# DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING FUZZY LOGIC

**A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY**

**By**
**KHALED ABDALLA ALMEZHGHWI**

**In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering**

**NICOSIA, 2015**

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are original to this work.

Name, Surname: Khaled Almezhghwi

Signature:

Date:

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# ABSTRACT

Induction machines have become very widely used in industrial and domestic applications due to their robustness, low cost and high efficiency. The induction machines are using simple structure for delivering mechanical power from electrical power. The need for variable exact driving speed of some industrial machines implies the use of methods to control the speed of induction machines. These methods include varying the voltage or frequency of the machine. Direct torque speed control method is a well known simple and efficient method for controlling the speed of induction machines. It uses the simple relations between speed, torque, flux, and voltage to generate control voltages of a machine. In this work, the use of fuzzy logic controller based DTC control method is proposed and discussed. Discussion includes simulation in the environment of MATLAB/Simulink. All results will be presented and discussed.

***Keywords*** **:** Fuzzy logic controllers; direct torque control; induction machines; asynchronous machines; induction motor

# ÖZET

İndüksiyon makineleri, sağlamlığı, düşük maliyeti ve yüksek verimliliği nedeniyle endüstriyel ve evsel uygulamalarda çok yaygın olarak kullanılır hale gelmiştir. İndüksiyon makineleri elektrik enerjisinden mekanik güç üreten basit bir yapı kullanmaktadır. Bazı endüstriyel makinelerin değişkenlerinin tam sürüş hızı için ihtiyacı indüksiyon makinelerinin hızını kontrol etmek için yöntemlerin kullanımını ifade eder. Bu yöntemler makinenin çeşitli voltaj veya frekansını içerir. Doğrudan moment kontrolü yöntemi indüksiyon makinelerinin hızını kontrol etmek için çok iyi bilinen basit ve etkili bir yöntemdir. Bir makinenin kontrol voltajını oluşturmak için hız, moment, akı ve gerilim arasındaki basit ilişkileri kullanır. Bu çalışmada bulanık mantık denetleyici tabanlı DTC kontrol yönteminin kullanılması önerilmiş ve tartışılmıştır. Tartışma, MATLAB / Simulink ortamında simulasyonu içermektedir. Tüm sonuçlar sunulacak ve tartışılacaktır.

***Anahtar Kelimeler***: Bulanık mantık denetleyicileri; doğrudan moment kontrolü; indüksiyon makineleri; asenkron makineler; indüksiyon motor

## TABLE OF CONTENTS

**CHAPTER 6: CONCLUSIONS**

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| $n_s$ : | Synchronous speed |
| $f$ : | Frequency |
| $P_p$ | Pairs of poles |
| $S$ : | Slip |
| $n$ : | Speed of motor |
| $n_r$ : | Speed of rotor |
| $R_s$ : | Stator resistance |
| $R_r$ : | Rotor resistance |
| $X_{lr}$, $X_{ls}$ : | Inductive reactance of rotor, stator |
| $X_m$ : | Equivalent reactance of magnetization. |
| $V_s$ : | Voltage of the supply. |
| $T_{mec}$ : | Mechanical torque obtained from the rotor. |
| $P_{mec}$ : | Mechanical output power of the motor. |
| $\omega_{mec}$ : | Mechanical speed of shaft or rotor. |
| $\varphi_s$ : | Stator's flux. |
| $\varphi_r$ : | Rotor's flux. |
| $\tau_e$ : | Electromechanical torque. |
| $i_s$ : | Stator current. |
| $\alpha_s$ : | Stator flux angle. |
| $\delta_s$ : | Stator current angle. |
| $\Delta T_e$ : | Error of torque. |
| $B_T$ : | Bandwidth of the torque hysteresis. |
| $dphi$ : | Output of flux hysteresis. |
| $B_\varphi$ : | Bandwidth of the flux hysteresis. |
| $\mu()$ : | Membership function. |
| $K_e$ : | Scaling factor of error. |
| $\Delta K_e$ : | Scaling factor of error's derivative. |

# CHAPTER 1
# INTRODUCTION

DC machines were widely employed in the applications that require variable speed, because their torque and flux can be controlled via armature and field current. The control of DC machines that requires four quadrant operation, high speed, or fast response is easy and needs no large efforts. The main drawback of DC motors is the use of commutator which is less effective in case of high speed or high voltage applications and very dangerous in the case of explosive or corrosive materials. The maintenance costs of commutators and brushes in DC machines that need regular maintenance is another drawback of this type of machines. For these reasons, the use of DC machines has decreased in the last few decades and became limited to some special applications.

Alternating current machines were developed and offered high efficiency and low cost compared to the DC machines. AC motors are simpler, more robust in their structure, less costly, and have good resistance for different circumstances and high loading. AC machines can also be used approximately for all types of applications including explosive or corrosive materials applications. For all these reasons, AC machines have recently replaced their antecedent DC machines in most of industrial and domestic applications. The main drawback of DC machines is the high cost of control units which is getting reduced recently.

There are different types of AC machines that can be categorized in two main categories namely, synchronous and asynchronous machines. The synchronous machines are the most suitable to be used as power generators. Whereas asynchronous type is more suitable to be used as motors due to their easy function principle and simple construction.

Induction machines are the most commonly used types of machines in industrial applications. They are reliable, low costly, rugged and available mostly in all sizes. They are mass produced and available with low prices for different applications. They took the name induction motor from the fact that the power is induced in the rotor from the stator instead of being supplied separately. Currents circulate in the rotor of an induction motor as result of voltage induction caused by stators magnetic flux. The circulation of these currents creates the rotating torque to turn the rotor of the machine.

The main drawback of induction machines resides in their speed control. The speed control of an induction machine implies varying the AC voltage supply, the frequency of the supply, or both of them. Controlling the AC voltage or frequency was very costly and less efficient until the end of the last century. With the development of power electronic products and their control; in addition to the revolution in the digital signal processing the control units started to be less costly and more efficient. New types of controllers with low cost have been developed and exist in the industry. These control units include soft starters, inverters, cyclo-inverters, controlled rectifiers, and many others. The use of these units combined with the proper control algorithms and suitable processors has noticeably reduced the costs of speed control of induction machines.

Different methods are used in the control of induction machines. Some methods are scalar and suitable for some applications while low efficient for others. Other methods are vectorial control that are a little more complex but offer more flexibility with different applications. The scalar methods use simple ideas to change the speed of the controlled machine. They control the machine via controlling directly the voltage of the supply, the frequency of the supply, or by keeping constant ratio between voltage and frequency. Other scalar methods use a rotor rheostat to control the speed of the motor. Or by changing the number of poles of the machine when two or three speeds are need to be obtained from the machine.

There are different vector based control methods of an induction machine. Among which Direct torque control (DTC) is one of best possible solution for variable frequency drives to control the torque and speed of induction motors. It involves measuring motor's voltages and currents that are then used to find the torque and magnetic flux developed in the motor. The calculated values are then used to decide the suitable torque and voltage to be applied on the machine. The applied voltage will lead the machine to work at the desired speed and torque with high precision, efficiency, and minimum effort.

