_0)^2)}$

(2.8)

If I_0 = rotor current per phase at standstill,

and I_r= rotor current per phase at slip S,

$I_0 = \frac{E_0}{\sqrt{R^2+X_0^2}}$

And $I_r = \frac{E_r}{\sqrt{(R^2+(sX_0)^2)}} = \frac{SE_0}{\sqrt{(R^2+(SX_0)^2)}}$

If $\emptyset_r$ be the phase difference between E_r and I_r

Tan $\emptyset_r = X_R/R = SX_0/R$

(2.9)

And

$\cos \emptyset_r = \frac{R}{\sqrt{(R^2 + X_r^2)}}$

(2.10)

2.8 Relationship Between The Rotor I^2R loss And The Rotor Slip

If T=torque, in Newton-meters. Exerted on the rotor by the rotating flux

And $n_1 =$ synchronous speed in revolutions per second,

Power transferred from stator to rotor $= 2\pi T n_1$ watts.

If $n_r =$ rotor speed in revolutions per second,

Total mechanical power developed by rotor= $2\pi T n_r$watts.

Total I^2R loss in rotor

≈Power transferred from stator to rotor−Total mechanical power developed by rotor

$= 2\pi T(n_1 - n_r)$ Watts

$$\frac{\text{total rotor } I^2R \text{ loss}}{\text{input power to rotor}} = \frac{2\pi T(n_1 - n_r)}{2\pi T n_1} = s$$

Or total I^2R loss (in watts)

$= S \times$ input power to rotor (in watts)

2.9 Factors Determining The Torque

If m = number of rotor phases,

Then, using the symbols given in (2.2) we have:

Electrical power generated in rotor $= mI_rE_r\cos\emptyset_r$ watts

$$= \frac{mS^2E_0^2R}{R^2 + (sX_0)^2}$$

All this power is dissipated as I^2R loss in the rotor circuits

Since input power to rotor $= 2\pi T n_1$ watts, hence from (2.10), we have:

$$s \times \pi T n_1 = \frac{mS^2E_0^2R}{R^2 + (SX_0)^2}$$

Consequently, for given synchronous speed and number of rotor phases,

$$T \propto \frac{SE_0^2R}{R^2 + (SX_0)^2} \propto \frac{S\emptyset^2R}{R^2 + (SX_0)^2}$$

Since $E_0 \propto \emptyset$

Variation of torque with slip, other factors remaining constant:

If the impedance of the stator winding is assumed to be negligible, then for a given supply voltage, Ø and E_0 remain constant,

torque

$$\propto \frac{SR}{R^2 + (sX_0)^2} \qquad (2.11)$$

The value of X_0 is usually far greater than the resistance of the rotor winding; so let us for simplicity assume $R = 1\ \Omega$ and X_0=8 Ω, and calculate the value of $sR/(R^2 + s^2X_0^2)$ for various values of the slip between 1 and 0 the results are represented by curve A in fig (2.4) it will be seen that for small values of the slip, the torque is almost directly proportional to the slip; whereas for slips between about 0.2 and 1, the torque is almost inversely proportional to the slip. These relationships can be easily deduced from expression (2.11).

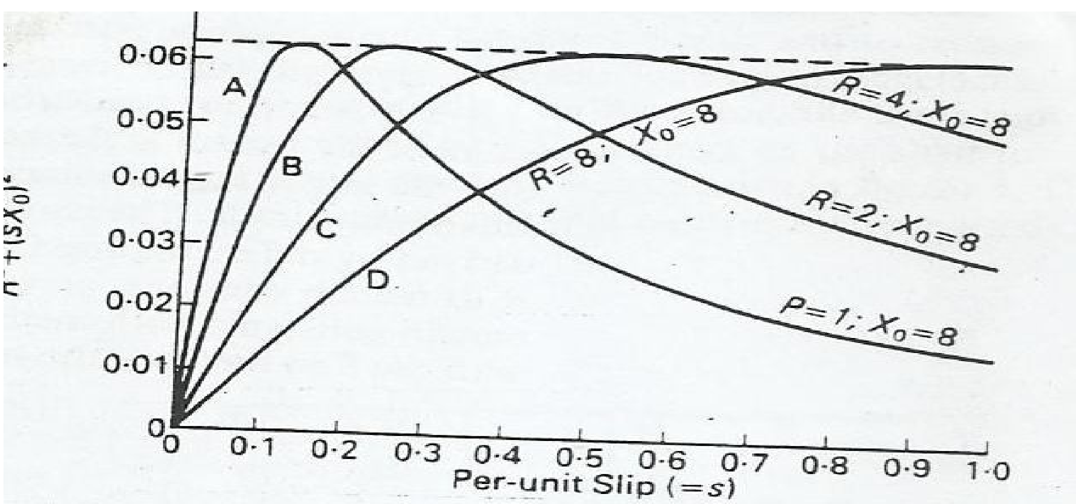

Figure2.4. torque/slip curves for an induction motor

Thus, in the case of the cage rotor, R is small compared with X_0,but for values of the slip less than about 0.1 per-units; $(X_0{}^2)$ is very small compared with R^2 , so that:

$$\text{torque} \propto \frac{sR}{R^2}$$

$$\propto \frac{s}{R} \qquad (2.12)$$

i.e. the torque is directly proportional to the slip when the latter is very small.

For large values of the slip, R^2 is very small compared with $(sX_0)^2$ for the cage rotor and for the slip-ring rotor with no external resistance

$$\text{torque} \propto \frac{sR}{(sX_0)^2}$$

$$\propto \frac{R}{s} \qquad (2.13)$$

Since X_0 is constant for a given motor; i.e. the torque is inversely proportional to the slip when the latter is large.

