Sudan University of Sciences & Technology
College of Engineering
School of Electrical Nuclear Engineering

Speed Control of Induction Motor three Phase by Using Scalar Control Techniques

(التحكم في سرعة المحرك الحثي ثلاثي الطور بإستخدام تقنيات التحكم القياسي)

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of Bachelor In Electrical Engineering.

Prepared By:

1. **Hassan Siralkhatim Hassan Altayeb**
2. **Mohamed Ahmed Alkhider Ibrahim**
3. **Mohamed Widaa Mohamed Khalafalla**
4. **Osman Altayeb Abdalla Daak**

Supervised By:

U. Hanaa gaafer

October 2018

الآيـــة

بسم الله الرحمن الرحيم

﴿ هوَ الَّذي جَعَلَ الشَّمْسَ ضِياءً وَالقمَرَ نُوراً وَقَدَّرَهُ مَنَازِلَ لِتَعْلَمُوا عَدَدَ السِنِينَ وَالحِسَاب مَا خَلَقَ الله ذلكَ إلاَّ بِالحقِّ يُفصِّلُ الأياتِ لِقَوْمٍ يَعْلَمُون ﴾

صدق الله العظيم

‘‘‘

سورة يونس الآيـــة {5}

الإهــداء

الى :

التي حملتني وهناً على وهن وسقتني حباً
وألهمتني فكرا

أمـي الحبيبـة

الى :

ذلك الشامخ بقامة النخيل الذي أفنى شبابه

ليرى في ذاتي امتداداً لذاته

أبــي العزيـز

الى جميـع :

أعزائـــي وأحبائـــي ...
وإخوانـــي وأخواتـــي ...

الشكر والعرفان

يقول المصطفى صلى الله عليه وسلم : (من لا يشكر الناس لا يشكر الله) من هذا الدليل أولاً وأخيراً الشكر لله عز وجل على ما انعم علينا به من جوده وكرمه ومن صحة وعافية حتى أكملنا هذا الجهد المتواضع .

والشكر الى من اخلص لنا جهده ... فأذاقنا طعم الانتصار في العلم

والشكر يمزجه الاهداء لكل الكوكبة التي كانت تنير دروب الظلام ومعالم الطريق , الى من وقف على المنابر وأعطى من حصيلة فكره لينير دربنا فكانوا نعم الاباء والمرشدين طول مسيرتنا العلمية , نسأل الله لهم دوام الصحة والعافية وأن يجدوها في ميزان حسناتهم .

أساتذتنا الكرام في مدرسة الهندسة الكهربائية والنووية

والشكر الأخص للتي كانت نعم المرشدة طوال مسيرة هذا المشروع وجزاها الله عنا كل خير فلها منا كل الاحترام والتقدير .

الأستاذة / هناء جعفر

ABSTRACT

A development of simulation model for scalar control of three phase induction motor is Presented in this report .scalar control as the name indicates is due to magnitude variation of the Control variable only , disregard any coupling effect in the machine. There are several methods Can be used to control the speed and torque of induction motor .But, the scalar control is a very Simple method for controlling the speed of induction motor compared to the vector control which Is more complex . this report presents the most popular method of scalar control to control the Torque and speed of induction motor , which is about volts/hertz control method . The purpose of This method is to maintain the air gap flux of induction motor in constant in order by maintaining The ratio voltage to frequency to achieve higher run time efficiency .This project is designed using Simulink/ Matlab software. this software also is used to simulate and plot the speed and torque Response of the V/Hz control system. These, in the steady state, are defined by their magnitude and frequency and if these are the parameters that are adjusted, the control technique belongs in the class of **scalar control methods**. A rapid change in the magnitude or frequency may produce undesirable transient effects, for example a disturbance of the normally constant motor torque. This, fortunately, is not important in low-performance ASDs, such as those of pumps, fans, or blowers. There, typically, the motor speed is **open-loop controlled**, with no speed sensor required (although current sensors are usually employed in over current protection circuits).

المستخلص

لابد من التحكم في سرعة المحرك الحثي ثلاثي الطور لما يمتاز به من موثوقية عالية هناك عدة طرق للتحكم في سرعة المحرك الحثي ثلاثي الطور بالإضافة الى تقنية التحكم العددي (ثبات نسبة الفولتيه الى التردد) والتي تعتبر من أبسط طرق التحكم في السرعة مقارنة بطريقة التحكم بإستخدام تقنية التحكم الإتجاهي التي تعتبر من أكثر الطرق تعقيدا .

الغرض من هذه الطريقة هو المحافظة على الفيض في الفجوة الهوائية بصورة ثابتة من أجل المحافظة على نسبة الفولتية على التردد وذلك من أجل تحقيق زمن دوران ذو كفاءة عالية ولتطبيق هذه التقنية يتم استخدام الكترونات القدرة التي يمكنها التحكم في سرعة محرك التيار المتردد كما يمكنها مراقبة عزم الدوران وكذلك تصحيح معامل القدرة . عندما يتم التحكم في سرعة المحرك الحثي ثلاثي الطور عن طريق تقنية التحكم العددي فإنه يتم توفير عامل الزمن وثبات الطور لقيم مختلفة لفولتية المصدر .

تم عمل محاكاة لهذه الدراسة بإستخدام برنامج ماتلاب كما تم أيضاً رسم إستجابة السرعة والتردد بتقنية التحكم العددي والتغيير السريع في قيمة الجهد والعزم قد ينتج تأثيرات عابرة غير مرغوب فيها .

TABLE OF CONTENTS

CHAPTER ONE

GENERAL INTRODUCTION

CHAPTER TWO

LITERTURE OVERVIEW

CHAPTER THREE
POWER ELECTRONICS DEVICES

CHAPTER FOUR
MAIN CIRCUIT DESGIN AND SIMULATION

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF SYMBOLS

T_M	Developed torque, N/m
ω_M	Rotor speed ,rpm
P_{out}	Output mechanical power, watt
Φ_s	Magnetic flux, tesla
Pp	Pairs of poles, pole
ω_{syn}	A synchronous velocity, rpm
n_{syn}	A synchronous speed, rpm
F	Frequency, hertz
V_{LLm}	Peak value of line to line input voltage, volt
L	Inductor, henry
C	Capacitor, farad
S_{cr}	Critical slip
$\mathbf{\Lambda}$	stator flux , tesla
$\mathbf{R}_s$	stator resistance, ohm
$\mathbf{R}_{rr}$	rotor resistance, ohm
$\mathbf{X}_{Is}$	stator leakage reactance, ohm
$\mathbf{X}_{Irr}$	rotor leakage reactance, ohm
$\mathbf{X}_m$	Magnetizing reactance, ohm
□S	Phasor of stator voltage, volt
□S	Phasor of stator EMF
□$_{rr}$	Phasor of rotor EMF
□S	Phasor of stator current, amber
□$_{rr}$	Phasor of rotor current, amber
□$_{m}$	Phasor of magnetizing current, amber
$\mathbf{\Lambda}^{\wedge}{}_{S}$	The stator flux, tesla
$\mathbf{\Lambda}^{\wedge}{}_{\mathbf{m}}$	Air gap flux, tesla
$\mathbf{\Lambda}^{\wedge}$	Rotor flux , tesla

$V_{s,rat}$	Stator rated voltage, volt
F_{rat}	Rated frequency ,hertz

THE LIST OF ABBREVIATIONS

Abbreviation	Interpretation
ASDs	Adjustable speed drivers
EMI	Electromagnetic interference
DSPs	Digital signal processors
MMFs	Magneto motive forces
EMF	Electromotive force
VSI	Voltage source inverter
CSI	Current source inverter
UPS	Un-interrupting power supply
PWM	Pulse width modulation
DC	Dirct current
AC	Alternating current
ITR	Ideal transformer
IGBT	Insulated gate bipolar transistor

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Induction motor:

Electrical machines were invented in the eighteenth century . Electrostatic generators were among the most important instrument in scientific laboratories of the eighteenth and Nineteenth centuries . There are classified into frictional electrical machines and induction Electrical machines depending on the electrification process employed.

Alessadro Volta (1745-1827) the Italian physicist invented the electrophorus in1775 It is a simple but ingenious instrument that provided an almost unlimited series of electrical discharge. The first induction machine which generated electricity by a complex set of electrostatic induction was derived from it . This category includes ”doublers”or ”multipliers” developed in in the late eighteenth century and used to “multiply” charges too weak to be measured. Nicola Tesla has identified the rotating magnetic field principle in 1882. He exploited the principle to design unique two-phase induction motor in 1883. Then, Galileo Ferraris independently researched the concept in 1885. Introduction of Tesla’s motor from 1888 onwards initiated what is known as the second Industrial Revolution , making possible the efficient generation and long distance distribution of electrical energy using the alternating current transmission system. Motors usually operated by continually passing a conductor through a stationary magnetic field before the invention of the rotating magnetic field. Tesla had suggested that the commentators from machine could be removed and the device could operate on a rotary field of force. After that , Tesla had attained U.S. Patent 041619, Electric motor(December 1889),which resembles the motor seen in many of Tesla's photos . This classic alternating current electromagnetic motor was known as un induction motor .Figure 1.1 shows the classic induction machine.

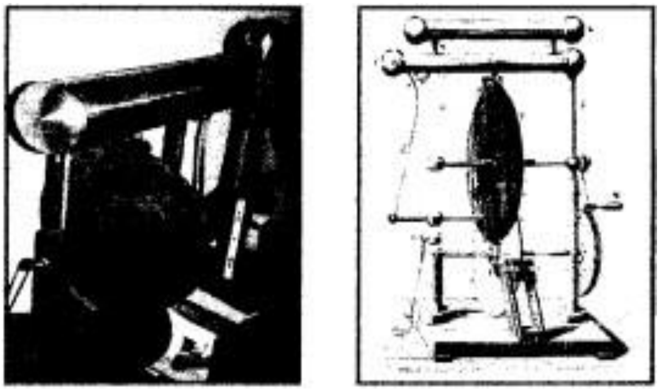


Figure 1.1: The classic induction machine

From the early twentieth century on, induction electrical machines were used extensively to generate electrical discharges ,to charge condensers, to power X-ray tubes, and for electrotherapy. Beside that, physicists have introduced the more efficient systems, such as transformers to produce high-voltage current led to the abandonment of induction machines. Today, induction machine has been improves to ensure its can be used widely in research laboratories and for industrial applications the cross section view of the new induction machine is shown in Figure 1.2.

Figure 1.2: Cross section view of the new induction machine

1.2 Problem statement:

The simulation model of scalar control of three phase induction motor is developed to overcome the problems arise. The problems are:

i. Informer times, people who have interest on scalar control feel hard to understand the concept and control technique.
ii. There was no simple simulation model of scalar control using Simulink/ Matlab to make the learning of scalar control become easier and interesting.
iii. Using vector control technique is more complex than using scalar control.

1.3 Project Objectives:

The main objectives of the development of simulation model of scalar control for three phase induction motor are as follows:

i. To constructs a simple simulation model of the scalar control of three phase induction motor using Simulink/Matlab.
ii. To study and understand the concept and control technique of the open loop scalar control of three phase induction motor.
iii. To do analysis of the response of volt/hertz control using Simulink/Matlab.
iv. Provide a package for learning purpose in controlling the speed and torque of induction motor.

1.4 Project Methodology:

This project aims to develop the simulation model for scalar control of three phase induction motor. The scope of this project in volt/hertz control that can control the speed and torque of induction motor . The speed and torque of induction motor can be change by changing the voltage and frequency supply to the stator, while the ratio of voltage and frequency must be kept constant to prevent the saturation of air gap flux.

1.5 Project structure:

Chapter two: This chapter talks about construction of in induction machine, and the main parts of induction motor(rotor&stator), and how to drive system with induction motor with ASDs, and the types of loads that can be connected with motor shaft and effects of load in the machine, also we talk about operating quadrants and the revolving magnetic filed that generated from stator wending and steady state equivalent&approximate circuit and we talk about can we control the stator voltage.

Chapter three: talks about PWM and power electronics, and how PWM generating different frequencies and we define inverters and rectifiers and operation theory each and they effect in the speed, also we talk about how to control voltage and current source inverters **.**

Chapter four: in this chapter we discus scalar and vector control methods and uses of each ,and we define the types of scalar control and also we talk about the open loop scalar speed control (Volts/Hertz) .

The simulation of the open loop scalar control by using Matlab/Simulink, with PWM and display the results and we made a comparison between the speed of induction motor before and after adding the controller.

Chapter five : This is the last chapter, and in this chapter we made the consolation of the research and the recommendations with all points the we see its important for understanding this etudes that we could not have the potentials to do it .

CHAPTER TWO

LITERATURE OVERVIEW

2.1 Construction of induction motor :

An induction motor consists of many parts, the stator and rotor being the basic subsystems of the machine. An exploded view of a squirrel-cage motor . The motor case (frame), ribbed outside for better cooling, houses the stator core with a three-phase winding placed in slots on the periphery of the core. The stator core is made of thin (0.3mm to 0.5 mm) soft-iron laminations, which are stacked and screwed together. Individual laminations are covered on both sides with insulating lacquer to reduce eddy-current losses. On the front side, the stator housing is closed by a cover, which also serves as a support for the front bearing of the rotor. Usually, the cover has drip-proof air intakes to improve cooling. The rotor, whose core is also made of laminations, is built around a shaft, which transmits the mechanical power to the load. The rotor is equipped with cooling fins. At the back, there is another bearing and a cooling fan affixed to the rotor The fan is enclosed by a fan cover.

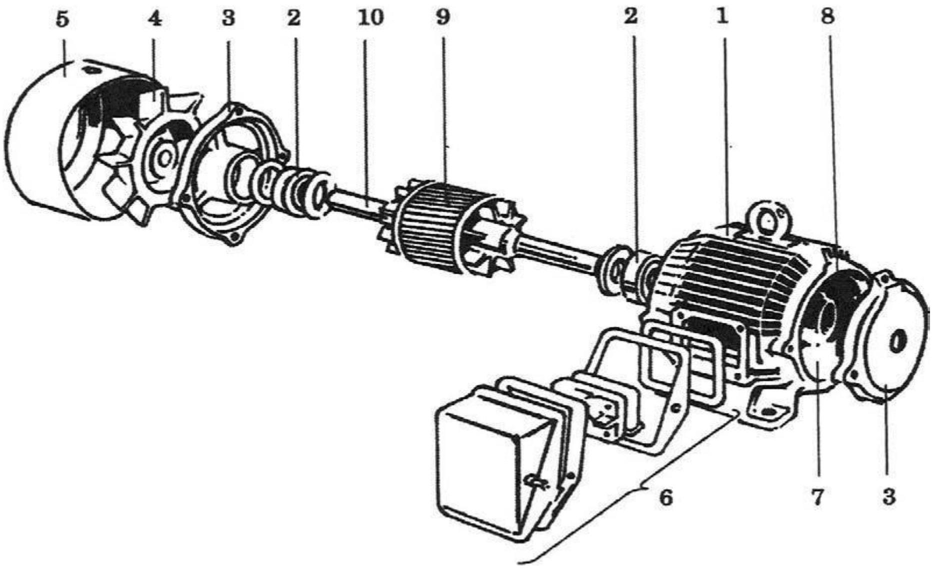


FIGURE 2.1: Exploded view of an induction motor

(1) motor case (frame) (2) ball bearings (3) bearing holders.
(4) cooling fan (5) fan housing. (6) connection box.
(7) stator core. (8) stator winding (not visible).
(9) rotor. (10) rotor shaft.

.

Access to the stator winding is provided by stator terminals located in the connection box that covers an opening in the stator housing. Open-frame, partly enclosed, and totally enclosed motors are distinguished by how well the inside of stator is sealed from the ambient air.

Totally enclosed motors can work in extremely harsh environments and in explosive atmospheres, for instance, in deep mines or lumber mills.

However, the cooling effectiveness suffers when the motor is tightly sealed, which reduces its power rating.

The squirrel-cage rotor winding, illustrated in Figure 2.2, consists of several bars connected at both ends by end rings. The rotor cage shown is somewhat oversimplified, practical rotor windings being made up of more than few bars (e.g., 23), not necessarily round, and slightly skewed with respect to the longitudinal axis of the motor. In certain machines, in order to change the inductance-to-resistance ratio that strongly influences mechanical characteristics of the motor, rotors with deep-bar cages and

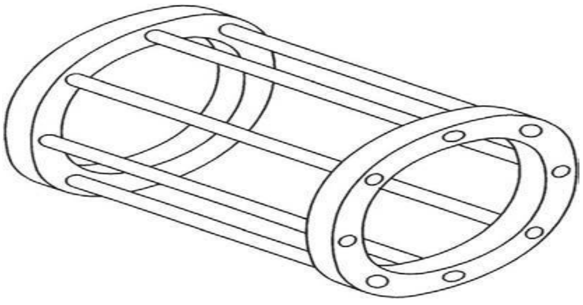


FIGURE 2.2: Squirrel-cage rotor winding.

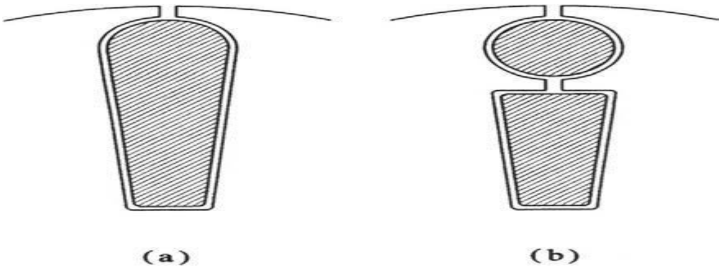


FIGURE 2.3: Cross-section of a rotor bar in (a) deep-bar cage, (b) double cage.

double cages are used. Those are depicted in Figures 2.3a and 2.3b, respectively.