Artificial intelligence has become a very important tool in the modern systems. It is widely used control systems due to its high efficiency especially with complex systems. In complex systems the mathematical description is mostly difficult if not impossible in some cases. As a result, linear and traditional control methods appear insufficient to provide suitable control of the systems. The use of modern non-linear intelligent controllers like fuzzy logic controllers or neural network controllers offers low effort and high efficiency solution. Such intelligent controller can predict the behavior of the system without having any idea about its mathematical model. Fuzzy logic is widely used nowadays in different control and prediction systems and present very high efficiency with reliable results.

In this work, the principles of direct torque control method combined with artificial intelligent controller based on fuzzy logic will be discussed and used. The controller with DTC control will be simulated on an induction machine of squirrel type under different conditions. All results will be discussed and presented.

## 1.2 Literature Review

The idea of fuzzy logic has appeared early in the 60s of the last century (Zadeh, 1965). And it has developed very fast since then. Many improvements have been introduced into its function. It is used nowadays in different scientific and industrial processes. It has been discussed in thousands of papers, thesis, books, and scientific articles. The direct torque control method is comparatively recent control method that has become very popular in the induction machines control due to its simplicity. It has also been discussed widely in literature since its first idea appeared in 1986 (Takahashi and Toshihiko, 1986).

In 1986, Takahashi and Noguchi proposed the so called direct torque control technique for induction motors. In that time, this method became an alternative of the field oriented control method (Takahashi and Toshihiko, 1986). In 1992, Habetler has proposed a direct torque control technique using predictive deadbeat control. The output voltage in this method is based on space vector PWM to optimize the output voltage (Habetler et al., 1992). In Lascu et al. (2000) a paper was introduced presenting a new direct torque and flux control method. This method was based on space vector PWM control method.

In Vasudevan et al. (2005) a comparison between adaptive intelligent direct torque control technique based on neural networks, fuzzy logic, and genetic algorithms was presented. The application of such intelligent methods was explained by obtaining high performance out of the control technique. In Casadei et al. (2006) the authors presented different advantages of

DTC over the other vector techniques. The advantages were mainly the independency of the technique from rotor parameters, coordinate transforms, current controllers, and PWM signals.

A simple approach for the design of a Direct Torque Controller of three phase squirrel cage induction motor using was proposed in (Allirani and Jagannathan, 2010).

In Kantari (2012), space vector PWM modulation based direct torque control of induction motor was proposed. In Manuel and Francis (2013), the design and simulation of a direct torque controller for induction motor drive system based on space vector modulation technique was proposed. Leonhard (2001) has discussed the construction of induction machine and different control methods. The DTC was discussed in the book under different conditions. Trzynadloski (2001) has discussed the construction and control of induction motors. Different control schemes including direct torque control and direct self control were discussed. Different drive systems were also studied and discussed in this book. Austin and Drury (2013) has presented types of the electrical machines and their control. Construction, modeling, and control of machines were presented and discussed in this book. Kandel and Langholz (1993) has presented the structure and construction of fuzzy logic systems in addition to some of their uses. The design of fuzzy logic systems was also covered by this publication. Mathematical concept, and operation of fuzzy controllers were discussed in (Reznik, 1997). The book discussed replacing linear controllers like PID, PI, PD, and others by fuzzy logic controllers. Study of fuzzy controllers and their uses in control systems was presented in (Passino and yurkovitch, 1998). The author presented different case studies for systems using fuzzy controllers in their control. Cirstea, Dinu, and McCormick (2002) has discussed the use of fuzzy logic controllers in the control of different electrical machines.

Andrews (2013) has discussed the direct torque control of a three phase induction machine fed by a three phase voltage source inverter. In Grabowski et al. (2000) a simple direct torque neuro-fuzzy control of an induction machine was presented and discussed. In Eldali (2012) a comp arative study between vector control and direct torque control was presented. Advantages and disadvantages of each one of them were also discussed. DTC control of induction motors was also discussed in (Toufouti et al., 2007).

# CHAPTER 2
# INDUCTION MOTORAND DRIVES

The induction motor is the most used motor type in the industrial and domestic applications. This type of motors is preferred due to its self-starting capability, simple and robust structure, low cost and reliability. Induction motors are also called asynchronous motor because the mechanical speed they offer is different from their electrical speed (Aspalli, 2014). Three phase induction motor is a single excitation motor whose stator winding is supplied from three phase source. The rotor of an induction motor gains its energy by means of induction from the stator. The three phase voltage creates a rotating magnetic field in the air gap; this rotating field interacts with the windings of the rotor inducing voltage and current in it. The rotating field rotates at a constant speed of synchronization. It forces the rotor to rotate generating mechanical torque at all speeds except for the synchronous speed. Induction motors can't run at synchronous speed, that's why they are also known as asynchronous machines (Austin and Drury, 2013).

Induction motors are using a simple structure of electromechanical energy conversion. In the squirrel-cage motors, the rotor can't be accessed under any condition. No need for brushes like in DC machines; or slip rings like in synchronous and wound AC machines. This fact increases the use of induction motor in environments where the danger of fire exists. Because brushes and moving contacts cause sparks that can be a source of fire. Another dimension of strength in squirrel cage motors resides in the lack of wiring in their rotors. These rotors windings are built of strong bars that can withstand higher currents and work under heavy electrical and mechanical overloads (Trzynadloski, 2001).

Wound-rotor induction motors are less common in industry and used in limited applications where there is need for access to the rotor's circuit. The rotor in these motors is provided with slip rings to give access to the moving windings from outside to add some external resistance to control the characteristics of the motor. When the motor reaches its nominal speed, the external resistances can be removed and the ends of the rotor's windings are short-circuited (Trzynadloski, 2001).

Speed control of industrial motors is a very important subject due to the vital influence of speed on some applications. Although squirrel cage motors are cheap in comparison with other types of motors, their control is a bit costly. Different speed and torque control methods exist for induction motors. The speed control of motors implies the use of power electronic converters to provide the desired control of different parameters of voltage and frequency.

Inverters are one of the most important power electronic drives that can be used in the control of induction motors. Their high performance and controllability in terms of voltage value and frequency can offer an amazing possibility to be employed.

In this chapter of our work, induction motor is construction and main structure will be discussed. The different main parts of the induction motor will be presented. An equivalent circuit of the induction motor will be developed and some important equations of torque and flux will be presented. Dynamic model of an induction motor will be studied in this chapter. At the end of chapter, drive system consisting of a three phase diode bridge with a power inverter will be studied and presented.

## 2.1 Construction of the Induction Motor

An induction motor consists of many parts; the main parts are the stator and the rotor. An inside view of a squirrel-cage induction machine is presented in Figure 2.1. Other parts are the frame, especially designed outside to help for air cooling, windings wound in slots of stator, magnetic isolated laminations, and a cover. The rotor is also laminated and built around a shaft that transmits the mechanical power to the load (Wildi, 2002).