2.10 Effect Of Rotor Resistance Upon the Torque /Slip Relationship

From (2.13) when R is small compared with sX_0, the torque for a given slip is directly proportional to the value of R; whereas from expression (2.12) it follows that when R is large compared with sX_0, the torque for a given slip is inversely proportional to the value of R. The simplest method of demonstrating this effect is to repeat the calculation of $sR/(R^2 + sX_0^2)$ with $R = 2$, $R = 4$ and $R = 8$. The results are represented by curves B, C and D respectively in figure(2.4) it will be seen that for a slip of, say, 0.05p.u., the effect of doubling the rotor resistance is to reduce the torque, by about 0.45 per unit, whereas for a slip of 1, the torque is nearly doubled when the resistance is increased from 1 to 2. Hence, if a large starting torque is required, the rotor must have a relatively high resistance.

It will also be noticed from figure(2.4) that the maximum value of the torque is the same for the four values of R and that the larger the resistance the greater is the slip at maximum torque can be derived by differentiating (2.11) with respect to s, assuming R to remain constant. Both methods give the same result; thus with the first method, the torque is maximum when:

$$\frac{d}{ds}\left(\frac{sR}{R^2 + s^2X_0^2}\right) = \frac{(R^2 + s^2X_0^2)R - sR \times 2sX_0^2}{(R^2 + s^2X_0^2)^2} = 0$$

i.e. $R^2 - s^2X_0^2 = 0$

so that $\quad sX_0 = R$

(2.14)

hence the torque is a maximum when the reactance is equal to the resistance. With $R = 1\Omega$ and $X_0 = 8\Omega$. Maximum torque occurs when $s = 0.125\text{p.u.}$; whereas with $R = 8\Omega$ and $X_0 = 8\Omega$ Maximum torque occurs when $s = 1$. Namely when the rotor is at standstill.

Substituting R for sX_0in expression(2.11) we have:

$$\text{maximum torque} \propto \frac{sR}{2R^2} \propto \frac{1}{2X_0}$$

But X_0 is the leakage reactance at standstill and is a constant for a given rotor; hence the maximum torque is the same whatever the value of the rotor resistance.

2.11 Starting Torque

At the instant of starting, $s = 1$, and it will be seen from figure(2.4)that is the motor having a low-resistance rotor, such as the usual type of cage rotor, the starting torque is small compared with the maximum torque available. On the other hand, if the bars of cage rotor were made with sufficiently high resistance to give the maximum torque at standstill, the slip for full-load torque usually about one-third to one-half of the maximum torque would be relatively large and the I^2R loss in the rotor winding would be high, with the result that the efficiency would be low; and if this load was maintained for an hour or two, the temperature rise would be excessive. Also the variation of the speed with load would be large. Hence when a motor is required to exert its maximum torque at starting, the usual practice is to insert extra resistance into the rotor circuit and to reduce the resistance as the motor accelerates. Such an arrangement involves a three-phase winding on the rotor, the three ends of the winding being connected via slip-rings on the shaft to external star-connected resistors R, as shown in figure(2.5) the three arms. A, are mechanically and electrically connected together.

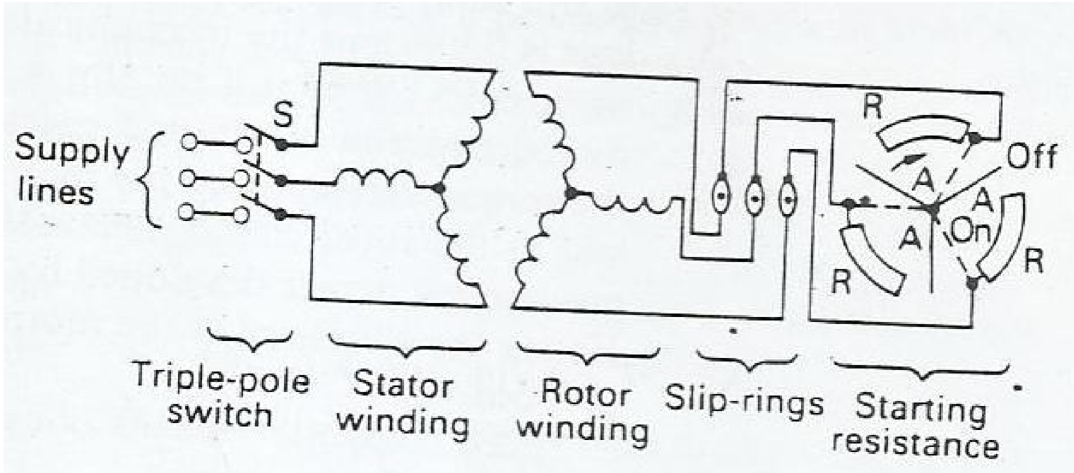

Figure2.5.Induction Motor Slip-Ring Rotor

2.12 Variation Of Torque With Stator Voltage, Other Factors Remaining Constant

From expression (2.11) , it is seen that for given values of the slip and of the rotor resistance and reactance,

$$\text{torque on rotor} \propto \emptyset^2$$

But for a given stator winding, $\emptyset$ is approximately proportional to the voltage applied to the stator winding[14].

$\text{torque on rotor} \propto (\text{stator applied voltage})^2$

(2.15)

2.13 Induction Motor Drives

Three-phase induction motors are commonly used in adjustable-speed drives and they have three-phase stator and rotor windings. The stator windings are supplied with balanced three-phase ac voltages, which produce induced voltages in the rotor windings due to transformer action. It is possible to arrange the distribution of stator windings so that there is an effect of multiple poles, producing several cycles of magneto motive force (m.m.f.) (or field) around the air gap. This field establishes a spatially distributed sinusoidal flux density in the air gap. The speed of rotation of the field is called the synchronous speed, which is defined by

$\omega_s = \frac{2\omega}{p}$

(2.16)

Wherepis the number of poles and ω is the supply frequency in rads per second.