2.2 Drive systems with induction motor:

An electric motor driving a mechanical load, directly or through a gearbox or a V-belt transmission, and the associated control equipment such as power converters, switches, relays, sensors, and microprocessors, constitute an electric drive system. It should be stressed that, as of today, most induction motor drives are still basically uncontrolled, the control functions limited to switching the motor on and off. Occasionally, in drive systems with difficult start-up due to a high torque and/or inertia of the load, simple means for reducing the starting current are employed. In applications where the speed, position, or torque must be controlled, ASDs with dc motors are still common. However, ASDs with induction motors have increasing popularity in industrial practice. The progress in control means and methods for these motors, particularly spectacular in the last decade, has resulted in development of several classes of ac ASDs having a clear competitive edge over dc drives.

Most of the energy consumed in industry by induction motors can be traced to high-powered but relatively unsophisticated machinery such as pumps, fans, blowers, grinders, or compressors. Clearly, there is no need for high dynamic performance of these drives, but speed control can bring significant energy savings in most cases. Consider, for example, a constant- speed blower, whose output is regulated by choking the air flow

in a valve. The same valve could be kept fully open at all times (or even disposed of) if the blower were part of an adjustable-speed drive system.

At a low air output, the motor would consume less power than that in the uncontrolled case, thanks to the reduced speed and torque.

High-performance induction motor drives, such as those for machine tools or elevators, in which the precise torque and position control is a must, are still relatively rare, although many sophisticated control techniques have already reached the stage of practicality. For better drive ability, high-performance adjustable-speed drives are also increasingly used in

electrical traction and other electric vehicles.

Except for simple two-, three-, or four-speed schemes based on pole changing, an induction motor ASD must include a variable-frequency source, the so-called inverter. Inverters are dc to ac converters, for which the dc power must be supplied by a rectifier fed from the ac power line.

The so-called dc link, in the form of a capacitor or reactor placed between the rectifier and inverter, gives the rectifier properties of a voltage source or a current source. Because rectifiers draw distorted, nonsinusoidal currents from the power system, passive or active filters are required at their input to reduce the low-frequency harmonic content in the supply currents.

Inverters, on the other hand, generate high-frequency current noise, which must not be allowed to reach the system. Otherwise, operation of sensitive communication and control equipment could be disturbed by the resultant electromagnetic interference (EMI). Thus, effective EMI filters are needed too.

For control of ASDs, microcomputers, microcontrollers, and digital signal processors (DSPs) are widely used. When sensors of voltage, current, speed, or position are added, an ASD represents a much more complex and expensive proposition than does an uncontrolled motor. This is one reason why plant managers are so often wary of installing ASDs. On the other hand, the motion-control industry has been developing increasingly

efficient, reliable, and user-friendly systems, and in the time to come ASDs with induction motors will certainly gain a substantial share of industrial applications.

2.3 Common loads:

Selection of an induction motor and its control scheme depends on the load. An ASD of a fan will certainly differ from that of a winder in apaper mill, the manufacturing process in the latter case imposing narrow tolerance bands on speed and torque of the motor. Various classifications.

Can be used with respect to loads. In particular, they can be classified with respect to:

(a) inertia.

(b) torque versus speed characteristic.

(c)control requirements.

High-inertia loads, such as electric vehicles, winders, or centrifuges, are more difficult to accelerate and decelerate than, for instance, a pump or a grinder.

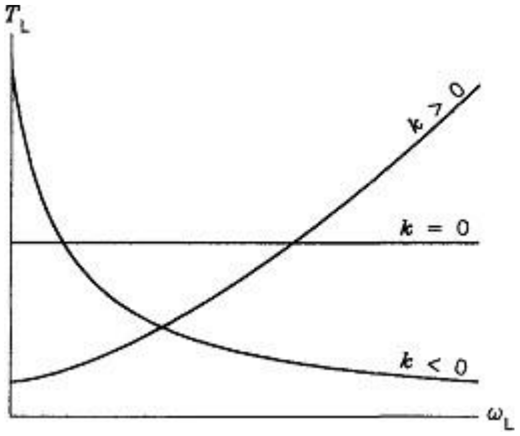


Figure 2.4: Mechanical characteristics of common loads.

1. Constant-torque characteristic, with k =0, typical for lifts and conveyors and, generally, for loads whose speed varies in a narrow range only.
2. Progressive-torque characteristic, with k > 0, typical for pumps, fans, blowers, compressors, electric vehicles and, generally, for most loads with a widely varying speed.
3. Regressive-torque characteristic, with k< 0, typical for winders. There, with a constant tension and linear speed of the wound tape, an increase in the coil radius is accompanied by a decreasing speed and an increasing torque.

Practical loads are better described by operating areas rather than mechanical characteristics. An operating area represents a set of all allowable operating points in the (ω_L,T_L) plane. Taking a pump as an example, its torque versus speed characteristic strongly depends on the pressure and viscosity of the pumped fluid. Analogously, the mechanical characteristic of a winder varies with changes in the tape tension and speed. Therefore, a single mechanical characteristic cannot account for all possible operating points.

2.4 Operating Quadrants:

The concept of operating quadrants plays an important role in the theory and practice of electric drives. Both the torque, T_m, developed in a motor and speed, ω_m, of the rotor can assume two polarities. For instance, watching the

motor from the front end, positive polarity can be assigned to the clockwise direction and negative polarity to the counterclockwise direction. Because the output (mechanical) power, P_{out}, of a motor is
given by:

$$P_{out}=T_m * \omega_m \tag{2.1}$$

The torque and speed polarities determine the direction of flow of power between the motor and load. With $P_{out} > 0$, the motor draws electric power from a supply system and converts it into mechanical power delivered to the load. Conversely, $P_{out} < 0$ indicates a reversed power flow, with the motor being driven by the load that acts as a prime mover. If proper arrangements are made, the motor can then operate as a generator and deliver electric power to the supply system. Such a regenerative mode of operation can be employed for braking a high-inertia load or lowering a load in a lift drive, reducing the net energy consumption by the motor. The operating quadrants in the already mentioned (ω_m,T_m) plane correspond to the four possible combinations of polarities of torque and speed, as shown in Figure 1.4. The power flow in the first quadrant and third quadrant is positive, and it is negative in the second and fourth quadrants. To illustrate the idea of operating quadrants, let us consider two drive systems, that of an elevator and that of an electric locomotive. When lifting, the torque and speed of elevator's motor have the same

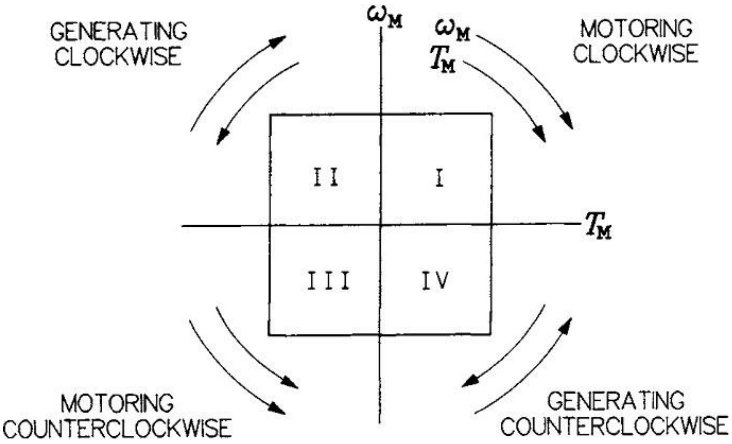


Figure 2.5: Operating quadrants in the (ω_M,T_M plane).

polarity. However, when lowering, the motor rotates in the other direction while the polarity of the torque remains unchanged. Indeed, in both cases the motor torque must counterbalance the unidirectional gravity torque. Thus, assuming a positive motor speed when lifting, the motor is seen to operate in the first quadrant, while operation in the fourth quadrant occurs when lowering. In the latter situation, it is the weight of the elevator cage that drives the motor, and the potential energy of the cage is converted into electrical energy in the motor. The supply system of the motor must be so designed that this energy is safely dissipated or returned to the power source.

As for the locomotive, both polarities of the motor speed are possible, depending on the direction of linear motion of the vehicle. Also, the motor torque can assume two polarities, agreeing with the speed when the locomotive is in the driving mode and opposing the speed when braking. The enormous kinetic energy would strain the mechanical brakes if they were the only source of braking torque. Therefore, all electric locomotives (and other electric vehicles as well) have a provision allowing electrical braking, which is performed by forcing the motor to operate as a generator. It can be seen that the two possible polarities of both the torque and speed make up for four quadrants of operation of the drive. For example, first quadrant may correspond to the forward driving, second quadrant to the forward braking, third quadrant to the backward driving, and fourth quadrant to the

backward braking. Yet, it is worth mentioning that, apart from electric vehicles, the four-quadrant operation is not very common in practice. Most of the ASDs, as well as uncontrolled motors, operate in the
first quadrant only.

Power electronic converters feeding induction motors in ASDs also can operate in up to four quadrants in the current-voltage plane. As known from the theory of electric machines, the developed torque and the armature current are closely related. The same applies to the speed and armature voltage of a machine. Therefore, if a converter-fed motor operates in a certain quadrant, the converter operates in the same quadrant.

2.5 Revolving magnetic field:

The three-phase stator winding produces a revolving magnetic field, which constitutes an important property of not only induction motors but also synchronous machines. Generation of the revolving magnetic field by stationary phase windings of the stator is explained in Figures 1.3 through 2.9. A simplified arrangement of the windings, each consisting of a one loop single-wire coil, is depicted in Figure 2.4 (in real motors, several Multi wire loops of each phase winding are placed in slots spread along the inner periphery of the stator). The coils are displaced in space by 120° from each other. They can be connected in wye or delta,

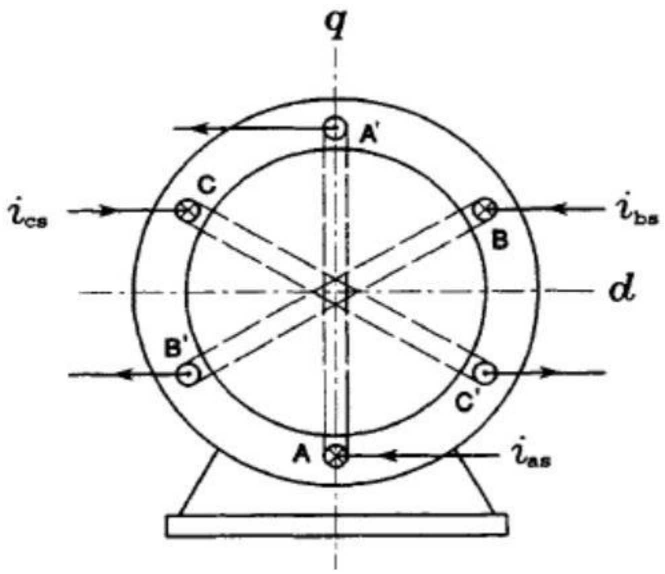


Figure 2.6 : Two-pole stator of the induction motor .

which in this context is unimportant. Figure 3.2 shows waveforms of currents I_{as}, I_{bs} ,and I_{cs} in individual phase windings. The stator currents are given by:

$$i_{as}=I_{s,m}\cos(\omega t) \tag{2.2}$$

$$I_{bs} = I_{bs} \cos(\omega t - \_\pi) \tag{2.3}$$

And

$$i_{as} = I_{s,m} \cos(\omega t - \pi) \tag{2.4}$$

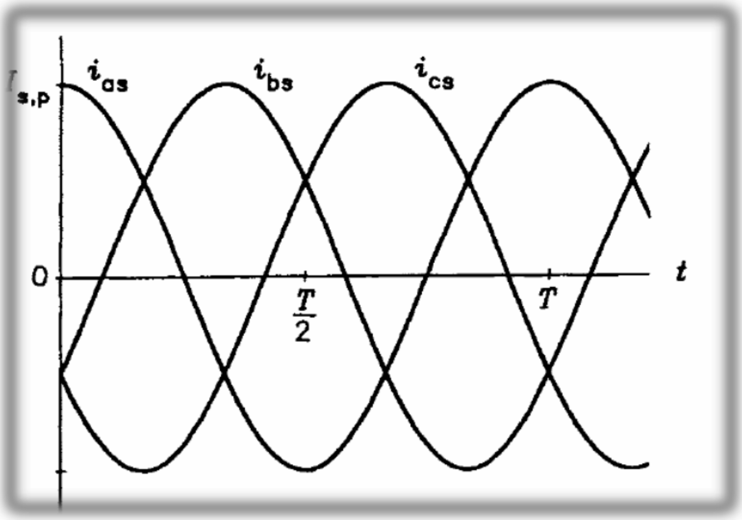


FIGURE 2.7: Waveforms of stator currents.

where $I_{s,p}$ denotes their peak value and ω is the supply radian frequency; they are mutually displaced in phase by the same 120°. A phasor diagram of stator currents, at the instant of t = 0, is shown in Figure 2.8 with the corresponding distribution of currents in the stator winding. Current entering a given coil at the end designated by an unprimed letter, e.g.,

A, is considered positive and marked by a cross, while current leaving a coil at that end is marked by a dot and considered negative. Also shown are vectors of the magneto motive forces (MMFs) ,F_{sa} , F_{sb} , and F_{sc} produced by the phase currents. These, when added, yield the vector, F_s ,of the total MMF of the stator, whose magnitude is 1.5 times greater than that of the maximum value of phase MMFs. The two half-circular loops

represent the pattern of the resultant magnetic field, that is, lines of the magnetic flux, ϕs , of stator.

At r = r/6, where T denotes the period of stator voltage, that is, a reciprocal of the supply frequency ,f , the phasor diagram and distribution.

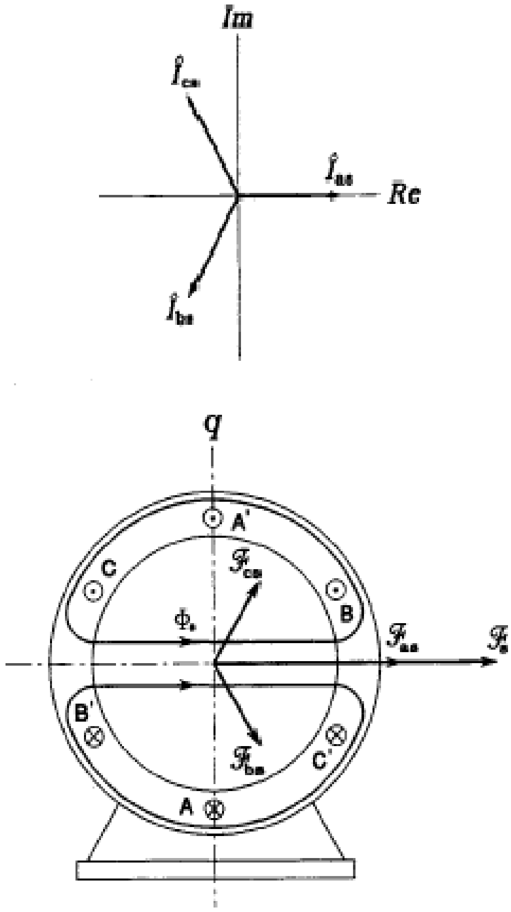


Figure 2.8: Phasor diagram of stator currents and the resultant magnetic field in a two-pole motor at $\omega_t = 0$.

of phase currents and MMFs are as seen in Figure 2.9. The voltage phasors have turned counterclockwise by 60°. Although phase MMFs did not change their directions, remaining perpendicular to the corresponding stator coils, the total MMF has turned by the same 60°. In other words, the special angular displacement, a, of the stator MMF equals the "electric angle," lot. In general, production of a revolving field requires at least two phase windings displaced in space, with currents in these windings displaced in phase.

The stator in Figure 2.6 is called a two-pole stator because the magnetic field, which is generated by the total MMF and which closes through the iron of the stator and rotor, acquires the same shape as that produced by two revolving physical magnetic poles. A four-pole stator is shown in Figure 2.8 with the same values of phase currents as those in Figure 2.8. When, T/6 seconds later, the phasor diagram has again turned by 60°, the pattern of crosses and dots marking currents in individual conductors of

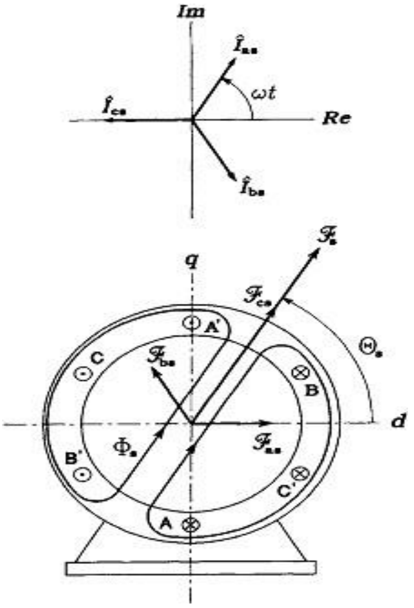


Figure 2.9: Phasor diagram of stator currents and the resultant magnetic field in a two-pole motor at $\omega_t = 60°$.