### 2.1.1 Construction of the Rotor

There are two types of rotors for induction machines; these are the wound rotor and squirrel cage rotor. Both rotors are constructed from stuck of steel laminations with evenly spaced slots punched around the circumference. Figure 2.2 presents the two types of rotors; the wound rotor has slots where the rotor windings can be fixed. Squirrel cage rotor slots are filled with a conductor material (generally aluminum) bars short circuited by end rings from both sides (Austin and Drury, 2013).

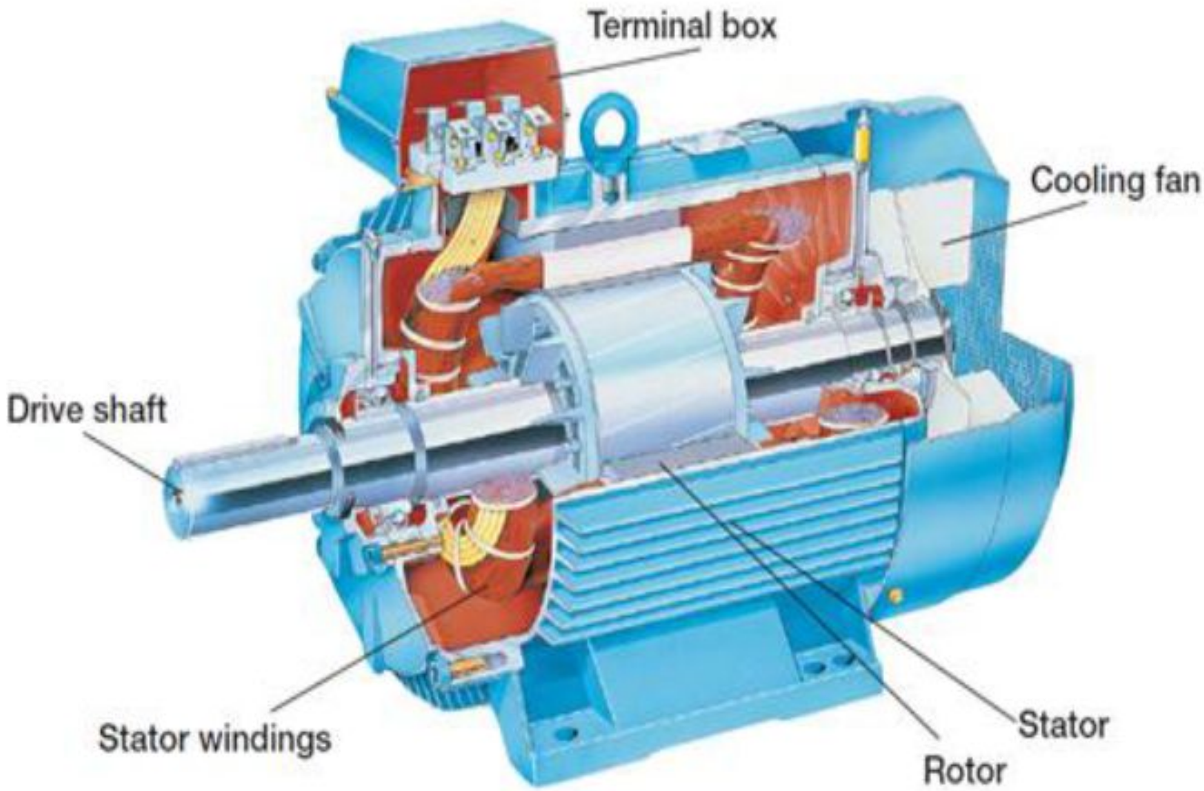


**Figure 2.1**: Main parts of an induction motor (Aspalli, 2014)

The rotor cage shown in the Figure is simplified; practical ones are constructed from more than few bars. The bars are slightly skewed to the longitudinal axis of the motor (Trzynadloski, 2001). Different types of bar cages are used in squirrel cage rotors to change the mechanical characteristics of the machine. Figure 2.3 shows deep bar cages and double bar cages used in squirrel cage rotors.

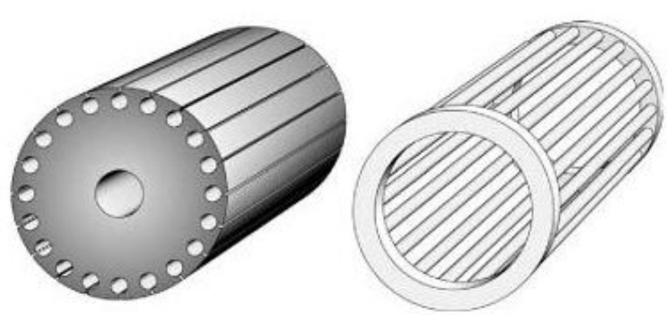

**Figure 2.2**: Two types of rotor for induction motor (Austin and Drury, 2013)

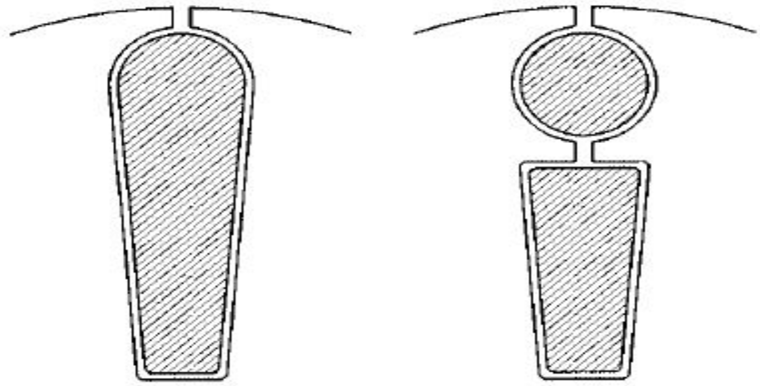

**Figure 2.3:** Deep slot cage (left) versus double cages rotor slots (right) (Austin and Drury, 2013)

The fact that the squirrel cage rotor is short circuited from the two ends imposes that no external control can be applied on the rotor's resistance. The currents of the rotor are induced by the air gap fields. The resistance of the rotor is chosen in the design stage of the motor to fit the desired application needs. This fact is considered as a drawback of the squirrel cage rotor which is solved by using the wound rotor. In the wound rotor, slots are containing three phase windings connected in star from one side. The other sides are brought out of the motor by means of three slip rings. The resistance of each phase can be varied externally to change the characteristics of the motor (Austin and Drury, 2013) .

## 2.2 Rotating Magnetic Field

In the three phase induction motors, three winding are arranged in the stator with 120 degrees angle apart. The current will flow equally (in an ideal case of balanced system) in all windings. As the current is alternative sinusoidal; its changing value and direction continuously. Each one of the currents will create a correspondent magnetic field with variable magnitude and direction. The three magnetic fields will then result in a one magnetic field with fixed magnitude and rotating in the stator and around its axe.