If a stator phase voltage, $V_s = \sqrt{2}v_s \sin \omega t$, produces a flux linkage (in the rotor) given by

$\emptyset(r)=$ $\emptyset_m \cos(\omega_m t + \varphi - \omega_s t)$

(2.17)

The induced voltage per phase in the rotor winding is:

$$e_r = N_r \frac{d\emptyset}{dt} = N_r \frac{d}{dt}[\emptyset_m \cos(\omega_m t + \varphi - \omega_s t)]$$

$$= -N_r \emptyset_m (\omega_s - \omega_m) \sin[(\omega_s - \omega_m)t - \varphi]$$

$=-sE_m \sin(s\omega_s t - \varphi)$

(2.18)

$=-s\sqrt{2}E_r \sin(s\omega_s t - \varphi)$

Where N_r= number of turns on each rotor phase;

ω_m= angular rotor speed or frequency, Hz;

φ = relative position of the rotor;

E_r = rms value of the induced voltage in the rotor per phase, V;

E_m= peak induced voltage in the rotor per phase, V;

Andsis the slip, defined as

$s = \frac{(\omega_s - \omega_m)}{\omega_s}$

(2.19)

Which gives the motor speed as $\omega_m = \omega_s(1 - s)$. The equivalent circuit for one phase of the rotor is shown in Figure2.6.

Where R_r is the resistance per-phase of the rotor windings;

X_r is the leakage reactance per phase of the rotor at the supply frequency;

E_r Represents the induced rmsphase voltage when the speed is zero or

$(s - 1)$.

The rotor current is given by:

$$I_r = \frac{sE_r}{R_r + jsX_r} \quad (2.20)$$

$$= \frac{E_r}{R/_s + jsX_r} \quad (2.20a)$$

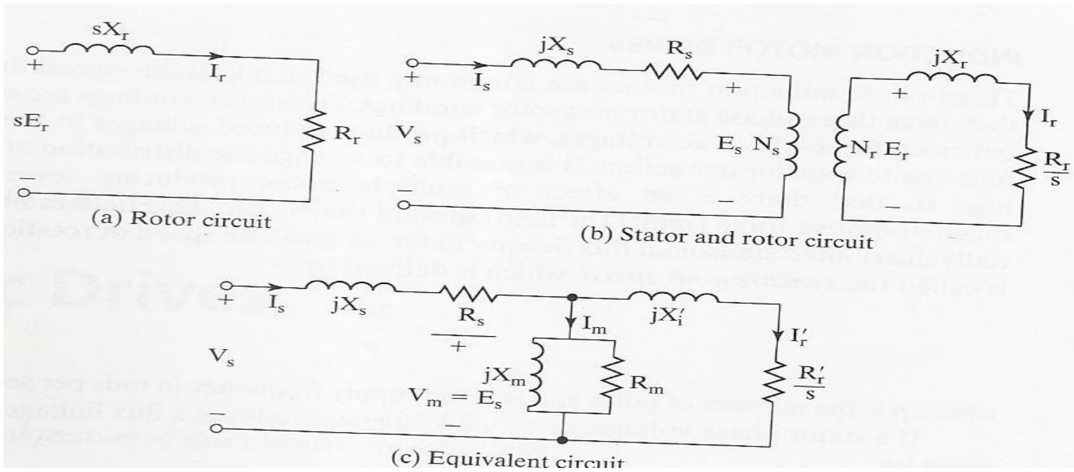

Figure2.6. Circuit Model Of Induction Motor

Where R_r ,and X_r are referred to the rotor winding.

The per phase circuit model of induction motors is shown in Figure2.6,where $R_s$and $X_s$are the per- phase resistance and leakage reactance of the stator winding. R_m Represents the resistance for excitation (or core) loss and X_m is the magnetizing reactance. R_r' and X_r' are the rotor resistance and reactance referred to the stator.I_r' is the rotor current referred to the stator. There will be stator core loss, when the supply is connected and the rotor core loss depends on the slip. The friction and winding loss $P_{no\,load}$ losses exists when the machine rotates. The core loss P_c may be included as a part of rotational loss$P_{no\,load}$.

2.13.1 Performance Characteristic

The rotor current I_r and stator current I_s can be found from the circuit model in Figure2.6c where R_r and X_r are referred to the stator windings. Once the values of I_r, and $I_s$are known, the performance parameters of a three-phase motor can be determined as follows:

Stator copper loss

$$P_{cu} = 3I_s^2 R_s \quad (2.21)$$

Rotor cupper loss

$$P_{cu} = 3(I_r')^2 R_r' \quad (2.22)$$

Core loss

$$P_c = \frac{3V_m^2}{R_m} \approx \frac{3V_s^2}{R_m} \quad (2.23)$$

Gap power (power passing from the stator to the rotor through the air gap)

$$P_g = 3(I_r')^2 \frac{R_r'}{S} \quad (2.24)$$

Developed power

$$P_d = P_g - P_{ru}$$

$$= 3(I_r')^2 \frac{R_r'}{S}(1 - S) \quad (2.25)$$

$$= P_g(1 - S) \quad (2.26)$$

Developed torque

$$T_d = \frac{P_d}{\omega_m} \quad (2.27)$$

$$= \frac{P_g(1-S)}{\omega_s(1-S)}$$

$$= \frac{P_g}{\omega_s} \quad (2.27a)$$

Input power

$$P_i = 3V_s I_s \cos\theta_m \quad (2.28)$$

$$= P_c + P_{cu} + P_g \quad (2.28a)$$

Where θ_m is angle between I_s and V_s output power

$$P_o = P_d - P_{noload}$$

Efficiency

$$\eta = \frac{P_o}{P_i}$$

$$= \frac{P_d - P_{noload}}{P_c + P_{su} + P_g} \qquad (2.29)$$

if $P_g \gg (P_c + P_{cu})$ and $P_d \gg P_{noload}$,the efficiency becomes approximately

$$\eta = \frac{P_d}{P_g} = \frac{P_g(1-S)}{P_g}$$

$$= 1 - S \qquad (2.29a)$$

The value of X_m is normally large and R_m, which is much larger, can be removed from the circuit model to simplify the calculations. If ${X_m}^2 \gg (R_s^2 + X_s^2)$, then $V_s \approx V_m$, and the magnetizing reactance X_m, may be moved to the stator winding to simplify further; this is shown in Figure 2.6