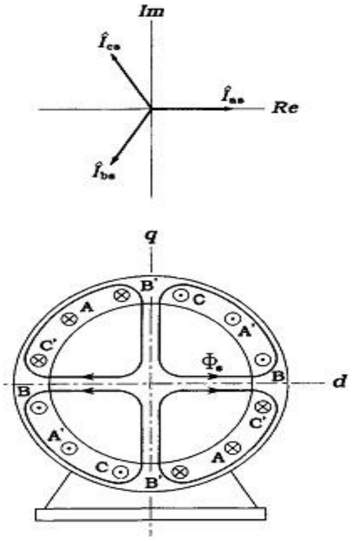


Figure 2.10: Phasor diagram of stator currents and the resultant magnetic field in a four-pole motor at ($\omega_t = 0$).

the stator has turned by 30° only, as seen in Figure 2.9. Clearly, the total MMF has turned by the same special angle, a, which is now equal to a half of the electric angle, ω_t. The magnetic field is now as if it were generated by four magnetic poles, N-S-N-S, displaced by 90° from each other on the inner periphery of the stator. In general,

$$\alpha = \omega t/Pp \qquad (2.5)$$

where Pp denotes the number of pole pairs. Dividing both sides of Eq.(2.13) by t, the angular velocity ω_{syn}, of the field, called a synchronous velocity, is obtained as

$$\omega_{syn} = \omega/Pp \qquad (2.6)$$

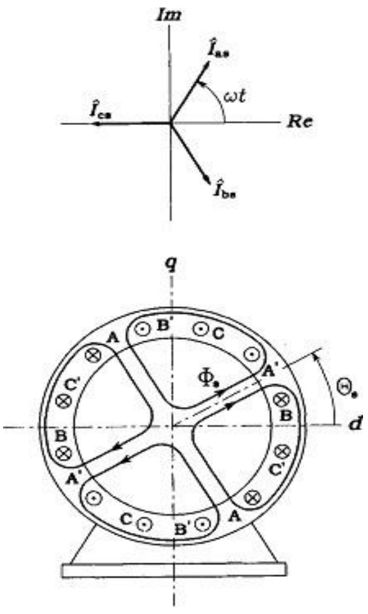


Figure 2.11: Phasor diagram of stator currents and the resultant magnetic field in a four-pole motor (ω_t =60°).

while the synchronous speed is n_{syn} of the field in revolutions per minute (r/min) is

$$n_{syn} = (60/Pp)f \qquad (2.7)$$

To explain how a torque is developed in the rotor, consider an arrangement depicted in Figure 2.10 and representing an "unfolded" motor. Conductor CND, a part of the squirrel-cage rotor winding, moves leftward with the speed U1 The conductor is immersed in a magnetic field produced by stator winding and moving leftward with the speed U2, which is greater than U1. The field is marked by small crossed circles representing lines of magnetic flux, ϕ, directed toward the page. Thus, with respect to the field, the conductor moves to the right with the speed
U3 = U2 - U1 This motion induces (hence the name of the motor) an electromotive force (EMF), e, whose polarity is determined by the well- known right-hand

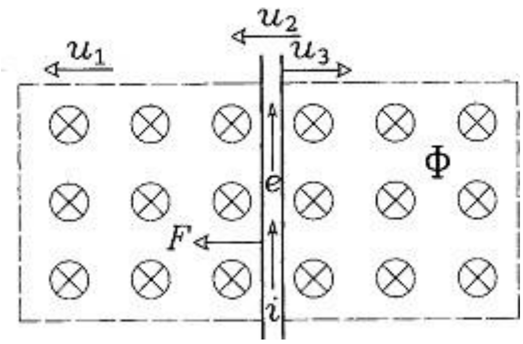


Figure 2.12: Generation of electro dynamic force in a rotor bar of the induction motor.

Clearly, no EMF would be induced if the speed of the conductor (i.e., that of the rotor) and speed of the field were equal, because according to Faraday's law the EMF is proportional to the rate of change of flux linkage of the conductor. If the conductor was stationary with respect to the field, that is, if the rotor rotated with the synchronous speed, no rule. changes would be experienced in the flux linking the conductor.

The EMF, e, produces a current, i, in the conductor. The interaction of the current and magnetic field results in an electro-dynamic force, F, generated in the conductor. The left-hand rule determines direction of the force. It is seen that the force acts on the conductor in the same direction as that of the field motion. In other words, the stator field pulls conductors of the rotor, which, however, move with a lower speed than that of the field. The developed torque, T_M, is a product of the rotor radius and sum of electro- dynamic forces generated in individual rotor conductors.

When an induction machine operates as a motor, the rotor speed, ω_M, is less than the synchronous velocity, ω_{syn}. The difference of these velocities, given by

$$\omega_{sl} = \omega syn - \omega_M \qquad (2.8)$$

and called a slip velocity, is positive. Dividing the slip velocity by ω_{syn} yields the so-called slip, s, of the motor, defined as

$$S= \omega_{Sl}/\omega_{syn} = -1 \qquad \omega_M/\omega_{syn} \quad (2.9)$$

Here, the slip is positive. However, if the machine is to operate as a generator, in which the developed torque opposes the rotor motion, the slip must be negative, meaning that the rotor must move faster than the field.

2.6 Steady-State equivalent circuit:

When the rotor is prevented from rotating, the induction motor can be considered to be a three-phase transformer. The iron of the stator and rotor acts as the core, carrying a flux linking the stator and rotor windings, which represent the primary and secondary windings, respectively. The steady-state equivalent circuit of one phase of such a transformer is shown in Figure 2.13.

The phasor notation based on rms values is used for currents and voltages in the equivalent circuit. Specifically,

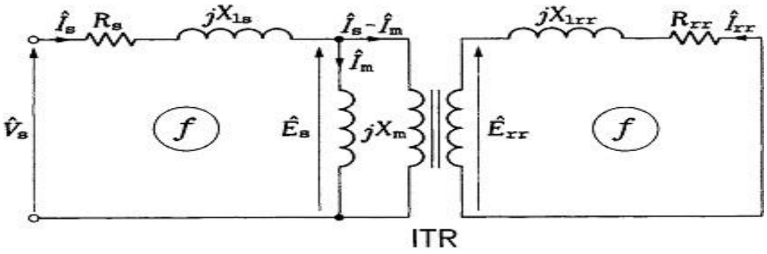


Figure 2.13: Steady-state equivalent circuit of one phase of the induction motor at standstill**.**

The frequency of these quantities is the same for the stator and rotor and equal to the supply frequency f . For formal reasons, it is convenient to assume that both the stator and rotor currents enter the ideal transformer, following a sign convention used in the theory of two port networks.

When the rotor revolves freely, the rotor angular speed is lower than that of the magnetic flux produced in the stator by the slip speed, ω_{sl}. As a result, the frequency of currents generated in rotor conductors is sf, and the rotor leakage reactance and induced EMF are sX_{rr} and sE_{rr} respectively. The difference in stator and rotor frequencies makes the corresponding equivalent circuit, shown in Figure 2.12, inconvenient for analysis. This problem can easily be solved using a simple mathematical trick. Notice that the **rms** value, $\mathbf{I_{rr}}$ of rotor current is given by

$$I_{rr}=\frac{sErr}{\sqrt{R^2rr+(sXlrr)^2}} \qquad (2.10)$$

This value will not change when the numerator and denominator of the right- hand side fraction in Eq. (2.7) are divided by s. Then,

$$I_{rr}=\frac{Err}{\sqrt{(\frac{Rrr}{s})^2+Xlrr^2}} \qquad (2.11)$$

which describes a rotor equivalent circuit shown in Figure 2.13, in which the frequency of rotor current and rotor EMF is f again. In addition, the rotor quantities can be referred to the stator side of the ideal transformer, which allows elimination of this transformer from the equivalent circuit of the motor. The resultant final version of the circuit is shown in Figure 2.16

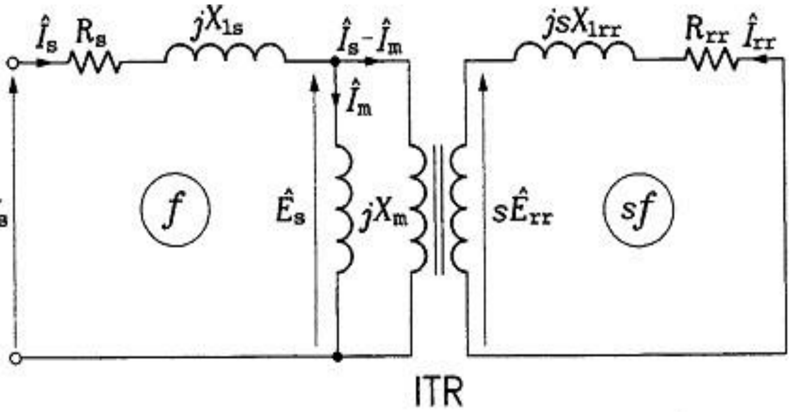


Figure 2.14: Per-phase equivalent circuit of a rotating induction motor with different frequencies of the stator and rotor currents.

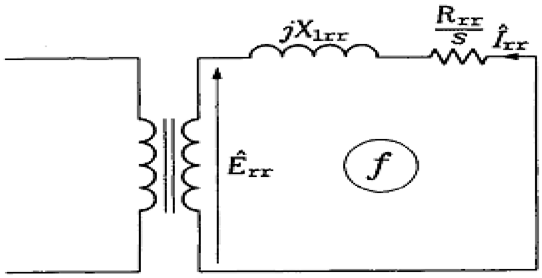


Figure 2.15: Transformed rotor part of the per-phase equivalent circuit of a rotating induction motor.

3.4 in which $\square_r$, $\square_r$, R_r and X_{lr}, denote rotor EMF, current, resistance, ad leakage reactance, respectively, all referred to stator.

In addition to the voltage and current phasors, time derivatives of magnetic flux phasors are also shown in the equivalent circuit in Figure 2.16. They are obtained by multiplying a given flux phasor jω Generally, three fluxes (strictly speaking, flux linkages) can be distinguished: small leakage fluxes. The air gap flux is reduced in comparison with the stator flux by the amount of flux leaking in the stator; and, with respect to the air gap flux, the rotor flux is reduced by the amount of flux leaking in the rotor.

To take into account losses in the iron of the stator and rotor an extra resistance can be connected in parallel with the magnetizing reactance

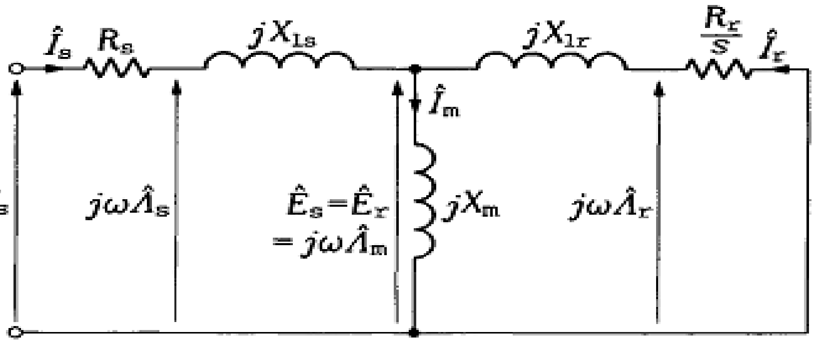


Figure 2.16: Per-phase equivalent circuit of the induction motor with rotor quantities referred to the stator.

Except at high values of the supply frequency, these losses have little impact on dynamic performance of the induction motor. Therefore, throughout the book, the iron losses, as well as the mechanical losses (friction and windbags), are neglected.

It must be stressed that the stator voltage, $V^{\wedge}_{s}$, and current, $\square_s$, represent the voltage across a phase winding of stator and the current in this winding, respectively. This means that if the stator windings are connected in wye, $V^{\wedge}_{s}$ is taken as the line-to-neutral (phase) voltage phasor and $\square_s$ as the line current phasor. In case of the delta connection, $V^{\wedge}_{s}$ is meant as the line to- line voltage phasor and $\square_s$ as the phase current.

Although the rotor resistance and leakage reactance referred to stator are theoretical quantities and not real impedances, they can directly be found from simple no-load and blocked-rotor tests.

2.7 Developed torque:

The steady-state per-phase equivalent circuit in Figure 3.4 allows calculation of the stator current and torque developed in the induction motor under steady state operating conditions. Balanced voltages and currents in individual phases of the stator winding are assumed, so that from the point of view of total power and torque the equivalent circuit represents one-third of the motor. The average developed torque is given by

$$T_M = \frac{Pout}{\omega m} \tag{2.12}$$

where P_{out} denotes the output (mechanical) power of the motor, which is the difference between the input power, P_{in}, and power losses, P_{loss} incurred in the resistances of stator and rotor.

The output power can conveniently be determined from the equivalent circuit using the concept of equivalent load resistance, R_L. Because the ohmic (copper) losses in the rotor part of the circuit occur in the rotor resistance, R_r the -resistance appearing in this circuit can be split into R_r and

$$R_L = \left(\frac{1}{s} - 1\right) R_r$$

as illustrated in Figure 2.15. Clearly, the power consumed in the rotor after subtracting the ohmic losses constitutes the output power transferred to the load. Thus,

$$P_{out} = 3R_L I^2_r \tag{2.14}$$

And

$$T_M = \frac{3R_L I_r^2}{\omega_M} \tag{2.15}$$

The stator and rotor currents, the latter required for torque calculation using Eq. (2.15), can be determined from the matrix equation

$$\begin{bmatrix} \hat{V}_s \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + jX_s & jX_m \\ jX_m & \dfrac{R_r}{s} + jX_r \end{bmatrix} \begin{bmatrix} \hat{I}_s \\ \hat{I}_r \end{bmatrix}, \qquad (2.16)$$

which describes the equivalent circuit in Figure 2.14. Reactances **Xs** and **X_r**, appearing in the impedance matrix, are called stator reactance and rotor reactance, respectively, and given by

$$x_s = x_{ls} + x_m \qquad (2.17)$$

and

$$x_r = x_{lr} + x_m \qquad (2.18)$$

An approximate expression for the developed torque can be obtained from the approximate equivalent circuit of the induction motor, shown

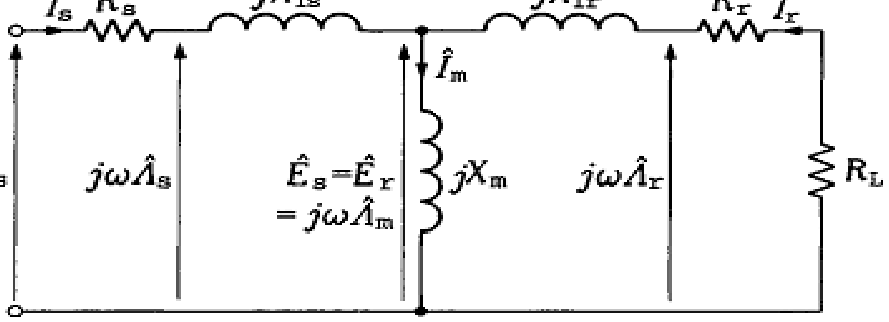


Figure 2.17: Per-phase equivalent circuit of the induction motor showing the equivalent load resistance.

in Figure 2.17. Except for very low supply frequencies, the magnetizing reactance is much higher than the stator resistance and leakage reactance. Thus, shifting the magnetizing reactance to the stator terminals of the equivalent circuit does not significantly change distribution of currents in the circuit. Now, the rms value, I_r of rotor current can be calculated as

$$I_r = \frac{Vs}{\sqrt{\left(Rs+\frac{Rr}{s}\right)^2+X1^2}} \qquad (2.19)$$

Where

$X_1=X_{ls}+X_{1r}$ (2.20)

denotes the total leakage reactance. When I_r given by Eq. (3.10), is substituted in Eq. (3.6), after some rearrangements based on Eqs. (2.15) and (2.17), the steady-state torque can be expressed as

$$T_M = \frac{1.5}{\pi}\frac{Pp}{f}V_s^2\frac{\frac{R_r}{s}}{\left(R_s+\frac{R_r}{s}\right)^2+X_l^2} \qquad (2.21)$$

The quadratic relation between the stator voltage and developed torque is the only serious weakness of induction motors. Voltage sags in power lines, quite a common occurrence, may cause such reduction in the torque that the motor stalls. The torque-slip relation (3.12) is illustrated in Figure

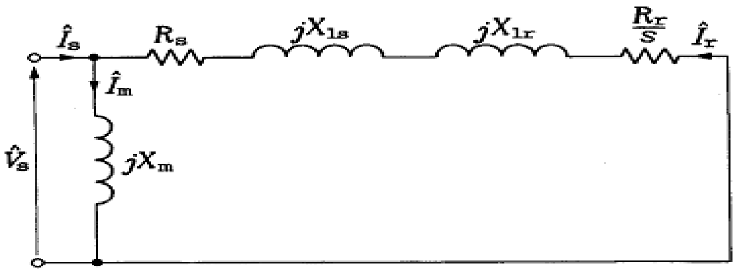


FIGURE 2.18: Approximate per-phase equivalent circuit of the induction motor.

3.7 for various values of the rotor resistance, R_r (in squirrel-cage motors, selection of the rotor resistance occurs in the design stage, while the

wound rotor machines allow adjustment of the effective rotor resistance by connecting external rheostats to the rotor winding). Generally, low values of $\mathbf{R_r}$. are typical for high efficiency motors whose mechanical characteristic, that is the torque speed relation, in the vicinity of rated speed is "stiff," meaning a weak dependence of the speed on the load torque. On the other hand, motors with a high rotor resistance have a higher zero-speed torque, that is, the starting torque, which can be necessary in certain applications. A formula for the starting torque, $T_{M,st}$ is obtained from Eq. (2.18) by substituting s = 1 , which yields

$$T_{M,st} = \frac{1.5}{\pi}\frac{Pp}{f}V_s^2\frac{\frac{R_r}{s}}{(R_s+R_r)^2+X_i^2} \tag{2.22}$$

The maximum torque $\mathbf{T_{M,max}}$ called a pull-out torque, corresponds to a critical slip, $\mathbf{s_{cr}}$ which can be determined by differentiating $\mathbf{T_M}$, with respect to **s** and equaling the derivative to zero. That gives

$$S_{cr} = \frac{R_r}{\sqrt{R_s^2+X_1^2}} \tag{2.23}$$

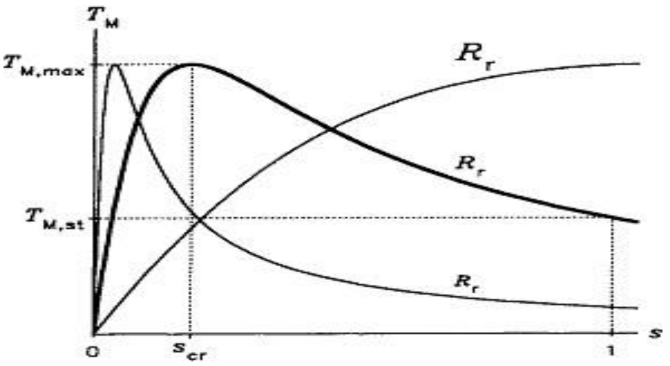


FIGURE 2.19: Torque-slip characteristics of induction motors with various values of the rotor resistance.