The speed of rotation of the rotating field is a function of the frequency of the electrical source. Hence, an electrical source of 50Hz frequency will create a rotating field of 50Hz (3000 rpm electrically) (Wildi, 2002). If more poles are used for each one of the three phases, the speed of rotation of the magnetic field will be reduced due to the fact that the magnetic field will rotate between different poles. The relation 2.1 can give the rotation speed of the magnetic field of a three phase AC machine in function of the frequency and number of poles.

The speed given by this formula is called synchronous speed. Synchronous speed is the maximum speed that rotor can have.

$$n_s = \frac{120 * f}{2 p_p} \tag{2.1}$$

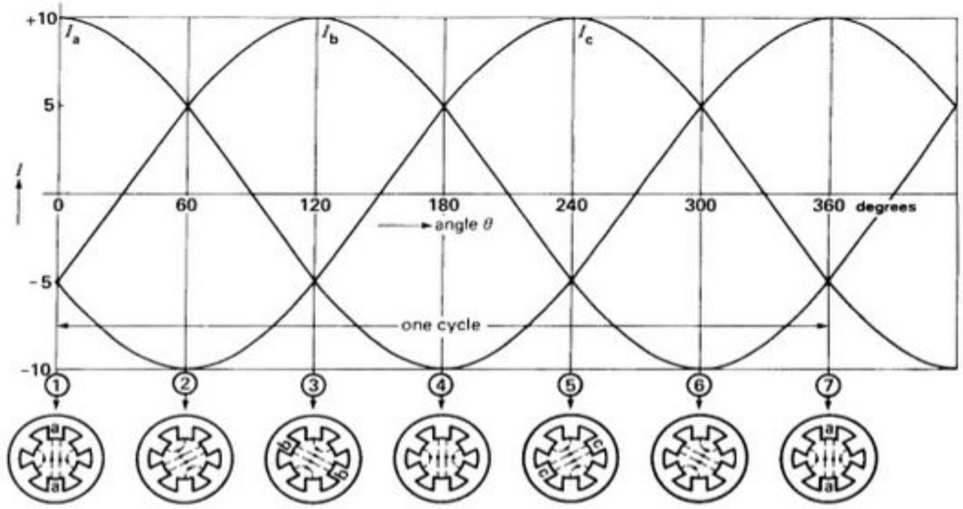


**Figure 2.4**: Three phase currents of stator and there rotating magnetic field position (Wildi, 2002)

## 2.3 Slip Speed in an Induction Motor

As known in the induction laws, the variable magnetic field that interacts with a conductor will induce a voltage in that conductor. Also, a current carrying conductor inside a magnetic field will dispose a force that tends to move that current from its place. The direction of the force will be vertical to both the direction of the current and the magnetic field. In the induction motors, the rotating field created by the stator windings is cutting the rotor bars or windings with the synchronous frequency. This will result in induced voltages and currents in the rotor circuit. The flow of current in the rotor circuit will interact with the rotating magnetic field and create a torque that rotates the rotor (if not locked). The rotation of the rotor will follow the rotation of the magnetic field. When the rotor speed is exactly equal to the synchronous speed, the created torque becomes null and it tends to decelerate. The rotor will accelerate again due to the developed torque and the speed will be fixed at a speed lower than the synchronous speed which is called slip speed. The slip is defined by the next equation (Chapman, 2005):

$$s = \frac{n_s - n}{n_s} \tag{2.2}$$

The slip is nearly zero when no load is connected to the motor, while it is 1 whenever the rotor is locked (Wildi, 2002). The rotor speed can be also given by (Chapman, 2005):

$$n_r = s n_s \tag{2.3}$$

### 2.4 Equivalent Circuit of an Induction Motor

Three phase induction motor is similar to three phase transformer (Austin and Drury, 2013). The primary of the transformer is the stator winding of the motor, while the secondary is present in form of a rotating part (rotor) the magnetic core resides in two parts which are the laminations of the stator and the air gap that separates the rotating part from the fix part of the motor. Just as in the transformer, the equivalent circuit of an induction motor can be given as shown in Figure 2.5.

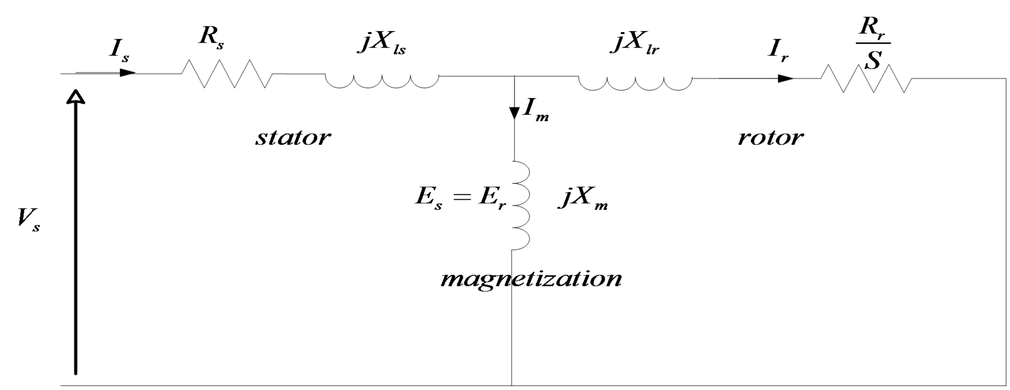


**Figure 2.5**: Equivalent circuit of a three phase induction motor (one phase referred to stator)(Trzynadloski, 2001)

Where Rs and Xs represent the stator impedance, Xr and Rr/s are the equivalent impedance of the rotor referred to the stator side. Xm presents the equivalent reactance of the magnetization circuit while Rc is the equivalent resistance for the iron losses. The parameters of the equivalent circuit of the induction motor can be found easily using a no load and short circuit (locked rotor) tests just as in the transformer (Wildi, 2002).

### 2.4.1 Torque in an Induction Motor

The equivalent circuit of an induction motor can help in calculating the torque and current of the machine. Assuming that the three phase of the induction motor are balanced, each one of these phases will share one third of the delivered power of the motor. The total delivered power is given by:

$$P_{mec} = T_{mec}\omega_{mec} \tag{2.4}$$

The developed mechanical torque can then be given by:

$$T_{mec} = \frac{P_{mec}}{\omega_{mec}} \tag{2.5}$$

The power can be also given in function of the rotor resistance and the current by:

$$T_{mec} = 3\frac{R_r}{s}\vec{I}_r^2 / \omega_{mec} \quad ] \tag{2.6}$$

An approximate expression for the rotor current can be obtained from the equivalent circuit and given by:

$$I_r = \frac{V_s}{\sqrt{(R_s + \frac{R_r}{s})^2 + X^2}} \tag{2.7}$$

And the torque is then given by (Chapman, 2005):

$$T_{mec} = \frac{3P_p}{2\pi f}\frac{V_s^2 \frac{R_r}{s}}{(R_s + \frac{R_r}{s})^2 + X^2} \tag{2.8}$$

## 2.5 Formulation and Model of the Induction Machine

The static and dynamic study of any system implies the ability to model that system and describe it using mathematical equations. In order to do so, the general model of an electrical machine will be studied in three phase reference. Then the three phase model will be simplified in two phase model form which is more suitable for our control purpose. As we said earlier in this chapter, the three phase machine has a fixed part called stator and a rotating part called rotor. The stator carries the windings of the machine separated by 120 degrees. In the aim of simplifying the study of the model of the machine, the next hypothesis will be accepted (Krause et al., 2002).