The input impedance of the motor becomes

$$Z_i = \frac{-X_m(X_s + X_r') + jX_m(R_s + R_r'/S)}{R_s + R_r'/S + j(X_m + X_s + X_r')} \qquad (2.30)$$

and the power factor (PF) angle of the motor

$$\theta_m = \pi - \tan^{-1}\frac{R_s + R_r'/S}{X_s + X_r'} + \tan^{-1}\frac{X_m + X_s + X_r'}{R_s + R_r'/S} \qquad (2.31)$$

From Figure 2.6, the $r.m.s$ rotor current

$$I_r' = \frac{V_s}{[(R_s + R_s'/S)^2 + (X_s + X_r')^2\,]^{\frac{1}{2}}} \qquad (2.32)$$

Substituting I,. from Eq. (2.32) in Eq. (2.24) and then Pg in Eq. (2.27) yields

$$T_d = \frac{3R_r'V_s^2}{S\omega_s[(R_s + R_r'/S)^2 + (X_s + X_r')^2]} \tag{2.33}$$

At starting, the machine speed is $\omega_m = 0$ and s = 1. The starting torque can be found from Eq. (2.33) by setting s = 1
as

$$T_s = \frac{3R_r'V_s'}{\omega_s[(R_s + R_r')^2 + (X_s + X_r')^2]} \tag{2.34}$$

The slip for maximum torque S_m can be determined by setting $dT_d/ds = 0$ and Eq. (2.33) yields

$$S_m = \pm\frac{R_r'}{[R_s^2 + (X_s + X_r')^2]^{\frac{1}{2}}} \tag{2.35}$$

Substituting $S = S_m$ in Eq. (2.33) gives the maximum developed torque during motoring, which is also called pull-out torque, or breakdown torque,

$$T_{mm} = \frac{3V_s^2}{2\omega_s[R_s + \sqrt{R_s^2 + (X_s + X_r')^2}} \tag{2.36}$$

and the maximum regenerative torque can be found from Eq. (2.33)by letting

$$S = -S_m$$

$$T_{mr} = \frac{3V_s^2}{2\omega_s[-R_s + \sqrt{R_s^2 + (X_s + X_r')^2}} \tag{2.37}$$

If R_s is considered small compared with other circuit impedances, which is usually a valid approximation for motors of more than 1-kW rating, the corresponding express ions become

$$T_d = \frac{3R_r' V_s^2}{S\omega_s[(R_r')^2 + (X_s + X_r')^2]} \tag{2.38}$$

$$T_s = \frac{3R_r' V_s^2}{\omega_s[(R_r')^2 + (X_s + X_r')^2]} \tag{2.39}$$

$$S_m = \pm \frac{R_r'}{X_s + X_r'} \tag{2.40}$$

$$T_{mm} = -T_{mr} = \frac{3V_s^2}{2\omega_s(X_s + X_r')} \tag{2.41}$$

Normalizing Eq. (2.38) and (2.39) with respect to Eq. (2.41) gives

$$\frac{T_d}{T_{mm}} = \frac{2R_r'(X_s + X_r')}{S[(R_r'/S)^2 + (X_s + X_r')^2]} = \frac{2SS_m}{S_m^2 + S^2} \tag{2.42}$$

And

$$\frac{T_s}{T_m} = \frac{2R_r'(X_s + X_r')}{(R_r')^2 + (X_s + X_r')^2} = \frac{2S_m}{S_m^2 + 1} \tag{2.43}$$

If $S < 1,\ S^2 \ll S_m^2$ and Equ (2.42) can be approximated to

$$\frac{T_d}{T_{mm}} = \frac{2S}{S_m} = \frac{2(\omega_s - \omega_m)}{S_m \omega_s} \tag{2.44}$$

which gives the speed as a function of torque,

$$\omega_m = \omega_s \left(1 - \frac{S_m}{2T_{mm}} T_d\right) \tag{2.45}$$

It can be noticed from Eq. (2.44) and (2.45) that if the motor operates with small slip, the developed torque is proportional to slip and the speed decreases with torque. The rotor current, which is zero at the synchronous speed, increases due to the decrease in R_r/S as the speed is decreased. The developed torque also increases until it becomes maximum at $S = S_m$ For $S < S_m$, the motor operates stably on the portion of the speed—torque characteristic. If the rotor resistance is low,S_m is low. That is, the change of motor speed from no-load to rated torque is only a small percentage. The motor operates essentially at a constant speed. When the load torque exceeds the breakdown torque, the motor stops and the overload protection must immediately disconnect the source to prevent damage due to overheating. It should be noted that for $S > S_m$,the torque decreases despite an increase in the rotor current and the operation[1].

2.14Anlysis Of Various Methods For Speed Control Of Induction Motor

Nowadays, common solutions for high-power applications are based on drives that include a voltage source inverter (VSI) feeding an induction motor or a permanent magnet synchronous motor. However, old-fashioned solutions based on a current source inverter or on thyristors are still employed, whereas old schemes based on dc series motors or direct dc motors are no longer used. Different control schemes are adopted and tailored to the specific application. Typically, variable structure controls are used for high-performance traction drive systems that change according to the operating conditions, particularly according to the speed and flux levels. The various methods of speed control of 3-phase Induction motor are as:

1. Pole Changing
2. Variable Supply Frequency
3. Variable rotor resistance control
4. Variable supply voltage control
5. Constant voltage frequency (V/f) control
6. Slip recovery
7. Vector Control

However, we shall not be analyzing the pole changing and the variable supply frequency methods as these are very rarely used.

2.14.1Variable Rotor Resistance

This method is applicable only to the wound rotor motor as external resistance can be added to it through the slip rings.