It must be reminded that Eqs. (2.17) through (2.24) are based on the approximate equivalent circuit of the induction motor and, as such, they yield only approximate values of the respective quantities.

2.8 Control of the stator voltage:

The speed of an induction motor can be controlled by changing the number of poles, slip, and the supply frequency. The pole changing has already been described, and, if the motor has that capability, it only requires an appropriate switch. Changes of slip can be effected by varying the stator voltage, particularly in motors with soft mechanical characteristics.

However, this method is inefficient, because rotor losses are proportional to the slip. Also, in most motors, it is ineffective because of the narrow range of controllable slip (from zero to the critical value). For wide- range speed control, adjusting the supply frequency constitutes the only practical solution. The frequency control must be accompanied by magnitude control of the stator voltage. To produce adjustable-frequency, adjustable- magnitude, three-phase voltage for induction motor drives, power electronic inverters are most commonly used. Inverters are dc to ac converters, so the regular 60-Hz (50-Hz in many countries) ac voltage must first be rectified to provide the dc supply for the inverter.

Much less common are cyclo-converters, which operate directly on the 60-Hz supply, but whose output frequency is inherently much lower than the input (supply) frequency.

CHAPTER THREE

POWER ELECTRONICS DEVICES

3.1 Rectifiers:

Rectifiers in induction motor ASDs supply dc voltage to inverters. The three-phase full-wave (six-pulse) diode rectifier, shown in Figure 3.10, is most commonly employed. At any time, only two out of six diodes conduct the output current, i_o These are the diodes, subjected to the highest line to-line input voltage. For instance, if at a given instant the highest line to- line voltage is V_{AB} diodes DA and DB' conduct the output current, so that $i_A = i_o$ and $i_{B=}$- i_o The other four diodes are then reverse biased, while the output voltage, v_o equals v_{AB}.

Because, thanks to the conducting diodes, the highest line-to-line input voltage appears at the output of the rectifier, the output voltage is the envelope of all six line-to-line voltages of the supply line.

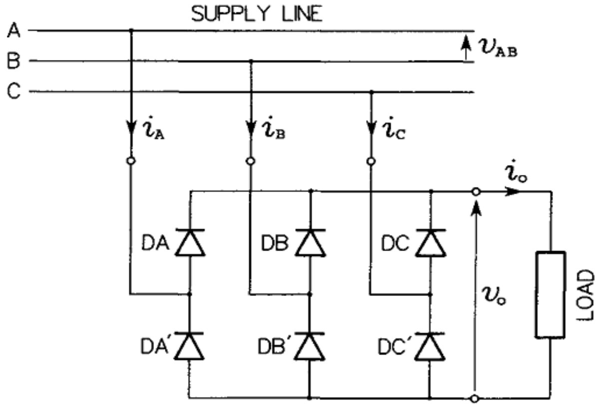


Figure 3.1: Six-pulse diode rectifier.

This is illustrated in Figure 3.7 which shows the line to-line voltages and output voltage of the six-pulse diode rectifier. The output voltage is not ideally of the dc quality, but it has a high dc component, V_o (average value of Vo), given by

$$V_o = \frac{3}{\pi} V_{LL,m} \approx 0.955\, V_{LL,m} \qquad (3.1)$$

where $V_{LL,m}$ denotes the peak value of line-to-line input voltage. The output current, whose example waveform is also shown in Figure 3.7 depends on the load, but its waveform has even less ripple (ac component) than does the voltage waveform.

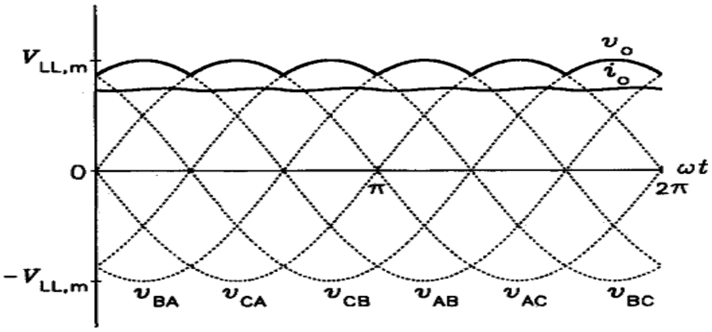


Figure 3.2: Wave forms of the output voltage and current in a six-pulse diode rectifier

The problem of harmonic pollution of the power system caused by power electronic converters, often called nonlinear loads, is very serious, and significant efforts to combat the system harmonics are being made.

The most common solution is to install appropriate filters, either between the power system and the offending converter (series filters) or in parallel with the converter (parallel filters). Filters can be passive or active.

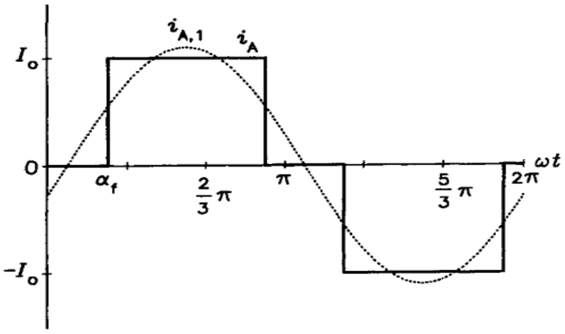


Figure 3.3: Wave form of the input current in a six-pulse phase-controlled rectifier.

filters are simple LC (inductive-capacitive) circuits designed to block and shunt current harmonics so that they are drawn from filter capacitors rather than from the power system. With respect to diode rectifiers, the so-called harmonic traps are often used. They are series-resonant LC circuits, tuned to frequencies of the lowest harmonics of the input current, for instance the 5th, 7th, 11th, and 13th. The harmonic traps shunt the respective harmonic currents from the power system. The remaining, unfiltered harmonics usually have such low amplitudes that waveforms of currents drawn from the system are close to ideal sinusoids.

The resonant frequencies of harmonic traps are relatively low, because even the 13th harmonic has a frequency well below 1 kHz. Therefore, the inductors and capacitors used in the traps are large and expensive. To significantly reduce the size of passive filters, pulse width modulated (PWM) rectifiers must be used. There are two types of these converters, the voltage source and current source PWM rectifiers.

The voltage source PWM rectifier, based on IGBTs, the most popular semiconductor power switch nowadays (the so-called non-punch-through IGBTs must be used because of the ac input voltages), is shown in Figure 3.2 The three-phase line with input filters based on inductors L_i and capacitors C_i constitutes the voltage source for the rectifier. The input inductors do not have to be physical components, because the supplying power system itself may possess sufficient inductance, but the capacitors are necessary. The output inductance, L_o which can be provided by the load,

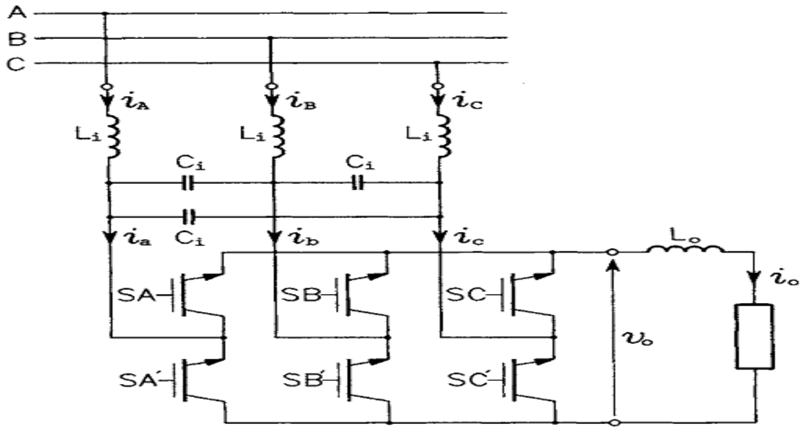
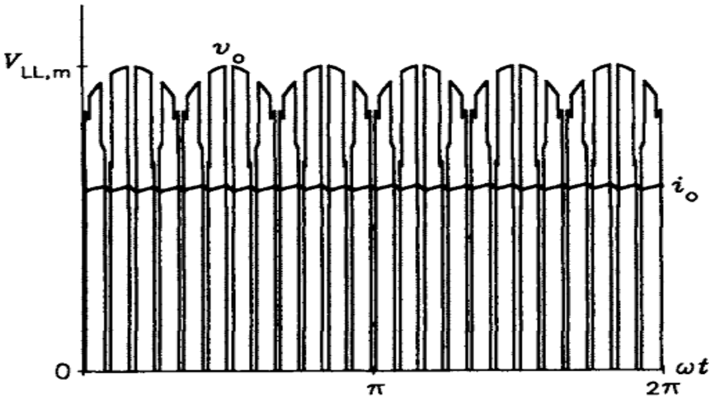


Figure 3.4:Voltage source PWM rectifier

smooths the output current. Switches, SA through SC, of the rectifier are turned on and off many times per cycle of the input voltage in such a way that the fundamental input currents follow desired reference values. Example waveforms of the output voltage, v_o and current, i_o of the rectifier are shown in Figure 3.10, and those of the input current, i_a, and its fundamental, $i_{a,1}$ in Figure 3.11. The fundamentals are supplied from the power line, while the high-frequency harmonic components of the pulsed currents, i_a, i_b and i_c are mostly drawn from the capacitors. As a result, waveforms of currents i_A ,i_B and i_C supplied by the power



FIGUE 3.5:Wave forms of the output voltage and current in a voltage source PWM rectifier.

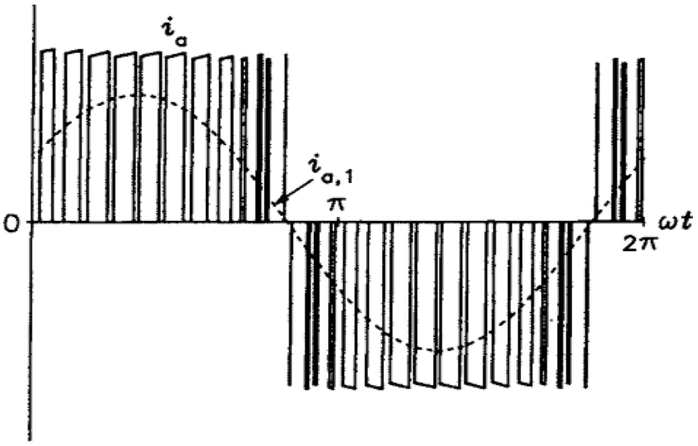


Figure 3.6: Wave forms of the input current and its fundamental in a voltage source PWM rectifier.

system and shown in Figure 4.9, are close to ideal sinusoids, with only a small amount of ripple.

The dc output voltage of the voltage source rectifier cannot be adjusted to a value greater than the peak value of line-to-line supply voltage. In contrast, the current source PWM rectifier shown in Figure 4.10 allows the boosting of the output voltage. The current source properties of the rectifier result from the input inductors, L_i. Because the rectifier switches provide direct connection between the input and output of the converter, the output capacitor, C_o is necessary to prevent connecting the input inductance, carrying certain current, with the load inductance, which may conduct a different current. The same capacitor smooths the output voltage.

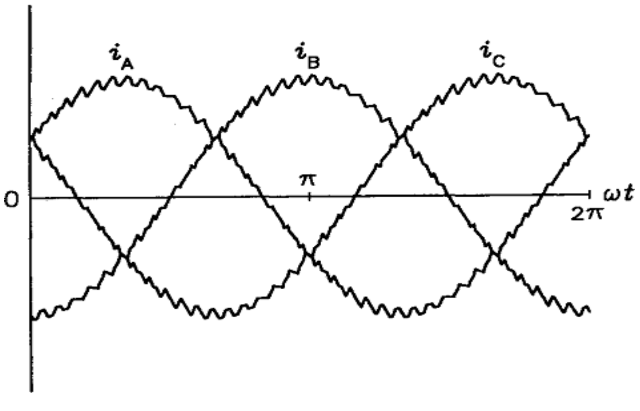


Figure 3.7: Wave forms of currents supplied by the power system to the voltage Source PWM rectifier.

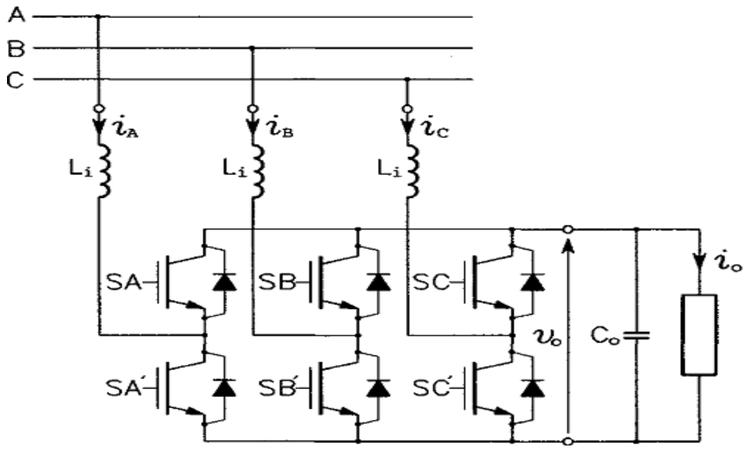


Figure 3.8: Current source PWM rectifier.

V_o. Analogously, should a smoothing capacitor be used in the voltage source PWM rectifier in Figure 4.6, a physical inductor L_i would have to be used between the rectifier output and the capacitor to avoid connecting this capacitor, charged to a certain voltage, across the input capacitor charged to a different voltage.

The semiconductor power switches are paired with inverse-parallel freewheeling diodes, which provide alternative paths for currents that cannot flow through switches. Suppose, for example, that switch SA' is turned on and conducts current i_A whose polarity is that shown in Figure 4.10. When the switch is turned off, the current cannot change instantly, having been maintained by the input inductor in phase A. As a result, the current will force its way through the freewheeling diode of switch SA. Thanks to the output capacitor, the output voltage and current waveforms are practically of the dc quality, with a minimal ripple. Currents drawn from the power system are similar to those in the voltage source PWM rectifier (see Figure 3.7).

The phase-controlled and PWM rectifiers have the capability of reversed power flow, necessary for efficient operation of the drive system in the second and fourth quadrants. In practice, multi-quadrant drives are much less common than the single-quadrant ones, which explains the already- mentioned dominance of diode rectifiers in induction motor ASDs. PWM rectifiers are mostly used in low- and medium-power drive systems, with phase-controlled rectifiers employed in the higher ranges of power.

3.2 Inverters:

The three-phase voltage source inverter (VSI) is shown in Figure 3.6. The voltage source for the inverter is made up from a rectifier and the so-called dc link, composed of a capacitor, C, and inductor, L. If the ac machine fed from the inverter operates as a motor (i.e., in the first or third quadrant), the average input current is positive. However, the instantaneous input current, i_i may assume negative values, absorbed by the dc-link capacitor which, therefore, is necessary. The capacitor also serves as a source of the high-frequency ac component of i_i so that it is not drawn from the power system via the rectifier. In addition, the dc link capacitor smooths and stabilizes the voltage produced by the rectifier. The optional dc-link inductor is less important, being introduced to provide an extra screen for the power system from the high-frequency current drawn by the inverter.

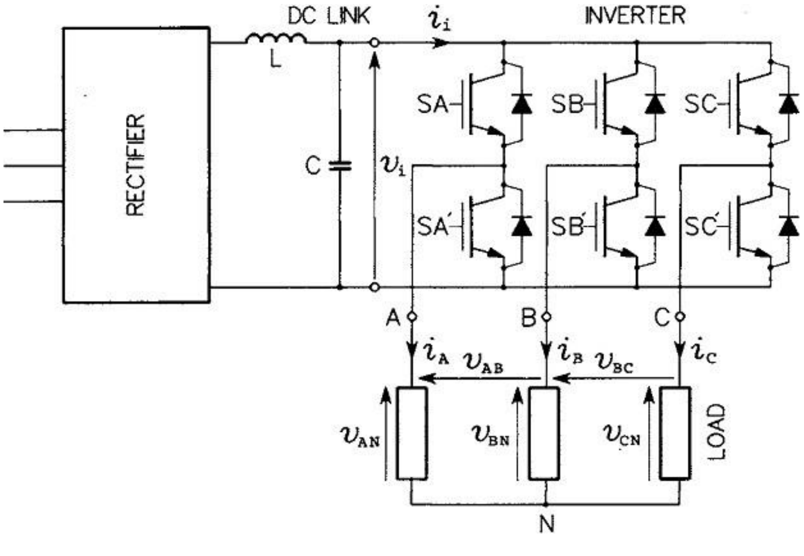


Figure 3.9: Voltage source inverter .

Clearly, the topology of the voltage source inverter represents an inverse of that of the current source PWM rectifier in Figure 4.10 (note that the load of the inverter contributes the inductances corresponding to input inductances, L_i, of the rectifier). Here, the freewheeling diodes provide alternative paths for output currents. Both semiconductor power switches in a given leg (phase) of the inverter may not be on simultaneously, because they would short the input terminals. On the other hand, with both switches off, the output voltage would be indeterminable, because the potential of the respective output terminal would depend on which diode is conducting the output current in that phase. This would make the open loop control of the output voltage impossible. Therefore, voltage source inverters are so controlled that one switch in each leg is on and the other is off. In this way, the turned-on switch connects one of the input terminals to the output terminal, and potentials of all three output terminals are always known. To avoid the so-called shot-through, that is, potentially damaging simultaneous conduction of both switches in the same leg, turn-on of a switch is delayed a little with respect to turn-off of the other switch. This delay, on the order of few microseconds, is called a dead time or blanking time.

The voltage source inverter can operate in both the PWM mode and the so-called square-wave mode, characterized by rectangular waveforms of the output voltage. The square-wave operation yields the highest voltage gain of the inverter, but the quality of output current is poorer than that in the PWM mode.