1 Symmetrical air gap.
2 Neglected effect of laminations.
3 Sinusoidal flux distribution in the air gap.
4 Magnetic circuit in the linear zone of the curve.

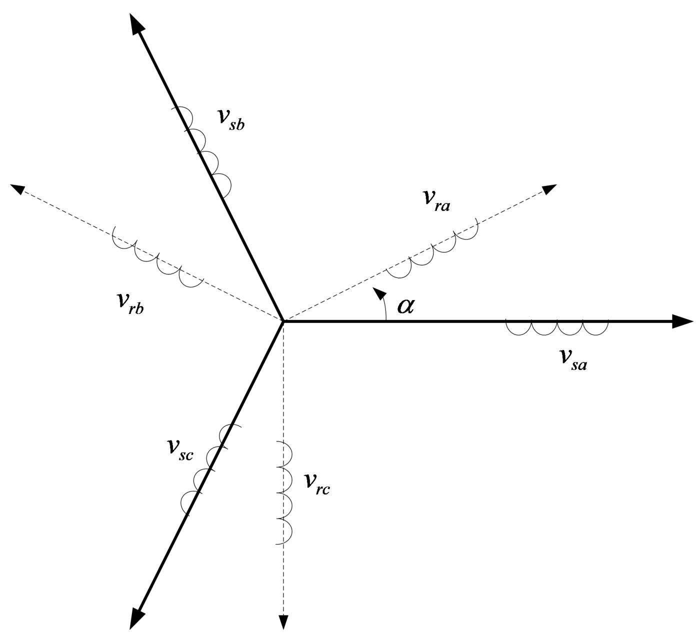


**Figure 2.6**: Stator and rotor windings representation in a three phase system

Figure 2.6 presents the stator and rotor windings represented in three phase reference. The angle $\alpha$ is the actual angle of rotor to the stator. The stator windings are fixed while rotor ones are rotating with an angular speed $\acute{\omega}=d\alpha/dt$. Using Faraday's and Lenz's laws in electromagnetic induction giving the general relation:

$$V = RI + \frac{d\varphi}{dt} \tag{2.9}$$

That leads to the equations of the stator winding given by:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix} \tag{2.10}$$

And for the rotor:

$$\begin{bmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{bmatrix} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} = 0 \tag{2.11}$$

The three phase system mentioned above can be represented in the form of two phase system using the transformation:

$$\begin{bmatrix} x_q \\ x_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{2.12}$$

Where, x denotes the variable to be processed; current or voltage. The voltage equations of stator and rotor become then:

$$\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} = \begin{bmatrix} R_{ss} & 0 \\ 0 & R_{ss} \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sq} \\ \varphi_{sd} \end{bmatrix} \tag{2.13}$$

$$\begin{bmatrix} v_{rq} \\ v_{rd} \end{bmatrix} = \begin{bmatrix} R_{rr} & 0 \\ 0 & R_{rr} \end{bmatrix} \begin{bmatrix} i_{rq} \\ i_{rd} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{rq} \\ \varphi_{rd} \end{bmatrix} = 0 \tag{2.14}$$

The magnetic flux of the stator can then be estimated using the equations:

$$\begin{aligned} \varphi_{sq} &= \int (v_{sq} - R_{ss} i_{sq})\, dt \\ \varphi_{sd} &= \int (v_{sd} - R_{ss} i_{sd})\, dt \end{aligned} \tag{2.15}$$

### 2.5.1 Electromechanical Torque

The electromechanical torque developed by the machine can be given using different formulas. The speed power formula gives:

$$T_{mec} = \frac{P}{\omega} \tag{2.16}$$

$$T_{mec} = \frac{3P_p}{2\pi f}\frac{V_s^2 \frac{R_r}{s}}{(R_s + \frac{R_r}{s})^2 + X^2} \tag{2.17}$$

$$T_{mec} = \frac{3p_p}{2}(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}) \tag{2.18}$$

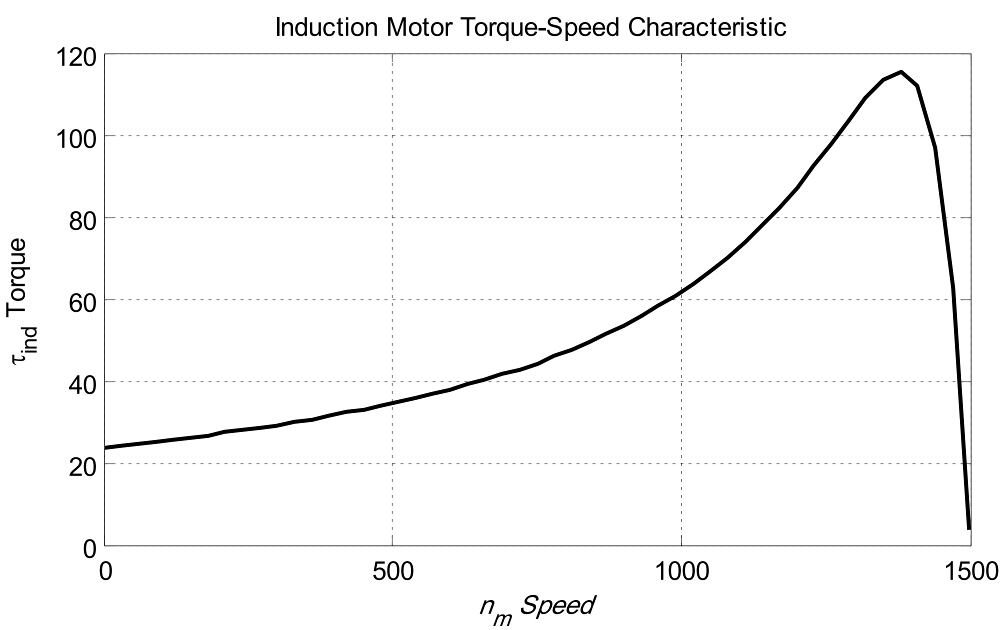


**Figure 2.7**: Torque speed characteristic of an induction motor (Fitzgerald, 2003)

## 2.6 Induction Motor Drive System

The control of induction motor implies the use of variable voltage and frequency sources. The suppliers of electrical power supply with fixed frequency of 50 or 60 Hz. In order to obtain variable voltage and frequency voltage source we need to implement a voltage rectifier with controlled voltage source inverter. The rectifier is used to convert AC voltages to DC voltage, while an inverter is a controlled device that can invert DC voltage into variable AC voltage. the scheme of the used system is shown in Figure 2.22.