External resistances can be connected in the rotor circuit during starting. This increases the starting torque and reduces the starting current making use of appropriate value of resistors, the maximum torque can be made to appear during starting. This can be used in applications requiring high starting torque. Once the motor is started, the external resistance can be cut out to obtain high torque throughout the accelerating range. As external resistances are connected, most of the I^2R loss is dissipated through them thus the rotor temperature rise during starting is limited. Variable Stator Voltage The torque developed by an induction motor varies as square of the voltage applied to its stator terminals. Thus by varying the applied voltage, the electromagnetic torque developed by the motor can be varied. This method is generally used for small squirrel-cage motors where cost is an important criterion and efficiency is not. However, this method has rather limited range of speed control. this method is shown in figur2.7

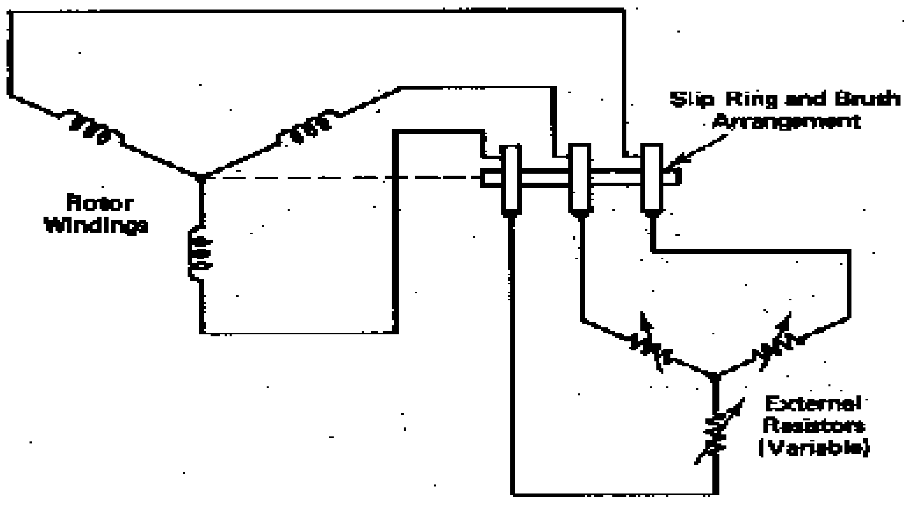

Figure2.7 Variable Rotor Resistance Control

2.14.2Constant Voltage/Frequency (V/f) Control

We vary the stator voltage in such a way that the flux remains constant by simultaneously varying the supply frequency such that the ratio voltage/frequency (V/f) remains constant.

The AC supply is rectified and then applied to a PWM inverter to obtain a variable frequency, variable magnitude 3-phase AC supply. The electromagnetic torque developed by the motor is directly proportional to the magnetic field produced by the stator and the flux produced by the stator is proportional to the ratio of applied voltage and frequency of supply. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range. This makes constant voltage/frequency method the most common speed control method of an induction motor.

-Closed Loop voltage/frequency (V/f) speed control method

-Open Loop voltage/frequency (V/f) speed control method using PI controller

-Closed Loop voltage/frequency (V/f) speed control method using PI controller

2.15 Vector Control Method

The induction motor is the most widely used electrical motor due to its rugged structure, low cost and reliability. However, the nonlinearity in the Torque-Voltage relationship of an induction motor makes its analysis difficult. Also it is a fifth order system making its dynamic response poor. Development of Vector Control analysis has enabled us to get as good dynamic performance from an induction motor as a dc motor. The torque and the flux components can be controlled independently using vector control just like in a dc motor.

In order to analyses vector control, we need to develop a dynamic model of the induction motor. This is done by converting the 3-phase quantities into 2-axes system called the d-axis and the q-axis. Such a conversion is called axes transformation. The d-q axes can be chosen to be stationary or rotating. Further, the rotating frame can either be the rotor oriented or magnetizing flux oriented. However, synchronous reference frame in which the d-axis is aligned with the rotor flux is found to be the most convenient from analysis point of view.

A major disadvantage of the per phase equivalent circuit analysis is that it is valid only if the three phase system is balanced. Any imbalance in the system leads to erroneous analysis. Even this problem is eradicated if we use the d-q model[8].

2.16 Stator Voltage Control

Equation

$$T_d = \frac{3R_r' V_s^2}{S\omega_s[(R_r')^2 + (X_s + X_r')^2\,]} \tag{2.38}$$

indicates that the torque is proportional to the square of the stator supply voltage and a reduction in stator voltage can produce a reduction in speed. If the terminal voltage is reduced to (bV_s), Eq. (2.46) gives the developed torque

$$T_d = \frac{3R_r'(bV_s)^2}{S\omega_s[(R_s + R_r'/S)^2 + (X_s + X_r')^2]} \tag{2.46}$$

Where $b \leq 1$

Figure (2.8) shows the typical torque-speed characteristics for various values of b.The points of intersection with the load line define the stable operating points. In any magnetic circuit, the induced voltage is proportional to flux and frequency, and the $r.m.s.$ air-gap flux can be expressed as

$$V_a = bV_s = K_m \omega \emptyset$$

or

$$\emptyset = \frac{V_a}{K_m \omega}$$

$$= \frac{bV_s}{K_m \omega} \qquad (2.47)$$

where K_m is a constant and depends on the number of turns of the stator winding. As the stator voltage is reduced, the air-gap flux and the torque are also reduced. At a lower voltage, the current can be peaking at a slip of $s_a = \frac{1}{3}$ The range of speed control depends on the slip for maximum torque s_m For a low-slip motor, the speed range is very narrow. This type of voltage control is not suitable for a constant torque load and is normally applied to applications requiring low-starting torque and a narrow range of speed at a relatively low slip[1].