3.3 Adjustable speed control drive using PWM VSI :

Inverter used to inverts DC to AC power by switching the DC input voltage (or current) in a pre-determined sequence so as to generate AC voltage (or current) output . the typical applications of inverters are in un- interruptible power supply (UPS), industrial(induction motor) drives, traction and HVDC .The types of inverters are voltage source inverters(VSI)and current source inverters(CSI).

Pulse width modulated (PWM) voltage source inverters(VSI) are widely utilized in AC motor drive applications and at a small quantity in controlled rectifier applications as a means of DC to AC power conversation devices. Many PWM-VSI drives employ carrier-based PWM methods due to their fixed switching frequency ,low ripple current, and well-defied harmonic spectrum characteristics. Block diagram of adjustable speed control drive for AC machine is shown in the figure 3.10.

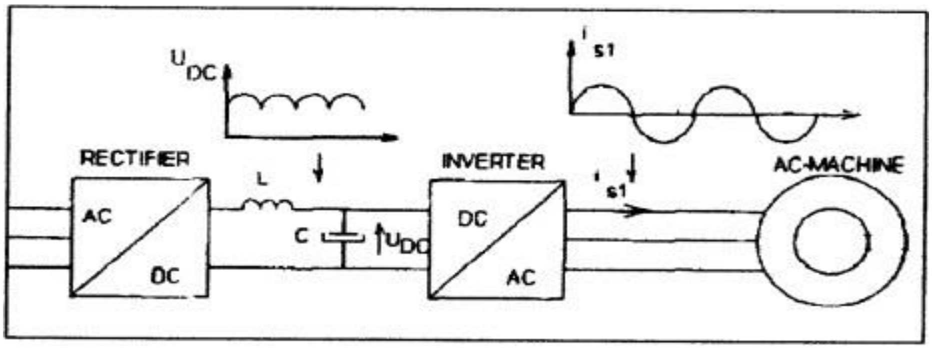


Figure 3.10: Block diagram of adjustable speed control drive for AC machine.

In this inverter ,the input DC voltage is essentially constant in magnitude where a diode rectifier is used to rectify the line voltage. Therefore the inverter must control the magnitude and the frequency of the AC output voltage. This is achieved by PWM is one of the various PWM schemes to pulse width modulate the inverter switches in order to shape the output AC voltage to be as close to a sine wave as a possible.

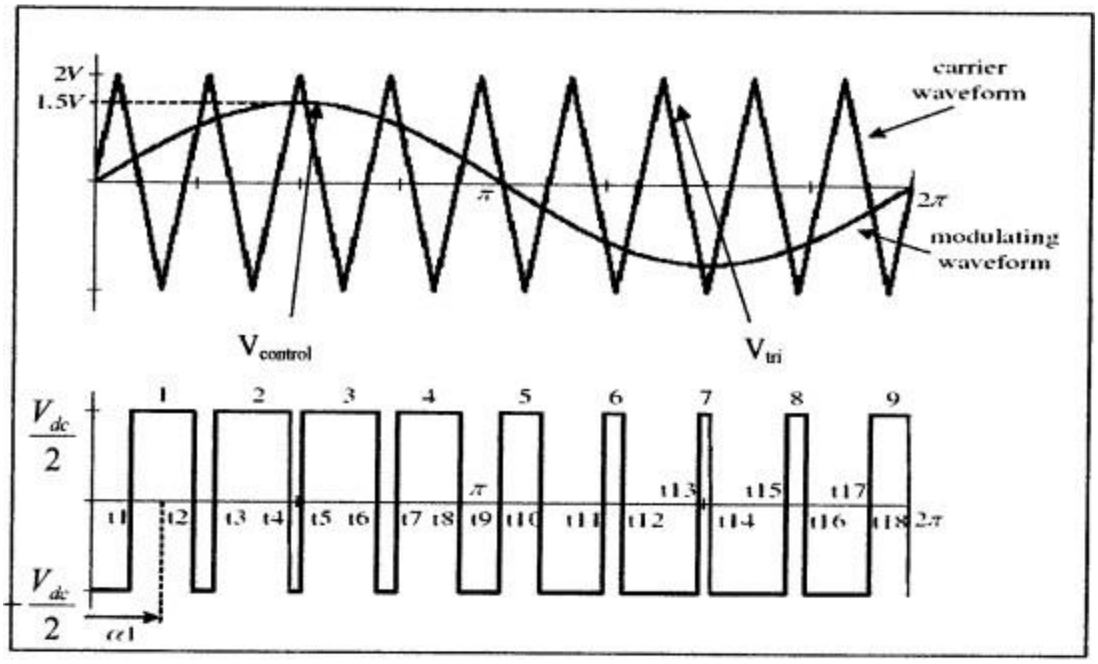


Figure 3.11: pulse width modulation

The triangular waveforme Vtri in figure 3.11 is at as a switching frequency (carrier frequency), which establishes the frequency with which the inverter switch .the signal Vcontrol is used to modulate the switch duty ratio and has afrequence (modulation frequency), which is the desired fundamental frequence of the inverter. The inverter output voltage will not be a perfect sine wave and will contain voltage component at harmonic frequency.

are off is not dangerous, but the voltage at the corresponding output terminal is undetermined. This is so because, depending on the polarity of the load current, the terminal would be connected, via one of the freewheeling diodes, to either the positive or negative dc bus. Therefore, in practice, except for the very short blanking time intervals, one switch in each phase is on, and the other is off. Consequently, each inverter leg can assume two states only, and the number of states of the whole inverter is eight (2^3). Taking as an example phase A, the switching variable a is defined to assume the value of 1 if switch SA is on and switch SA' is off. If, conversely, SA is off and SA' is on, a assumes the value of 0. The other two switching variables, b and c, are defined analogously. An inverter state can be denoted as abc2^ For example, with a = 1, b= 0, and c = 1, the inverter is said to be in State 5, because 101_2=5.

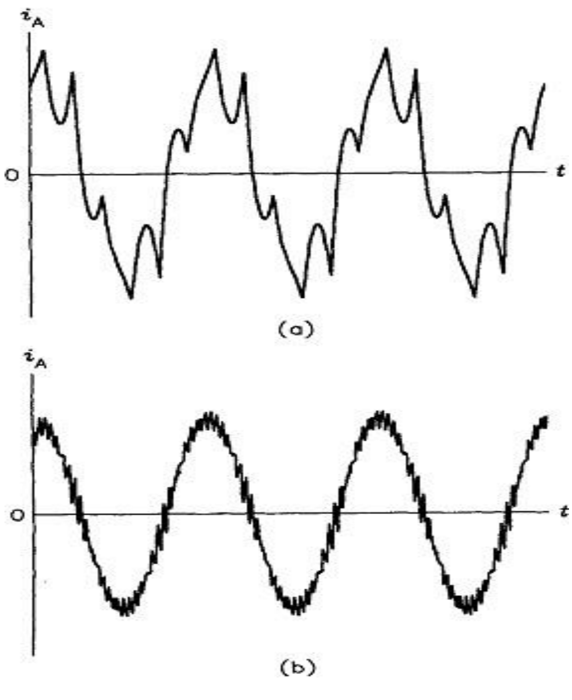


Figure 3.12:Wave forms of the output current in a voltage source inverter feeding an induction motor:(a)square-wave operation,(b)PWM operation.

3.4 Control of current source inverters:

Current source inverters are less commonly used in induction motor ASDs than voltage source inverters, mostly due to the poorer quality of output currents. Still, they have certain advantages, such as imperviousness to over currents, even with a short circuit in the inverter or the load. The absence of freewheeling diodes further increases the reliability. Also, current source inverters are characterized by inherently excellent dynamics of the phase angle control of the output current. Such control is realized by changing the state of inverter and the resultant redirecting of the source current. However, the magnitude adjustments of output currents can only be performed in the supplying rectifier. The rectifier allows bidirectional flow of power, and, because the input current is always positive, the input voltage becomes negative when the power flows from the load to the supply power system. Therefore, semiconductor power switches used in a current source inverter must have the reverse blocking capability.

In contrast with voltage source inverters, the simultaneous on-state of both switches in the same inverter leg is safe and recommended for a short period of time initiating a state change of the inverter. This is to avoid the danger of interrupting the current, which would result in an overvoltage. Consequently, switching variables are defined differently than those in the voltage source inverter. In the subsequent considerations, variables a, b, and c are assigned to switches SA, SB, and SC (e.g. a = 1 means that SA is on), and variables a', b' and c' to switches SA', SB', and SC .Then, the output line currents, i_A, i_B and i_C of the current source inverter can be expressed as:

$i_A = (a - a')I_i$

$i_B = (b - b')\, I_i$ (3.2)

and

$i_c = (c - c')\, I_i$

where I_i denotes the constant input current .If the motor has a delta connected stator , then the currents ,i_{AB} ,i_{BC} and i_{CA} in the individual phase windings are given by:

$$\begin{bmatrix} i_{AB} \\ i_{BC} \\ i_{CA} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix}. \qquad (3.3)$$

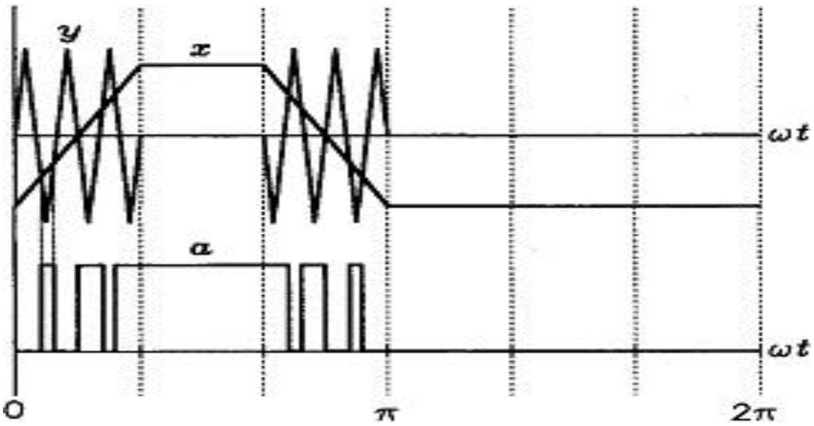


Figure 3.13: Illustration of a PWM technique for a current source inverter.

CHAPTER FOUR

MAIN CIRCUIT DESGIN AND SIMULATION

4.1 Scalar and Vectors Control Methods:

Induction motors can be controlled in many ways. The simplest methods are based on changing the structure of stator winding. Using the so-called wye-delta switch, the starting current can easily be reduced. Another type of switch allows emulation of a gear change by the already-mentioned pole changing, that is, changing the number of magnetic poles of the stator. However, in modem ASDs, it is the stator voltage and current that are subject to control. These, in the steady state, are defined by their magnitude and frequency; and if these are the parameters that are adjusted, the control technique belongs in the class of scalar control methods. Arapid change in the magnitude or frequency may produce undesirable transient effects, for example a disturbance of the normally constant motor torque. This, fortunately, is not important in low-performance ASDs, such as those of pumps, fans, or blowers. There, typically, the motor speed is open-loop controlled, with no speed sensor required (although current sensors are usually employed in overcurrent protection circuits).

In high-performance drive systems, in which control variables include the torque developed in the motor, vector control methods are necessary.

The concept of space vectors of motor quantities will be explained later. Here, it is enough to say that a vector represents instantaneous values of the corresponding three-phase variables. For instance, the vector of stator current is obtained from the current in all three

phases of the stator and, conversely, all three phase currents can be determined from the current vector. In vector control schemes, space vectors of three-phase motor variables are manipulated according to the control algorithm. Such an approach is primarily designed for maintaining continuity of the torque control during transient states of the drive system.

Needless to say, vector control systems are more complex than those realizing the scalar control. Voltage and current sensors are always used; and, for the highest level of performance of the ASD, speed and position sensors may be necessary as well. Today, practically all control systems for electric motors are based on digital integrated circuits of some kind, such as microcomputers, microcontrollers, or digital signal processors
(DSPs).

4.2 Type of scalar control :

Many type of scalar control techniques that can use to control the speed and torque of an induction motor. This speed and torque can be varied by one of the following mean:

i. Stator voltage control.
ii. Rotor voltage control.
iii. Frequency control.
iv. Stator voltage and frequency control.
v. Stator current control.
vi. Voltage ,current and frequency control.

4.3 Open loop scalar speed control (constant Volts/Hertz):

From the equation of developed torque :

$$T_M = 3P_p \frac{\Lambda_s^2}{R_R} \frac{\omega_r}{(\tau_r.\omega_r)^2 + 1} \tag{4.1}$$

1. If ωr=1/Tr then the maximum (pull-out) torque, , is developed in the motor. It is given by:

$$T_{m,max}=1.5Pp\frac{\Lambda_s^2}{L_L} \qquad (4.2)$$

And the corresponding critical slip, s_{cr} is:

$$S_{cr}=\frac{1}{\tau_r\omega} \qquad (4.3)$$

2. Typically, induction motors operate well below the critical slip, so that < 1/ . Then, + 1 ≈ 1 , and the torque is practically proportional to For a stiff mechanical characteristic of the motor, possibly high flux and low rotor resistance are required.

3. When the stator flux is kept constant, the developed torque is independent of the supply frequency, f. On the other hand, the speed of the motor strongly depends on f.

It must be stressed that Eq. (4.1) is only valid when the stator flux is kept constant, independently of the slip. In practice, it is usually the stator voltage that is constant, at least when the supply frequency does not change. Then, the stator flux does depend on slip, and the critical slip is different from that given by Eq(4.2) Generally, for a given supply frequency, the mechanical characteristic of an induction motor strongly depends on which motor variable is kept constant.

Assuming that the voltage drop across the stator resistance is small in comparison with the stator voltage, the stator flux can be expressed as:

$$\Lambda_s \approx \frac{V_s}{\omega} = \frac{1}{2\pi}\frac{V_s}{f}$$

Thus, to maintain the flux at a constant, typically rated level, the stator voltage should be adjusted in proportion to the supply frequency. This is the simplest approach to the speed control of induction motors, referred to as Constant Volts/Hertz (CVH) method. It can be seen that no feedback is inherently required, although in most practical systems the stator current
is measured, and provisions are made to avoid overloads.

for the low-speed operation, the voltage drop across the stator resistance must be taken into account in maintaining constant flux, and the stator voltage must be appropriately boosted. Conversely, at speeds exceeding that corresponding to the rated frequency, , the CVH condition cannot be satisfied because it would mean an overvoltage. Therefore, the stator voltage is adjusted in accordance to the following rule:

$$V_s = \begin{cases} (V_{s,rat} - V_{s,0})\dfrac{f}{f_{rat}} + V_{s,0} & \text{for } f < f_{rat} \\ V_{s,rat} & \text{for } f \geq f_{rat} \end{cases} \qquad (4.5)$$

where $V_{s,0}$ denotes the rms value of the stator voltage at zero frequency. Relation (4.5) is illustrated in Figure 5.3. For the example motor, $V_{s,0}$ = 40 V. With the stator voltage so controlled, its mechanical characteristics for various values of the supply frequency are depicted in Figure 4.2.

Frequencies higher than the rated (base) frequency result in reduction of the developed torque. This is caused by the reduced magnetizing current, that is, a weakened magnetic field in the motor. Accordingly, the motor is said to operate in the field weakening mode. The region to the right from the rated frequency is often called the constant power area, as distinguished from the constant torque area to the left from the said frequency. Indeed, with the torque decreasing when the motor speed increases, the product of these two variables remains constant. Note that the described characteristics of the motor can easily be explained by the impossibility of sustained operation of an electric machine with the output power higher than rated.

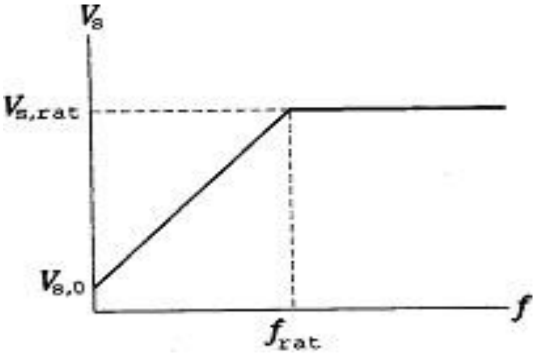


Figure 4.1: Voltage versus frequency relation in the CVH drives.

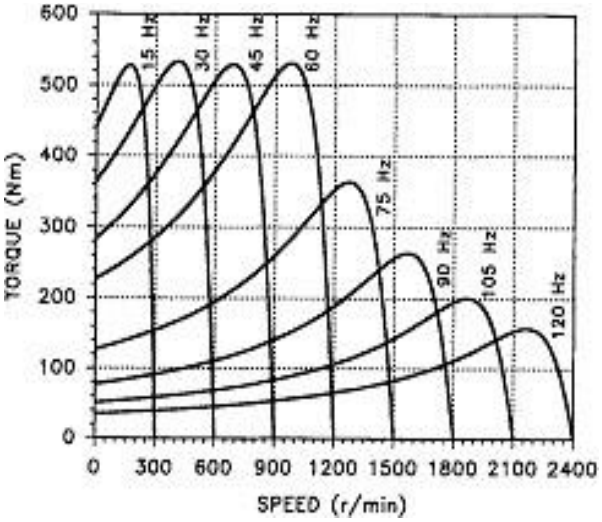


Figure 4.2 : Mechanical characteristics of the example motor with the CVH control.

A simple version of the CVH drive is shown in Figure 4.16 A fixed value of slip velocity, corresponding to, for instance, 50% of the rated torque, is added to the reference velocity of the motor to result in the reference synchronous frequency, This frequency is next multiplied by the number of pole pairs, Pp, to obtain the reference output frequency, of the inverter, and it is also used as the input signal to a voltage controller. The controller generates the reference signal, V*, of the inverter's fundamental output voltage. Optionally, a current limiter can be employed to reduce the output voltage of the inverter when too high a motor current is detected. The current, i_{dc}, measured in the dc link is a dc current, more convenient as a feedback signal than the actual ac motor current.