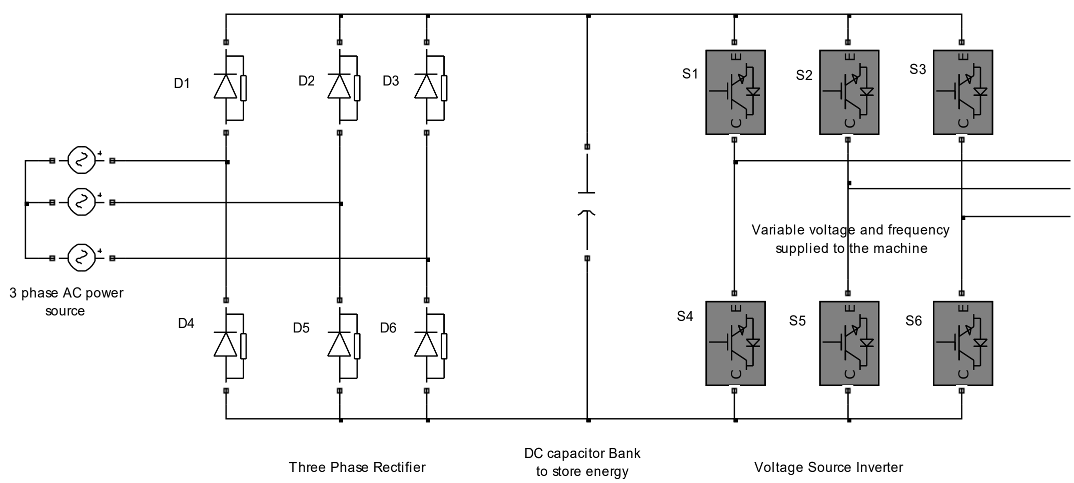


**Figure 2.8**: Rectifier inverter system used in the control of induction machine

The system shown in Figure 2.8 shows the main three parts of the power system used to feed the machine that is to be controlled. It consists of three phase rectifier, DC capacitor, and the inverter.

### 2.6.1 Three Phase Voltage Rectifier

Voltage rectifier is a static power electronic device used to convert AC power into DC power by means of a set of semi-conductor diodes. In a three phase system, six diodes are used to construct a full wave rectifier. Supposing the three phase input of the rectifier described as follow:

$$
\begin{aligned}
v_1 &= \sqrt{2}\, v_{rms} \sin(2\pi\, ft) \\
v_2 &= \sqrt{2}\, v_{rms} \sin(2\pi\, ft - \frac{2\pi}{3}) \\
v_2 &= \sqrt{2}\, v_{rms} \sin(2\pi\, ft + \frac{2\pi}{3})
\end{aligned}
\qquad (2.19)
$$

Figure 2.9 below shows the three phase AC system of a 240 volt. As the diode is in the state ON just if its Anode's voltage is higher than its Cathode's voltage. Each one of the three upper diodes D1, D2, D3 is active just when its connected phase's voltage is the highest of the three phases. Each one of the other three diodes D4, D5, and D6 are ON just when the voltage of its correspondent phase is the lowest among the three phases. The output DC voltage of the voltage rectifier is presented in Figure 2.10.

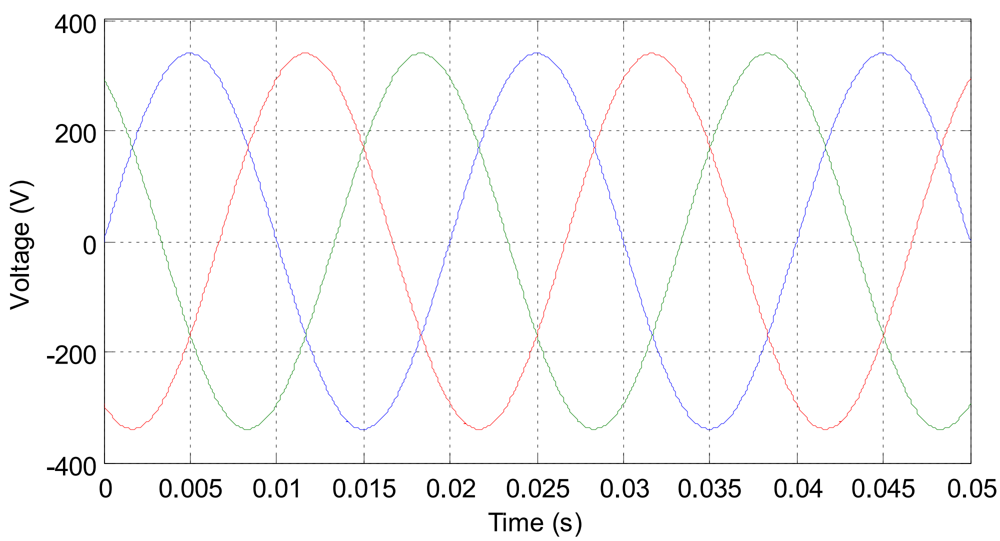


**Figure 2.9**: Three phase mains AC voltage wave forms

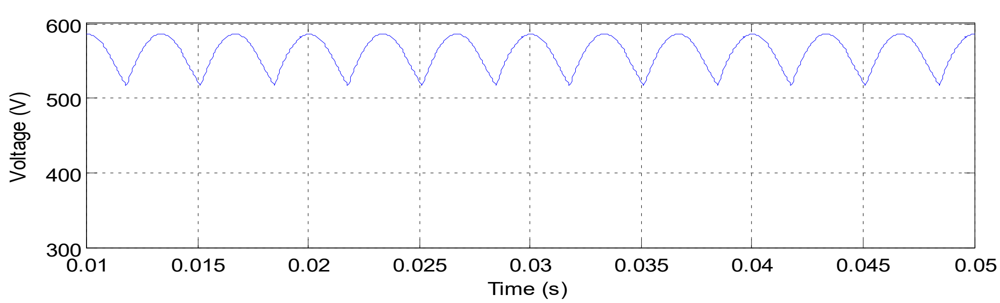


**Figure 2.10**: Output DC voltage of the three phase diode rectifier

From three phase voltage curves and based on the conditions of switch on of the diodes, the output voltage can be given by:

$$
\begin{aligned}
\overline{V}_{out} &= \frac{3}{\pi}\left(\int_{\pi/6}^{\pi/2} (v_1 - v_2)\,dt + \int_{\pi/2}^{5\pi/6} (v_1 - v_3)\,dt\right) \\
\overline{V}_{out} &= -\frac{3V_m}{\pi}\left[-1.73 - 0.86 + 0.86\right] \\
\overline{V}_{out} &= 1.65\,V_m = 1.65 * \sqrt{2} * V_{rms}
\end{aligned}
\tag{2.20}
$$

### 2.6.2 Three Phase Voltage Source Inverter

Figure 2.35 present the general structure of a three phase voltage source inverter. It can be seen that it is using a fully controlled switches (IGBT/MOSFET) connected in anti-parallel with recovery diodes. The principle of function of an inverter is based on switching between positive and negative poles of the DC source very fast to produce AC voltage as shown in Figure 2.28.