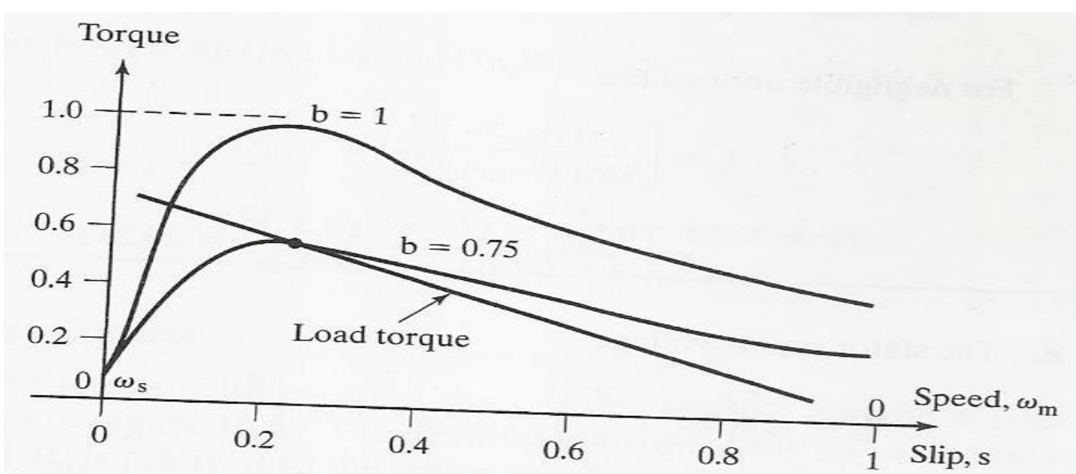

Figure2.8. Torque-Speed Characteristics With Variable Stator Voltage

The stator voltage can be varied by three-phase AC voltage controllers, voltage-fed variable DC link inverters, and PWM inverters.

However, due to limited speed range requirements, the AC voltage controllers are normally used to provide the voltage control. The AC voltage controllers are very simple. However, the harmonic contents are high and the input power factor of the controllers is low.

CHAPTER THREE

SIMULATION

3.1Motor Rating and Parameters

Table3.1 shows typical values used for example

Table3.1 IM specifications

Number Of Phase	**3**
Rated stator voltage Y-Connection	**415 v**
Operation Frequency	**60** Hz
Number Of Poles	**4**
Stator Resistance	**1.01 Ω**
Rotor Resistance	**0.69 Ω**
Stator Reactance	**1.3 Ω**
Rotor Reactance	**1.94 Ω**
Magnetizing Reactance	**43.5 Ω**
The motor speed	**1550$r.p.m.$**

The no-load loss $P_{no-load}$ is negligible.

The load torque, which is proportional, is 41N.m at 1740 rpm

The motor speed is 1550 pm ,$\omega = 2\pi \times 60\, rad/sec$,$\omega_s = 377 \times \frac{2}{4} =$ 188.5rad/sec , s = (188.5-162.3)/188.5 =0.139 ,since torque is proportional to speed squared Eq. (2.48)

T_L

$= K_m \omega_m^2$ (2.48)

At $\omega_m = \frac{1740\pi}{30} = 182.2 rad/sec, T_L$=41N.M and Eq.(i) yields K_m =41/182.2^2=1.235$\times 10^{-3}$ and ω_m=1550$\pi/30$ =162.3rad/s

From Eq.(2.19)

$s = \frac{(\omega_s - \omega_m)}{\omega_s}$

(2.19)

3.2The MATLAB Codes

The following code shows MATLAB for execution for torque and speed characteristic

3.2.1Execution For Torque And Speed Characteristic

% Torque-Speed characteristics of induction motor

% 2014

%%

% First, initialize the values needed in this program.

r_1=1.01; % Stator resistance

x_1 =1.3; % Stator reactance

r_2 =0.69; % Rotor resistance

x_2 =1.94; % Rotor reactance

x_m =43.5; % Magnetization branch reactance

v_phase = 415 / sqrt(3); % Phase voltage

n_sync =1800; % Synchronous speed (r/min)

w_sync = 188.5; % Synchronous speed (rad/s)

% Calculate the Thevenin voltage and impedance

v_th = v_phase * (x_m/ sqrt(r1^2 + (x1 +)x_m^2));

z_th = ((1j*)x_m * (r1 + 1j*x1)) / (r1 + 1j*(x1 +)x_m);

r_th = real(z_th);

x_th = imag(z_th);

% Now calculate the torque-speed characteristic for many

% slips between 0 and 1

s = (0:1:50) / 50; % Slip

s(1) = 0.001;

nm = (1 - s) * n_sync; % Mechanical speed

% Calculate torque for rotor resistance

for counter = 1:51

tau(counter) = (3 * v_th^2 * r2 / s(counter)) /(w_sync * ((r_th + r2/s(counter))^2 + (x_th + x2)^2));

end

% Plot the torque-speed curve

```
plot(nm,tau);
xlabel('Speed \itn_{m} (rpm)','Fontweight','Bold');
ylabel('Torque \tau (N.m)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid on;
```

3.2.2 MATLAB Code Execution For Torque And Slip Characteristic

For the same values of stator and rotor resistances and reactance and magnetizing reactance.

```
% Torque-Slip characteristics of induction motor
% % 2014
%%
clc, clear, clear all
% First, initialize the values needed in this program.
r1=1.01;                % Stator resistance
x1=1.3;                 % Stator reactance
r2 =0.69;               % Rotor resistance
x2 =1.94;               % Rotor reactance
xm =43.5;               % Magnetization branch reactance
v_phase = 415 / sqrt(3);    % Phase voltage
n_sync = 1800;          % Synchronous speed (r/min)
w_sync = 188.5;         % Synchronous speed (rad/s)
% Calculate the Thevenin voltage and impedance
v_th = v_phase * (/xm sqrt(r1^2 + (x1+xm)^2) );
z_th = ((1j*) xm* (r1 + 1j*x1)) / (r1 + 1j*(x1 +xm));
r_th = real(z_th);
x_th = imag(z_th);
% Now calculate the torque-speed characteristic for many
% slips between -2 and 2
s = [0:0.01:2];
% Calculate torque for rotor resistance
for counter = 1:201
```

```
tau(counter) = (3 * v_th^2 * r2 / s(counter)) /(w_sync * ((r_th + r2/s(counter))^2 +
(x_th +x2)^2));
end
% Plot the torque-slip curve
plot(s,tau,'LineWidth',2);
xlabel('Slip','Fontweight','Bold');
ylabel('Torque \tau (N.m)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid
```