Clearly, highly accurate speed control is not possible, because the actual slip varies with the load of the motor. Yet, in many practical applications, such as pumps, fans, mixers, or grinders, high control accuracy is unnecessary. The basic CVH scheme in Figure 4.16 can be improved by adding slip compensation based on the measured dc-link current. The

signal is generated in the slip compensator as a variable proportional to i_{dc} so modified drive system is shown in Figure 4.4.

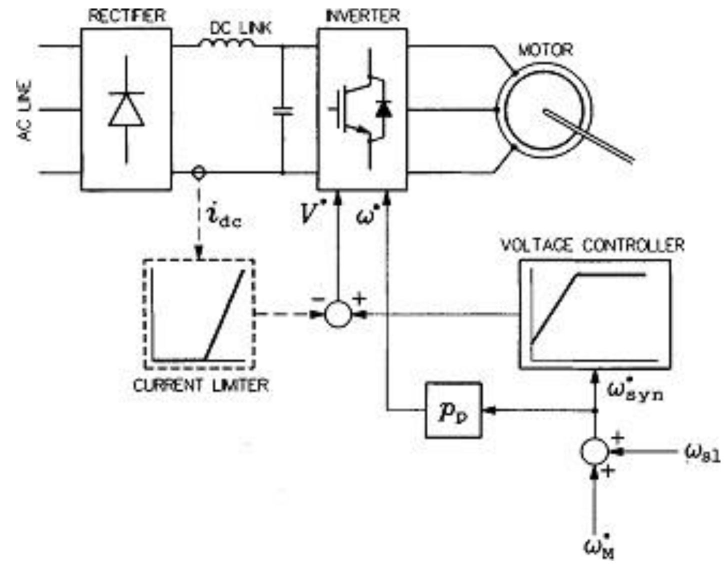


Figure 4.3 : Basic CVH drive system.

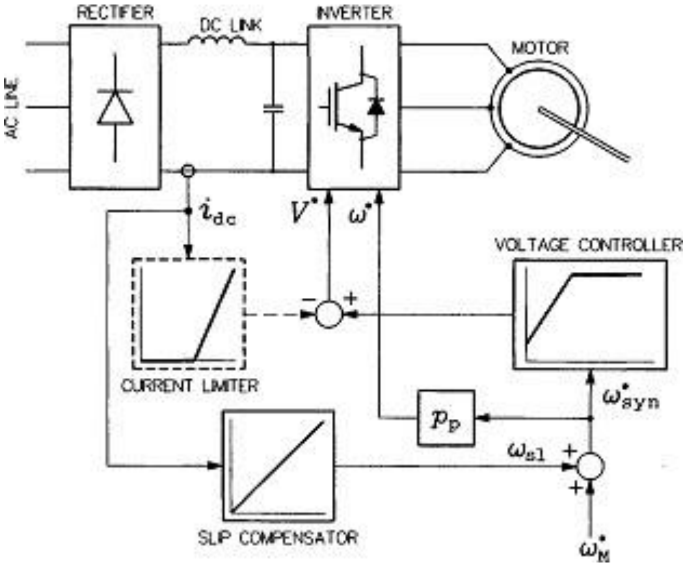


Figure 4.4: CVH drive system with slip compensation.

4.4 The components of speed control of induction motor circuit :

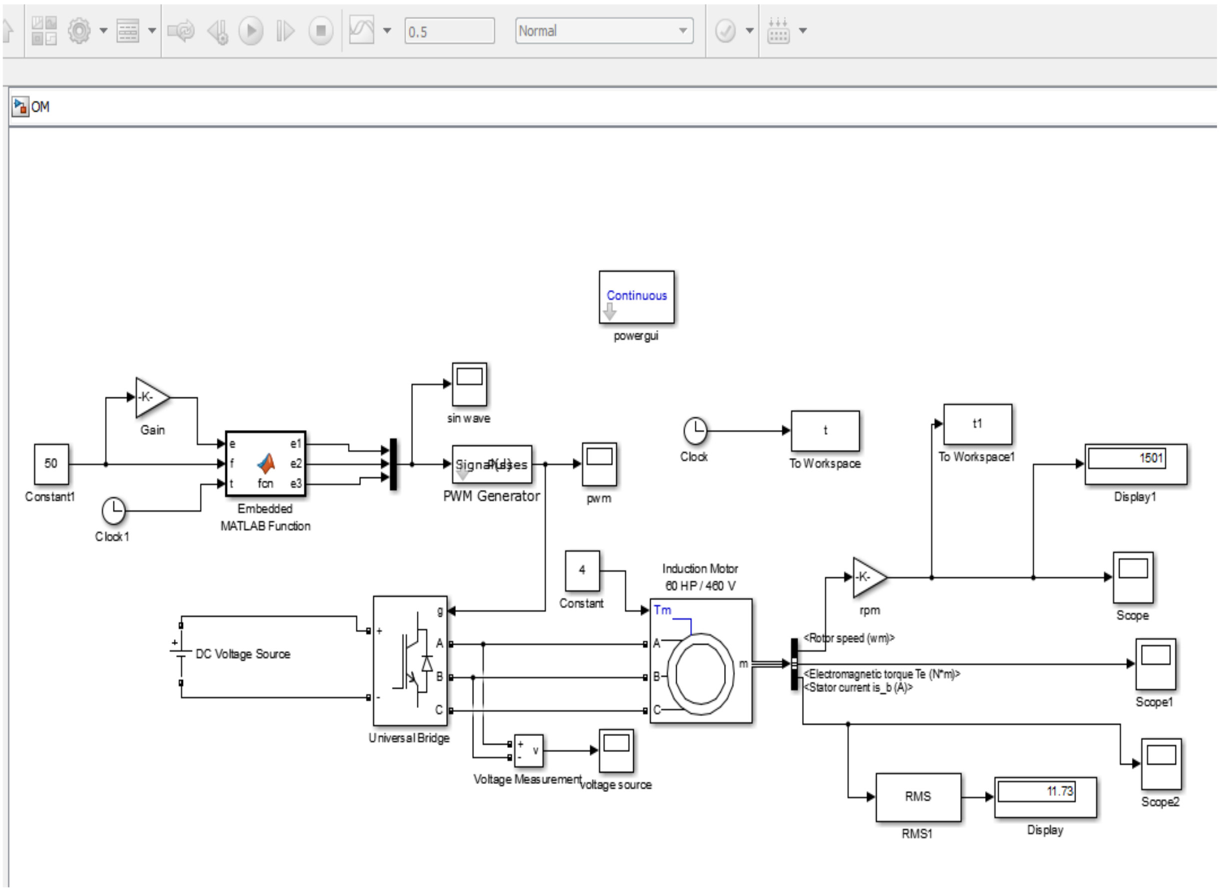


Figure (4-5) : Speed control of induction motor by using scalar control techniques.

i. Induction motor (380v,50Hz,1500rpm).
ii DC Voltage source (380v) .
iii. Universal bridge.
iv. Pulse width modulation (PWM).
v. Embedded matlab function.
vi. Powergui.

4.5 Induction motor :

4-5-1 The block of induction motor as:

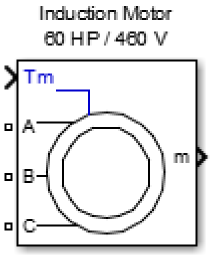
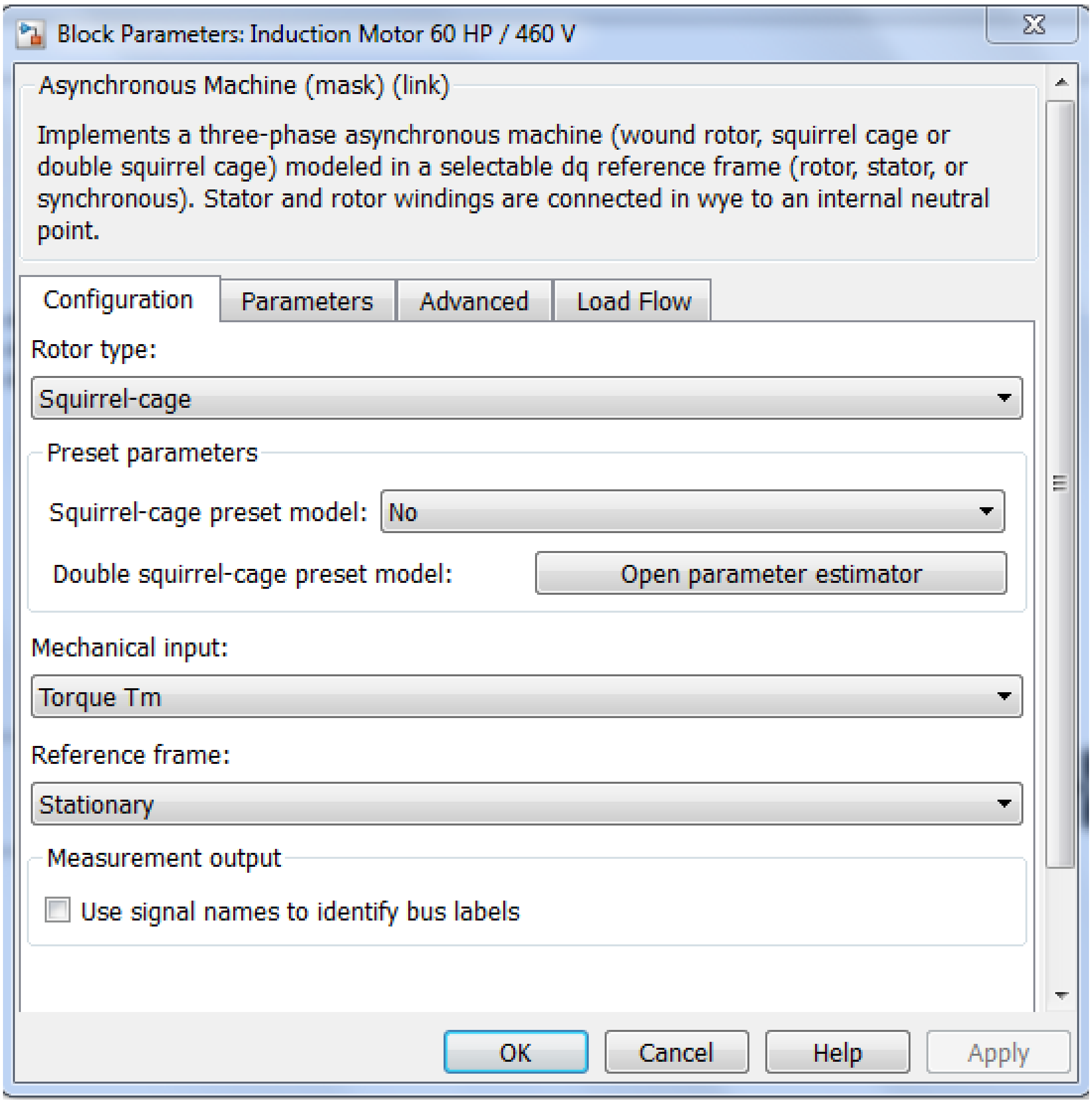


Figure 4.6: block diagram of induction motor.

4-5-2 The parameters:



Asynchronous Machine (mask) (link)

Implements a three-phase asynchronous machine (wound rotor, squirrel cage or double squirrel cage) modeled in a selectable dq reference frame (rotor, stator, or synchronous). Stator and rotor windings are connected in wye to an internal neutral point.

Rotor type: Squirrel-cage

Preset parameters

Squirrel-cage preset model: No

Double squirrel-cage preset model:

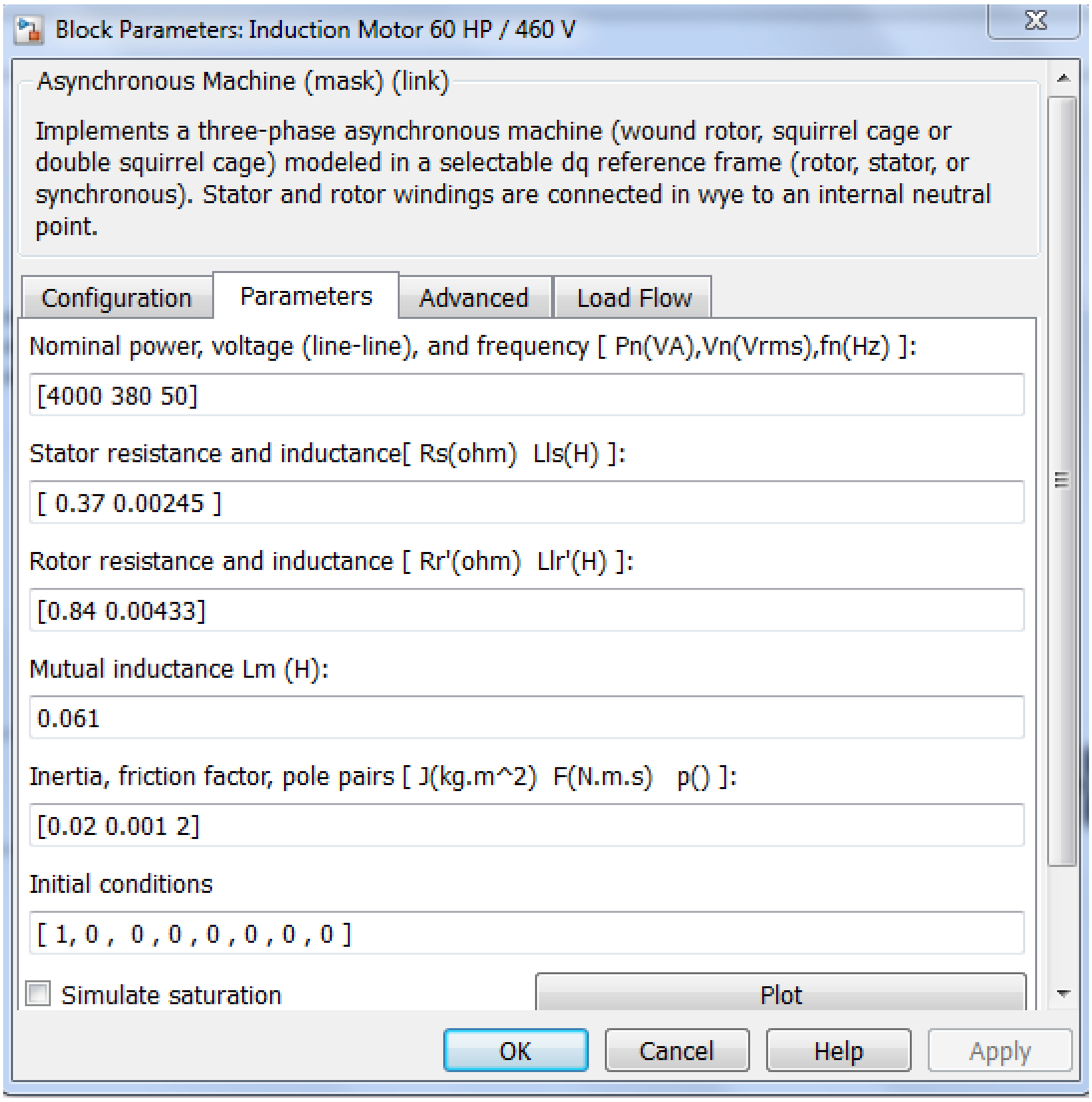
Mechanical input: Torque Tm

Reference frame: Stationary

Measurement output

☐ Use signal names to identify bus labels

Figure 4.7: The configuration of induction motor



Block Parameters: Induction Motor 60 HP / 460 V

Asynchronous Machine (mask) (link)

Implements a three-phase asynchronous machine (wound rotor, squirrel cage or double squirrel cage) modeled in a selectable dq reference frame (rotor, stator, or synchronous). Stator and rotor windings are connected in wye to an internal neutral point.

Nominal power, voltage (line-line), and frequency [Pn(VA),Vn(Vrms),fn(Hz)]:
[4000 380 50]

Stator resistance and inductance[Rs(ohm) Lls(H)]:
[0.37 0.00245]

Rotor resistance and inductance [Rr'(ohm) Llr'(H)]:
[0.84 0.00433]

Mutual inductance Lm (H):
0.061

Inertia, friction factor, pole pairs [J(kg.m^2) F(N.m.s)   p()]:
[0.02 0.001 2]

Initial conditions
[1, 0 , 0 , 0 , 0 , 0 , 0 , 0]

☐ Simulate saturation

Figure 4.8: The parameters of induction motor.