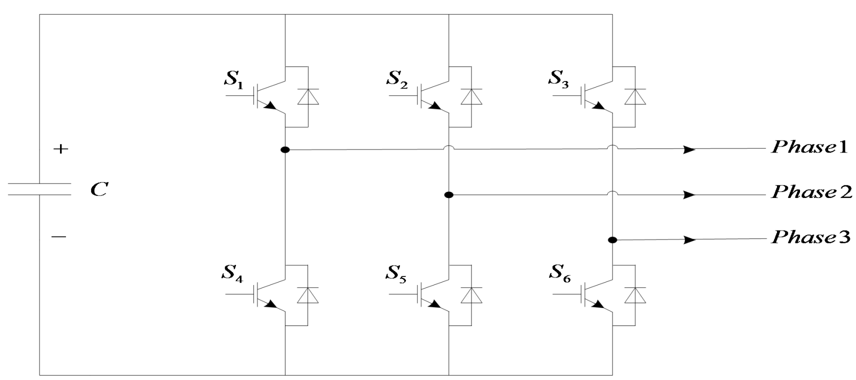


**Figure 2.11:** Three phase voltage source inverter structure

The upper and lower switches of each leg of the inverter can't be switched on at the same time. They are complimentary to each other. That is; the described structure can generate a maximum of eight different vectors of voltage as seen from Figure 2.12. it shows the states of switches 1, 2 and 3 in addition to the correspondent generated voltage vector. It is useful to mention here that six of the eight possible voltages are active and the other two are zero volt vectors. This structure of VSI is very useful in the DTC control method and will be explained later in this work.

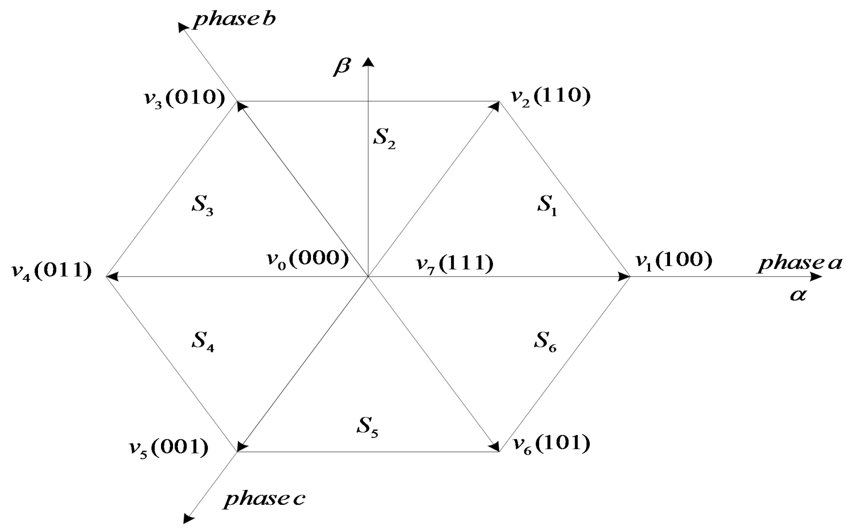


**Figure 2.12**: Eight different output voltage vectors of a VSI

The flow of current in the inverter switches is allowed in both directions. That allows the production of AC voltage from a DC source. The DC source can be either a battery or a stocking capacitor that is used to stock energy and supply the inverter. The output voltage and current of voltage source inverter are shown in Figure 2.13 and 2.14.

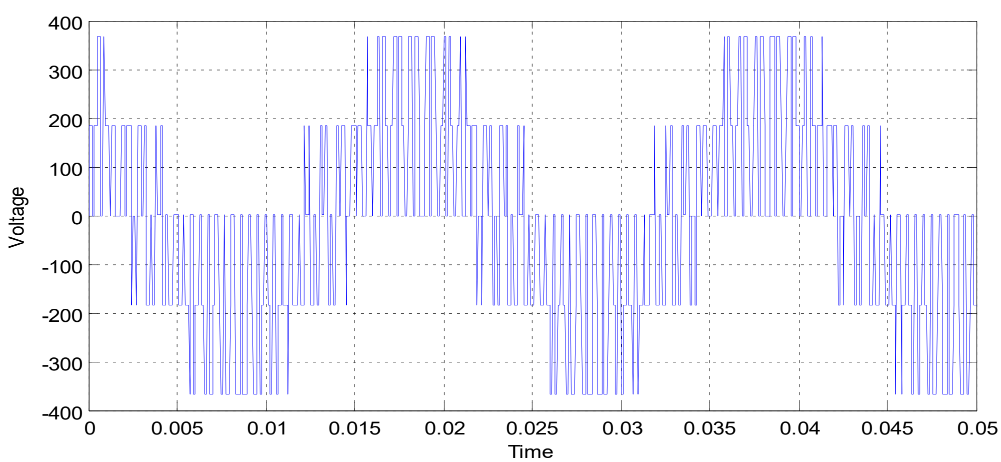


**Figure 2.13:** Output voltage wave form of three phase VSI (line-line)

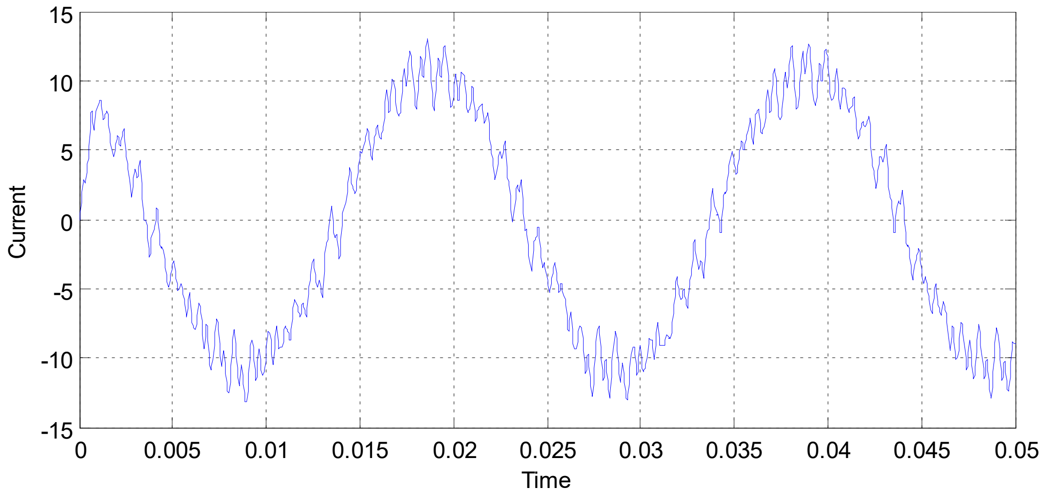


**Figure 2.14:** Line current of a three phase VSI

# CHAPTER 3
# CONTROL OF INDUCTION MOTORS AND DTC

Induction motors are the mostly used types of motors nowadays in different industries. The spread of such types of motors is due to their simple construction and high performance. In contrary to the DC motors that need more service and extra costs, the induction motors are less costly and need less maintenance during their function life. The main advantage of DC machines over AC machines is the ease of control of these machines. With the development of semiconductor industries and power electronic switching devices, the control of induction machines is becoming more and more simple and feasible.