3.2.3 Execution For Induction Motor/Generator Mode

```
% Torque-Speed characteristics of induction motor
% 2014
%%
clc, clear, clear all
% First, initialize the values needed in this program.
r1=1.01;                % Stator resistance
x1=1.3;                 % Stator reactance
r2=0.69;                % Rotor resistance
x2=1.94;                % Rotor reactance
xm=43.5;                % Magnetization branch reactance
v_phase = 415/ sqrt(3);    % Phase voltage
n_sync = 1800;             % Synchronous speed (r/min)
w_sync = 188.5;            % Synchronous speed (rad/s)
% Calculate the Thevenin voltage and impedance
v_th = v_phase * (xm/ sqrt(r1^2 + (x1+xm)^2) );
z_th = ((1j*xm) * (r1 + 1j*x1)) / (r1+ 1j*(x1 +xm));
r_th = real(z_th);
x_th = imag(z_th);
% Now calculate the torque-speed characteristic for many
% slips between -2 and 2
s = (-2:0.01:2);
```

```
% Calculate torque for rotor resistance
for counter = 1:401
tau(counter) = (3 * v_th^2 * r2 / s(counter)) /(w_sync * ((r_th + r2/s(counter))^2 +
(x_th + x2)^2));
end
% Plot the torque-slip curve
plot(s,tau,'LineWidth',2);
xlabel('Slip','Fontweight','Bold');
ylabel('Torque \tau (N.m)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid
```