4-6 Universal Bridge :

4-6-1 The block of universal bridge :

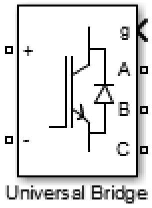
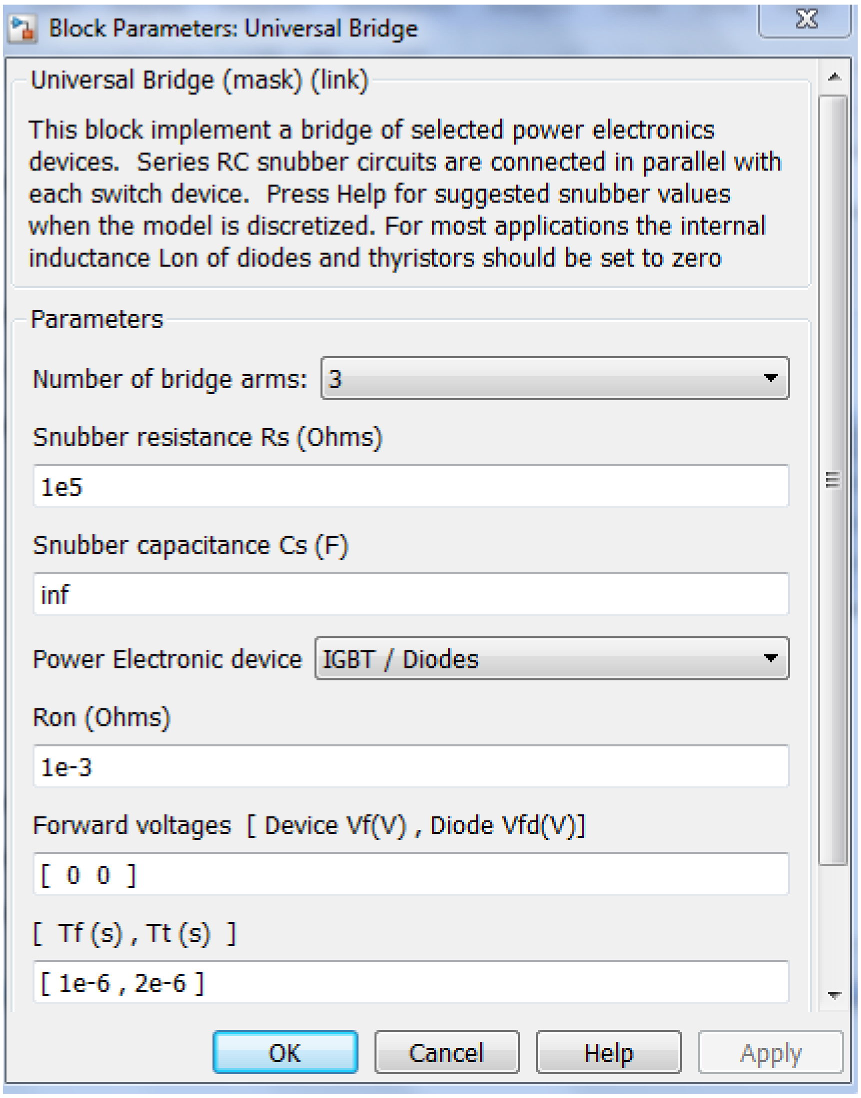


Figure 4.9: Block diagram of universal bridge.

4-6-2 The parameters:



Block Parameters: Universal Bridge

Universal Bridge (mask) (link)

This block implement a bridge of selected power electronics devices. Series RC snubber circuits are connected in parallel with each switch device. Press Help for suggested snubber values when the model is discretized. For most applications the internal inductance Lon of diodes and thyristors should be set to zero

Parameters

Number of bridge arms: 3

Snubber resistance Rs (Ohms): 1e5

Snubber capacitance Cs (F): inf

Power Electronic device: IGBT / Diodes

Ron (Ohms): 1e-3

Forward voltages [Device Vf(V) , Diode Vfd(V)]: [0 0]

[Tf (s) , Tt (s)]: [1e-6 , 2e-6]

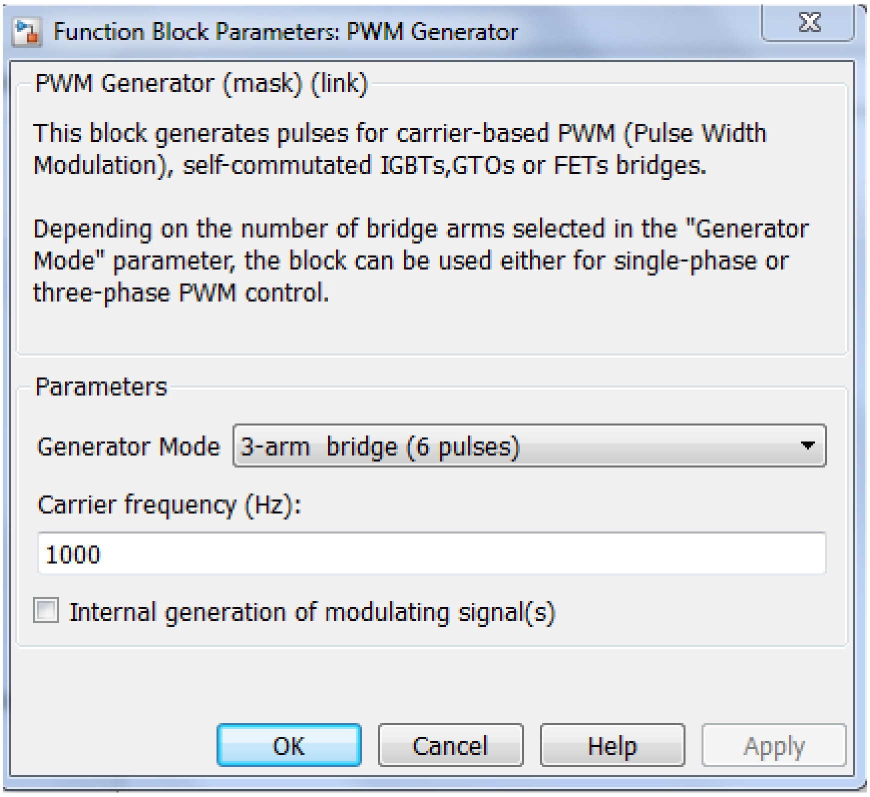
Figure 4.10:the parameter of universal bridge

4-7 .Pulse width modulation :

4-7-1 The block of PWM :

Figure 4.11: Block diagram of PWM.

4-7-2 The parameters:



Function Block Parameters: PWM Generator

PWM Generator (mask) (link)

This block generates pulses for carrier-based PWM (Pulse Width Modulation), self-commutated IGBTs,GTOs or FETs bridges.

Depending on the number of bridge arms selected in the "Generator Mode" parameter, the block can be used either for single-phase or three-phase PWM control.

Parameters

Generator Mode: 3-arm bridge (6 pulses)

Carrier frequency (Hz):

1000

☐ Internal generation of modulating signal(s)

Figure 4.12: The parameters of PWM

4-8 Embedded matlab function:

4-8-1 The block of Embedded matlab function:

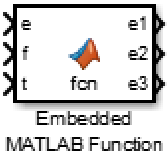
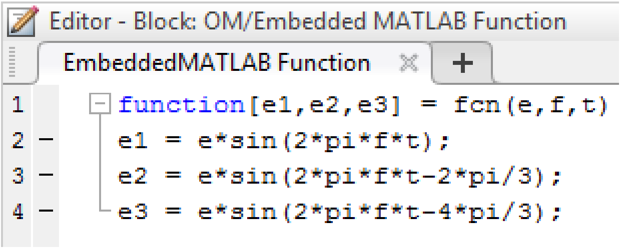


Figure 4.13: Block diagram of Embedded matlab function.

4-8-2 The program editor is:



```
function[e1,e2,e3] = fcn(e,f,t)
e1 = e*sin(2*pi*f*t);
e2 = e*sin(2*pi*f*t-2*pi/3);
e3 = e*sin(2*pi*f*t-4*pi/3);
```

Figure 4.14: The program editor of Embedded matlab function.

4.9 The components of induction motor circuit without controller :

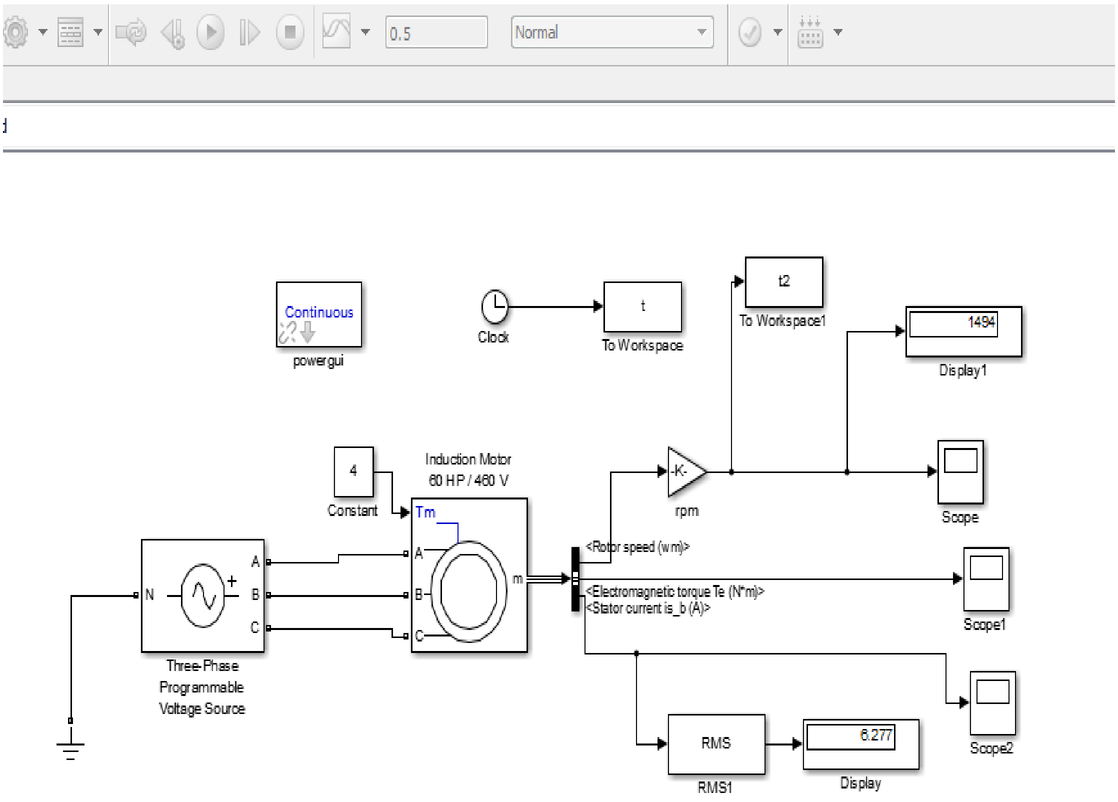


Figure 4.15: Induction motor circuit without controller .

i. Induction motor (380v,50Hz,1500rpm).
ii. Three phase programmable voltage source.
iii. Powergui.
iv. Ground.

4-10 Three phase programmable voltage source:

4-10-1 The block:

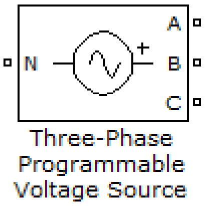
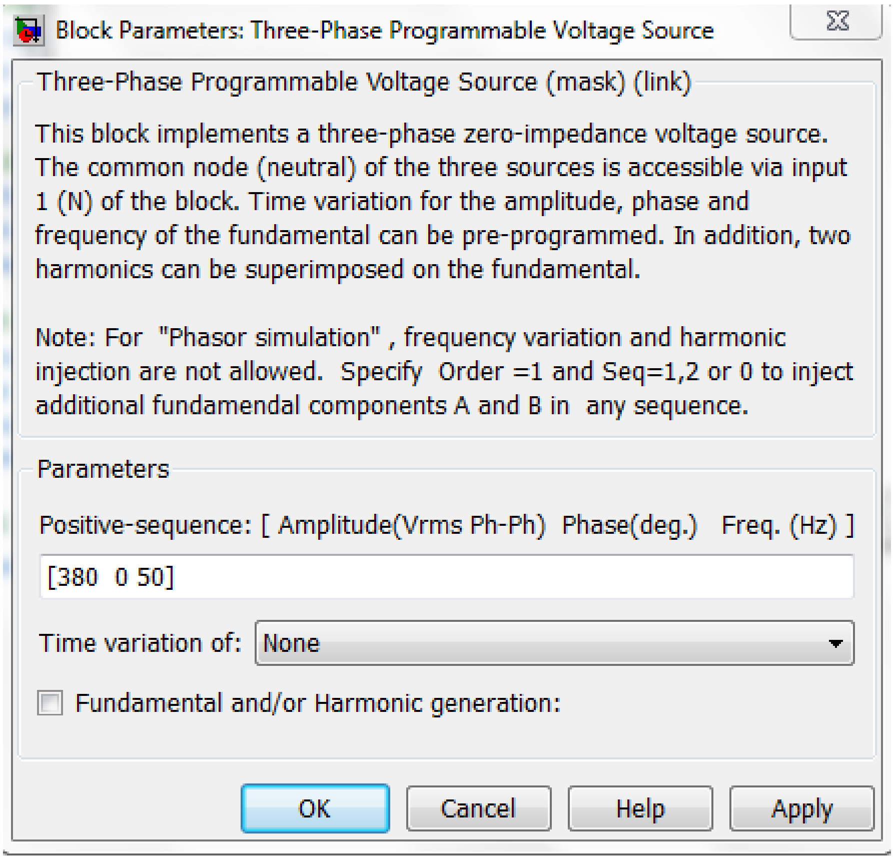


Figure 4.16: block diagram of Three phase programmable voltage source.

4-10-2 The parameters:



Three-Phase Programmable Voltage Source (mask) (link)

This block implements a three-phase zero-impedance voltage source. The common node (neutral) of the three sources is accessible via input 1 (N) of the block. Time variation for the amplitude, phase and frequency of the fundamental can be pre-programmed. In addition, two harmonics can be superimposed on the fundamental.

Note: For "Phasor simulation" , frequency variation and harmonic injection are not allowed. Specify Order =1 and Seq=1,2 or 0 to inject additional fundamendal components A and B in any sequence.

Parameters

Positive-sequence: [Amplitude(Vrms Ph-Ph) Phase(deg.) Freq. (Hz)]

[380 0 50]

Time variation of: None

☐ Fundamental and/or Harmonic generation:

Figure 4.17: The parameters of Three phase programmable voltage source.

4-11 Simulation Results:

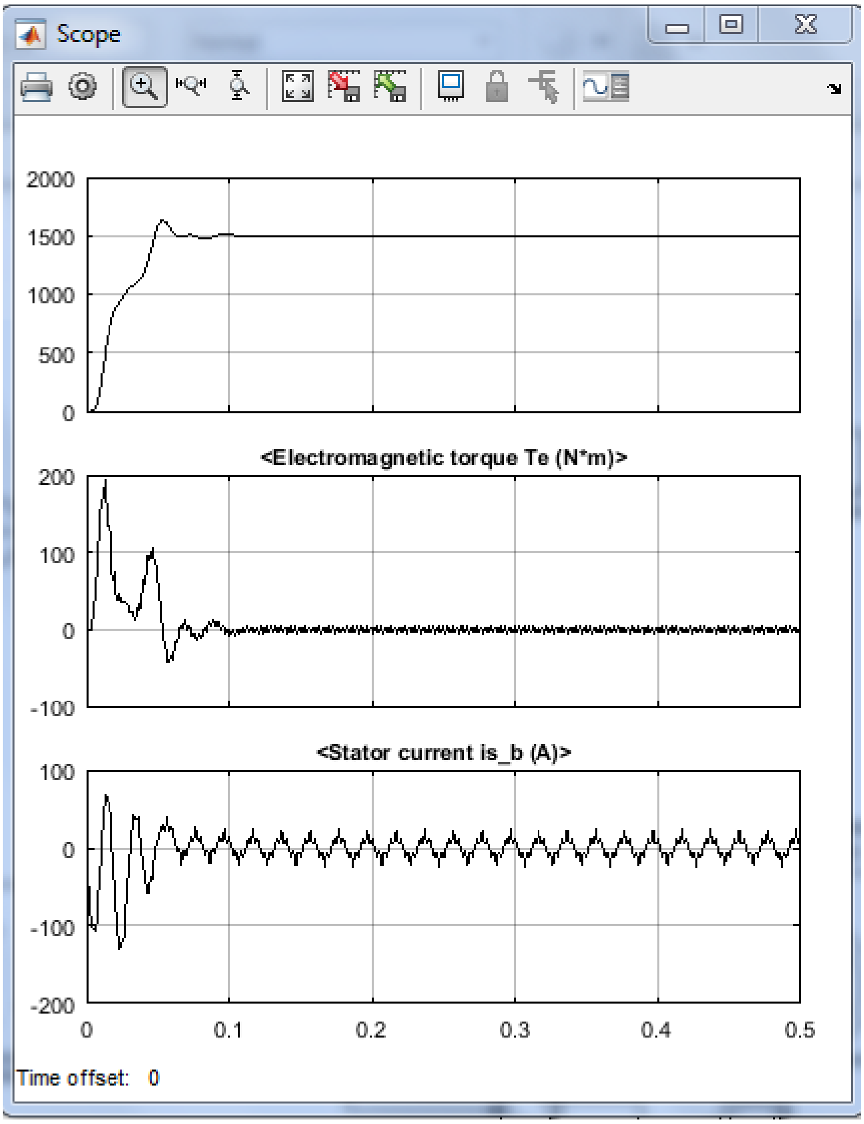


Figure 4.18 :The curves of stator current , speed and electromagnatic torque.

4-11-1 Speed control of induction motor by using scalar control :

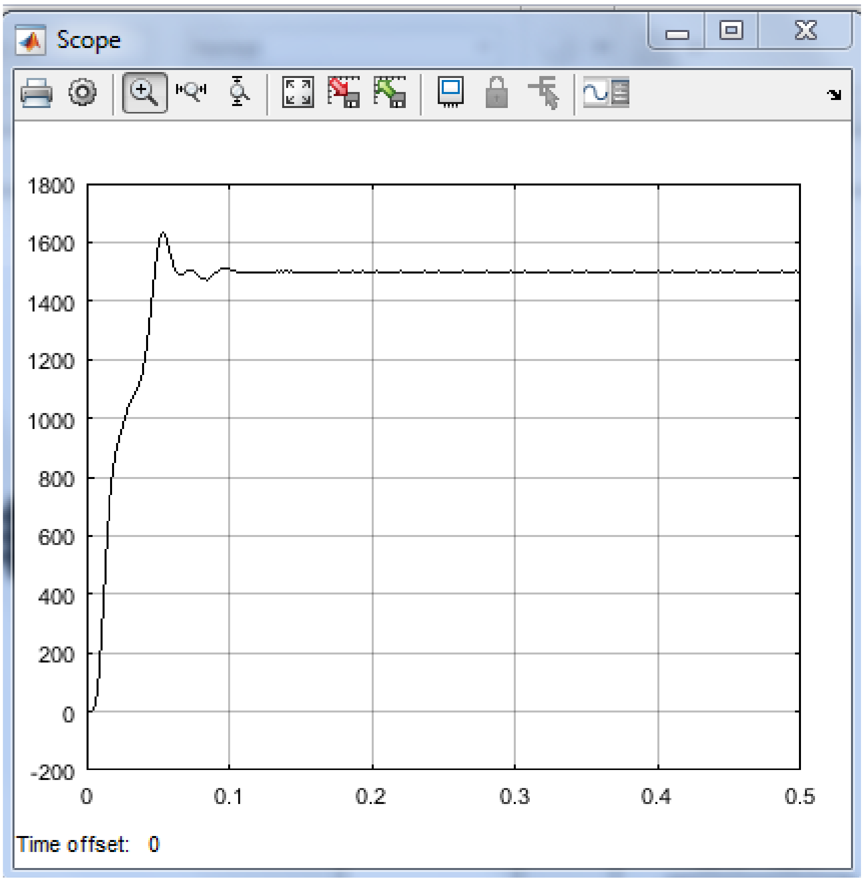


Figure 4.19 : The curve of Speed of induction motor by using scalar control.

4-11-2 Voltage source with PWM :

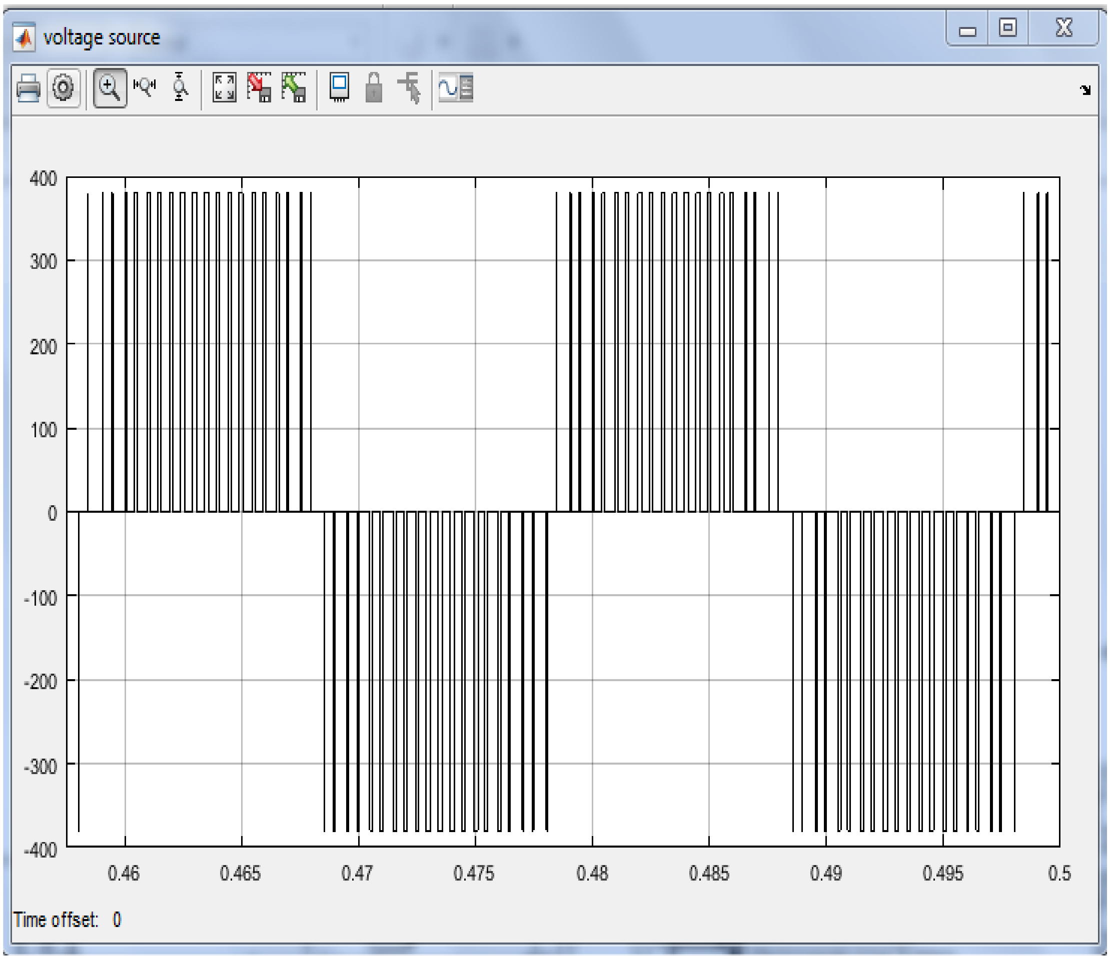


Figure 4.20 : The curve of Voltage source with PWM.

4-11-3 Voltage source after addition the controller:

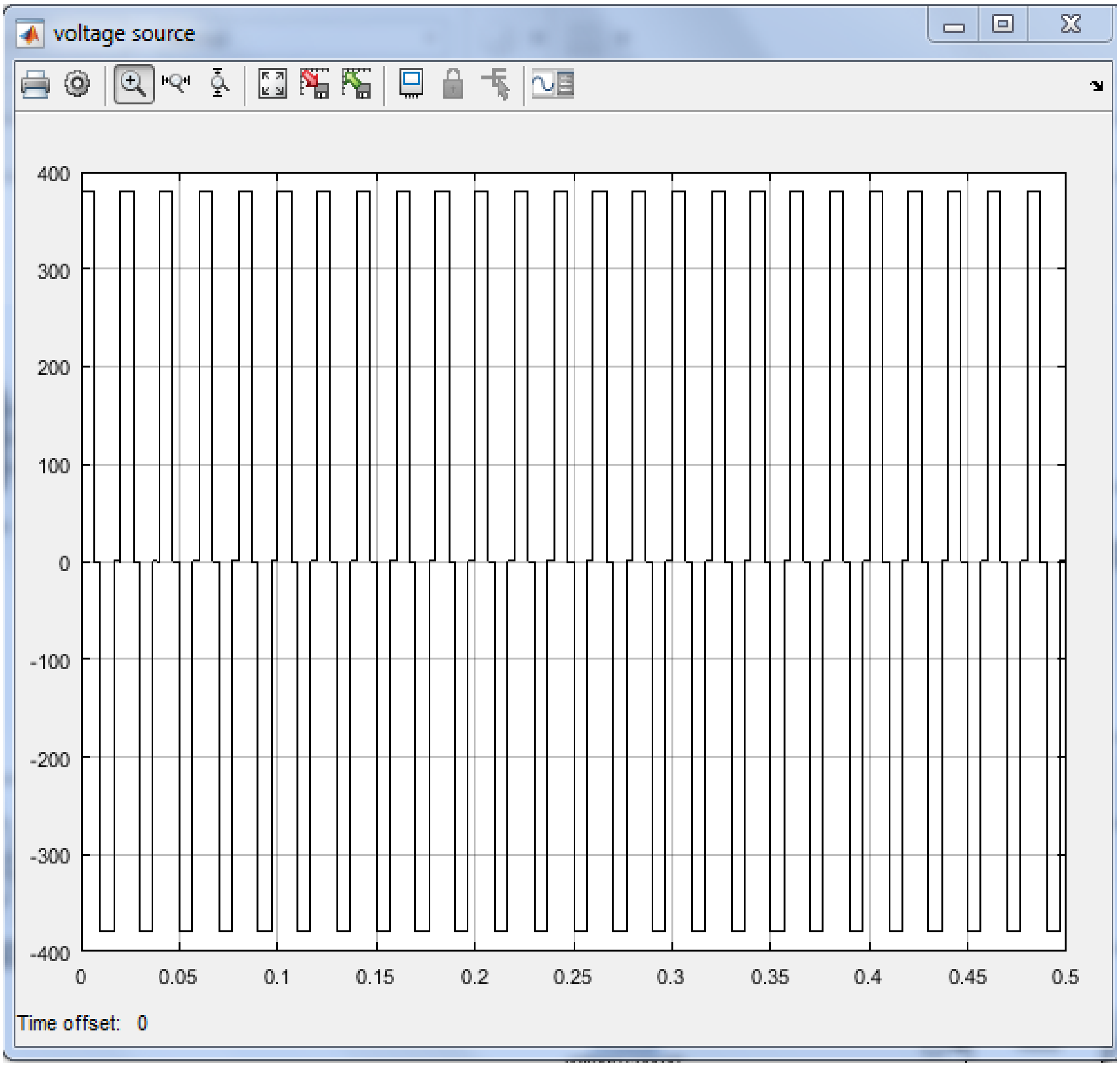


Figure 4.21 : The curve of Voltage source after addition the controller.

4-11-4 Compare between response time for speed motor before and after addition the scalar control:

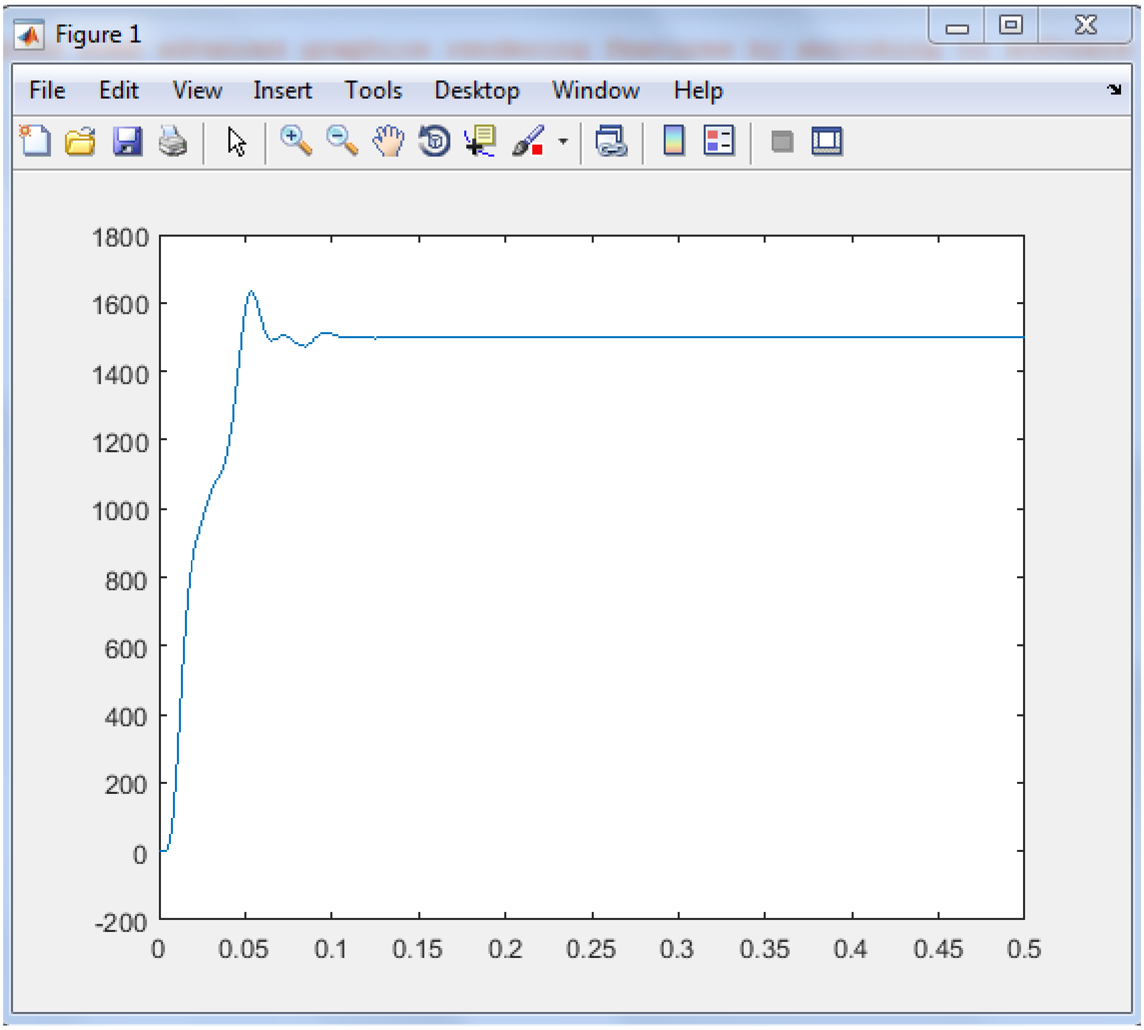


Figure 4.22 : Response time for speed motor after addition the scalar control.

Before addition the scalar control:

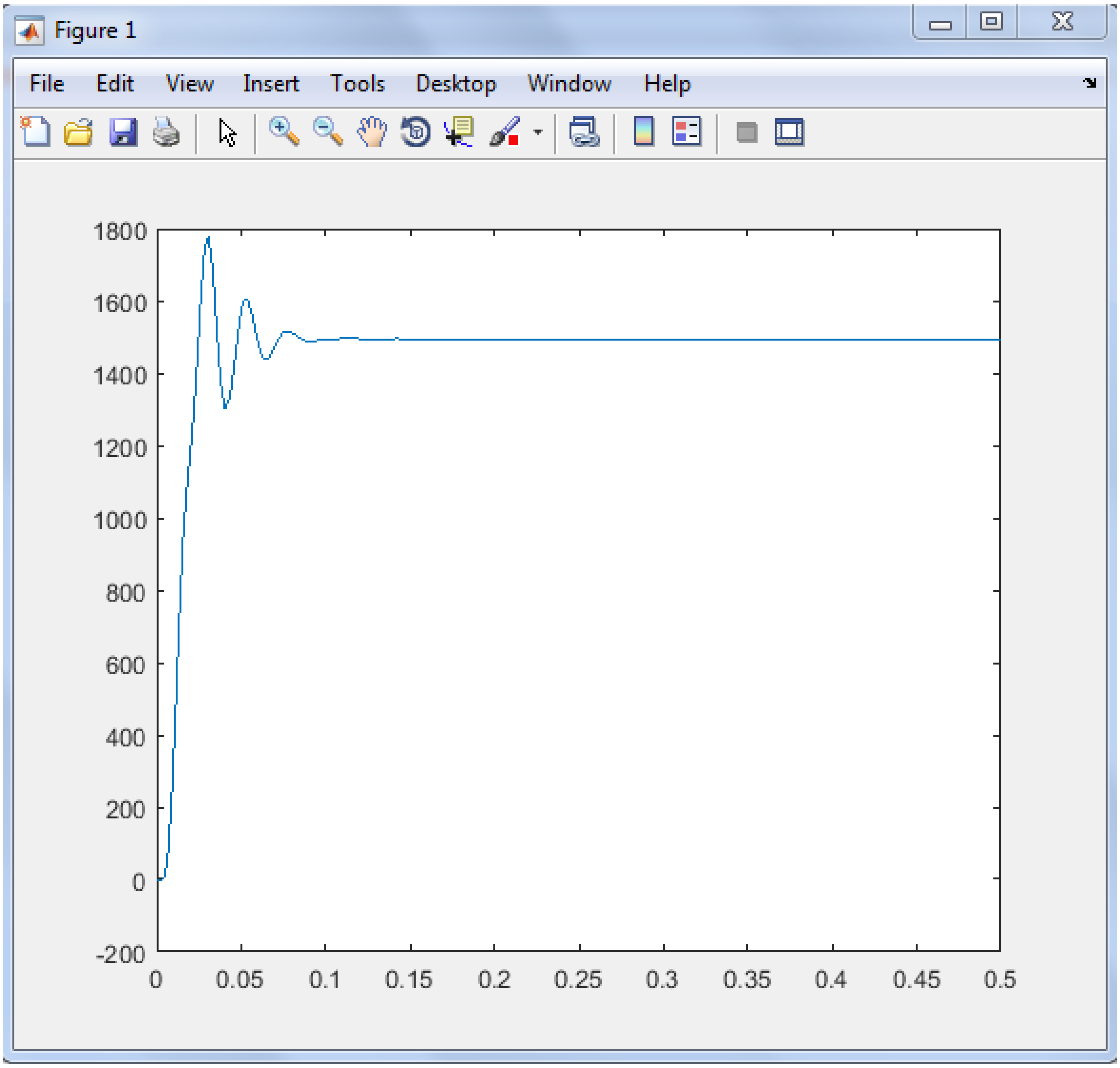


Figure 4.23 : Response time for speed motor before addition V/H controller .

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5-1 Conclusion :

From this research we know two techniques to control the speed of induction motor (vector and scalar) ,the scalar control consisting in adjusting the magnitude and frequency of stator voltages or currents, does not guarantee good dynamic performce of the drive; because transient states of the motor are not considered in control algorithms.

In many practical applications, such performance is unimportant, and the CVH drives, with open-loop speed control, are quite sufficient. In these drives, the stator voltage is adjusted in proportion to the supply frequency, except for low and above-base speeds. The voltage drop across stator resistance must be taken into account for low-frequency operation, while with frequencies higher than rated, a constant voltage to frequency ratio would result in overvoltage. Therefore, above the base speed, the voltage is maintained at the rated level, and the magnetic field and maximum available torque decrease with the increasing frequency. Operation of the CVH drives can be enhanced by slip compensation. Scalar torque control is based on decomposition of the stator current into the flux-producing and torque producing components. Scalar control techniques with the speed feedback are being phased out by the more effective vector control methods.

5-2 Recommendations:

i. Expansion study in this technique.

ii. Design and execute the practical circuit .

iii. Study the close loop scalar control .

REFRENCE :

[1] Austin Hughes- Fundamentals, Types and Application -Elsevier –Third edition 2006 .

[2] Bose, B.K.,Power Electronics and AC Drives ,Prentic-Hall,Englewood Cliffs,N,J.,1986.

[3] Electric Machinery Fundamentals, Stephan J. Chapman, McGRAW-Hill, 1191.

[4] An introduction to Electrical Machines and transformers, George Mc Pherson, John Wiley & Sons, 1981.

[5] Electric Machines, M.S. Sarma, West Publishing Company, 1994.

[6] Electrical Technology , B.L. Theraja and A.K. Theraja, Nirja Construction & Development, 1989.