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1Results of Simulations

This figures below represent the result of the simulations

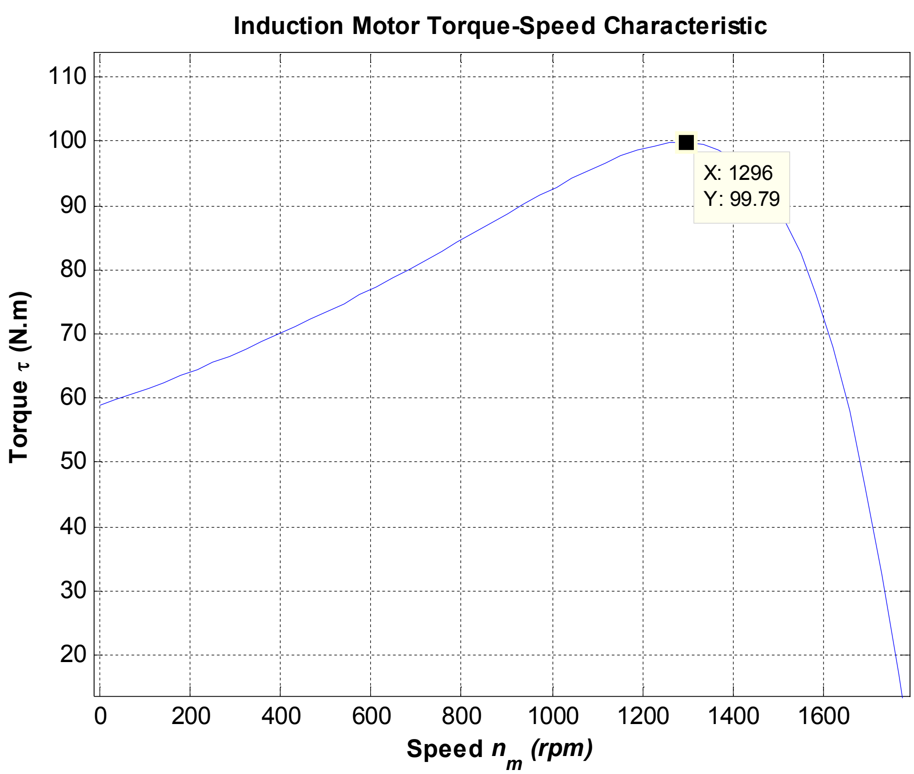

Figure4.1.Induction Motor Torque -Speed Characteristic

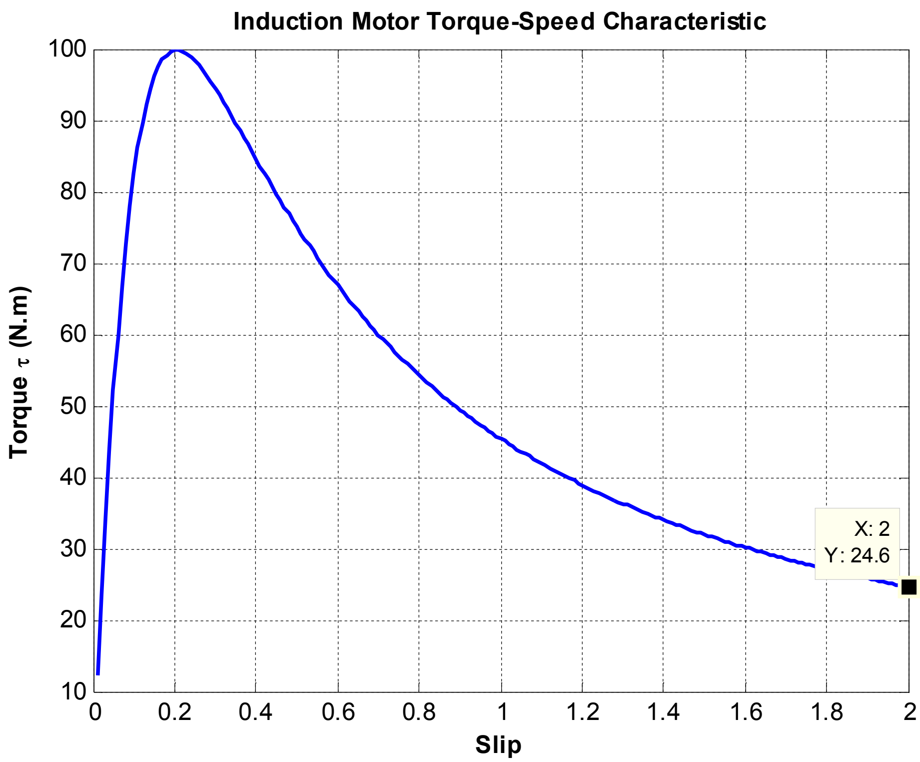

Figure4.2.Torque and Slip Curve

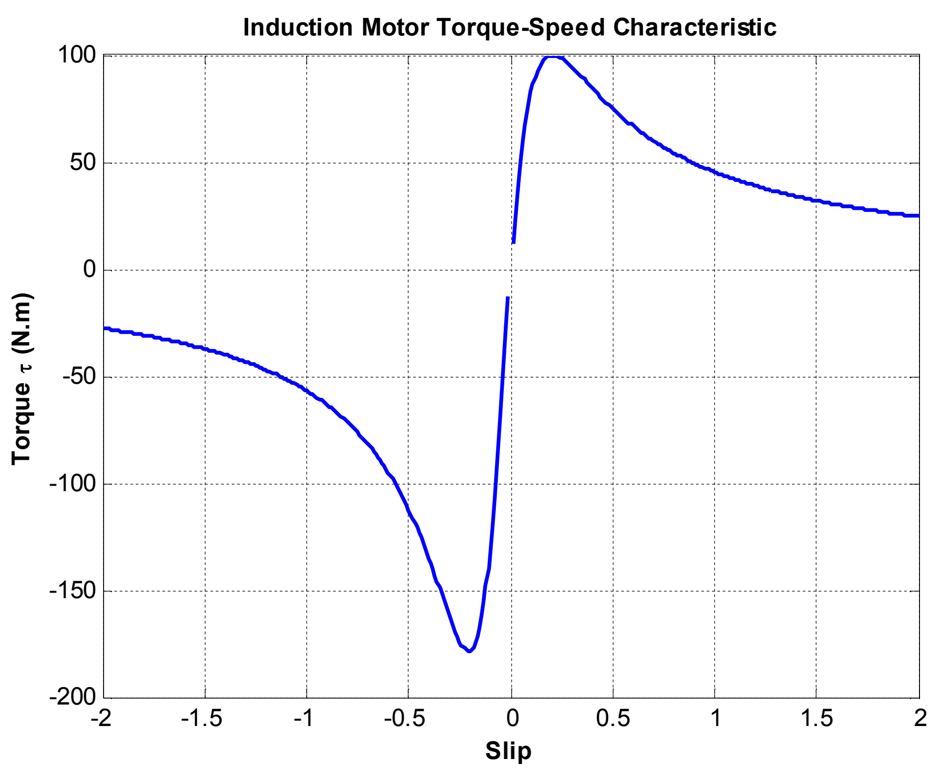

Figure4.3:Induction Motor/Generator Mode

4.1.Results Discussion

In figure4.1 Maximum torque is obtained approximately at speed of 1300 r.p.m ,Torque increase as the speed increased

In figure4.2 Maximum torque is occurred at slip of s= 0.2 it is equal approximately 99.79N.M,as the slip is increase the torque is drop. At slip of s=2the torque is about 24.6 N.M

At Synchronous Speed Induced torque of motor is zero. The starting torque is greater than full load torque. For a given slip the torque is proportional to the square of the applied voltage. when the motor is supplied from a fixed source with a consider frequency the torque develop is a function of slip.

figure4.3 shows the region of operation what are: Regeneration mode, Motoring mode and Plugging mode. Regeneration mode is for slip s is $s < 0$, Motoring mode is for slip s is $0 \leq s \leq 1$ and for Plugging mode is for slip s is $1 \leq s \leq 2$.

In motoring, the motor rotates in the same direction as the field; and as the slip increases, the torque also increases while the air-gap flux remains constant. Once the torque reaches its maximum value, $T_m$at $S = S_m$, the torque decreases, with the increase in slip due to reduction of the air-gap flux. In regeneration, the speed $\omega_m$is greater than the synchronous speed $\omega_s$with $\omega_m$and ω_s in the same direction, and the slip is negative. Therefore, R_r/S is negative. This means that power is fed back from the shaft into the rotor circuit and the motor operates as a generator. The motor returns power to the supply system. The torque-speed characteristic is similar to that of motoring, but having negative value of torque.

In reverse plugging, the speed is opposite to the direction of the field and the slip is greater than unity. This may happen if the sequence of the supply source is reversed while forward motoring, so that the direction of the field is also reversed. The developed 'torque ,which is in the same direction as the field, opposes the motion and acts as braking torque. Because s > 1, the motor currents are high, but the developed torque is low. The energy due to a plugging brake must be dissipated within the motor and this may cause excessive heating of the motor. This type of braking is not normally recommended.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1Conclusion

In a thesis, we studied the characteristics of speed and torque in induction motors using stator voltage parameters, we Derived the mathematical model, Determined Torque and Speed characteristic and Developed Torque Speed characteristic duty cycle.

We obtained The Maximum Torque 99.79 N.M at Slip of $\frac{1}{3}$ and synchronous speed of 1300 r.p.m

4.2.Recommendations

Since the research focused on identifying the characteristics of speed and torque of the Induction motors using it I recommend using PID controller to control induction motors and test the result practically , also study and analysis the crossing point between three region of operation due to slip values.

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