Different control methods of induction machines have been proposed like voltage frequency control, vector control, field acceleration, and direct torque control. Each one of these methods has its advantages and disadvantages as will be seen in this chapter. The main differences lie in the cost of controller and the performance of the motor.

The different methods will be discussed in this chapter while the direct torque control will be explained and used for the rest of our work.

## 3.1 Control Methods of Induction Motors

There is different control methods of induction motor divided into scalar and vector control methods.

### 3.1.1 Stator Voltage Control Method

This method is an economical and simple control method of speed control of induction motor. The frequency of the power supply is kept constant in this method while the line voltage is variable by using a switching device. As known from the last chapter that the developed torque in an induction motor is a function of the square of the stator voltage. Hence, any change in the stator voltage will cause some change in the developed torque. This way, continuous speed control can be achieved easily by changing the developed torque of the motor (Aspalli, 2014). This control method suffers from different disadvantages like the low power factor of the motor, the variable torque developed by the motor, in addition to the low control range where the reduction of small speed needs high reduction in voltage. For these reasons, the stator voltage control is used mostly in small power machines. Figure 1 presents the speed torque curve under variable supply voltage. It is obvious from the Figure that reducing the voltage will reduce the developed torque, the machine then will work with speed far from the synchronous speed and the slip will be higher.

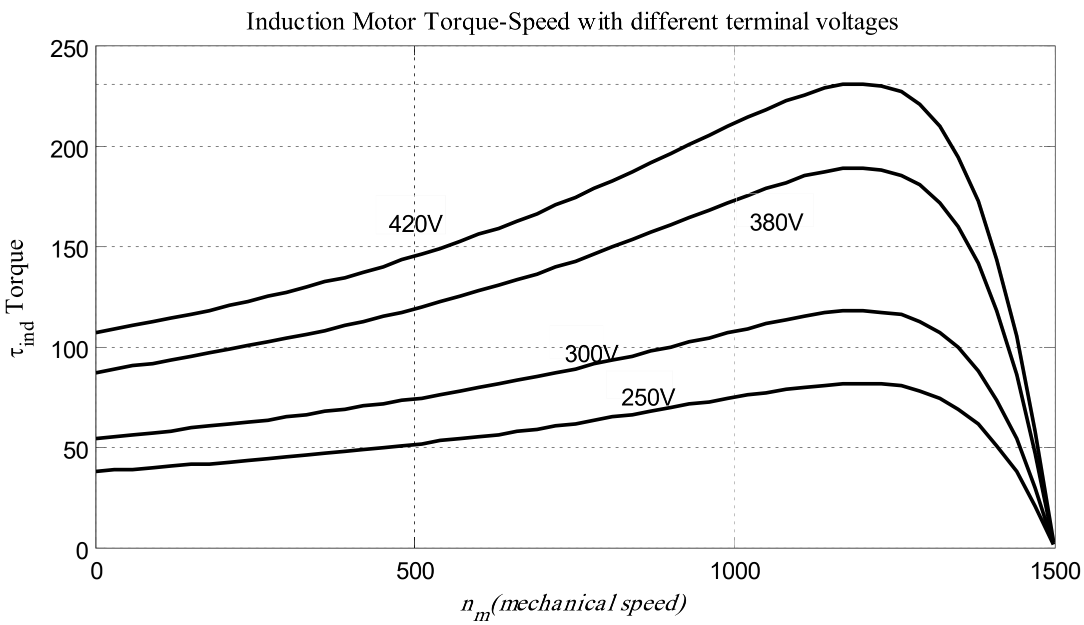


**Figure 3.1:** Torque speed characteristics with variable voltage control

### 3.1.2 Frequency Control Method

This method is based on the equation 3.1. The synchronous speed of a motor is given by:

$$n_s = \frac{120 * f}{p} \tag{3.1}$$

If we accept that the number of pairs of poles is constant, the speed of the motor can then be changed by simply changing the frequency of the power supply under fixed voltage. The relation between the frequency and the speed is proportional as seen from the last equation. Decreasing the frequency under constant voltage will lead to the saturation of the air gap, the torque will be increased and the speed will fall. If the frequency is increased, the speed will increase and the developed torque will be decreased. This method is rarely used in the control of induction motors due to the magnetic saturation which causes high currents and losses. Figure 3.2 shows the curve of speed torque control by frequency variation. The developed torque decreased under higher frequencies while it increases with low speeds.

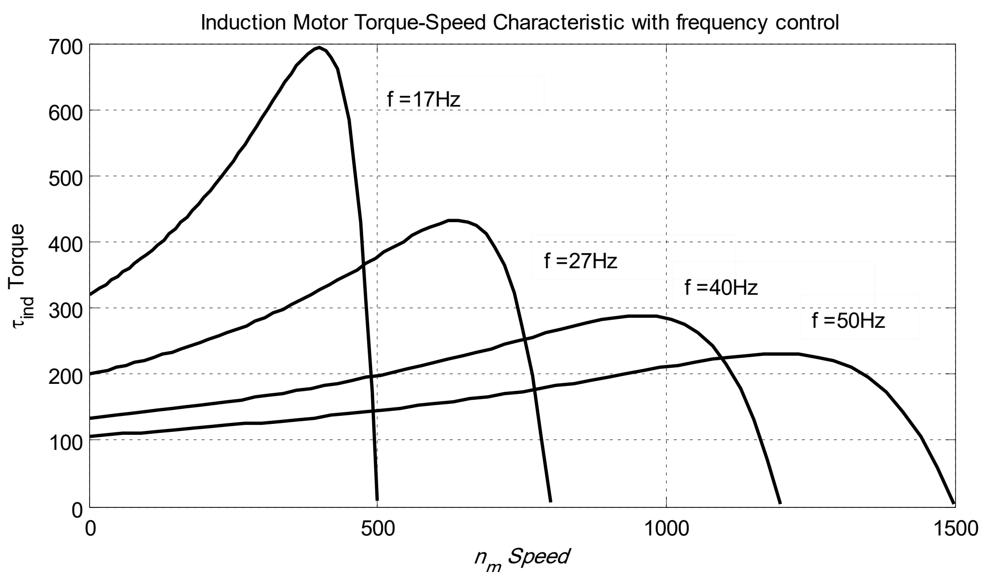


**Figure 3.2**: Torque speed characteristics with variable frequency control

### 3.1.3 Voltage/Frequency Control of Induction Motor

The constant voltage frequency controlled is a combination of the last two methods. It is widely used and preferred in the speed control of motor. In this method, the ratio between supply voltage and frequency is kept constant all the time. If the speed is to be reduced, the frequency and the voltage are reduced to keep the ratio in its nominal value. This arrangement prevents the saturation of the air gap flux that leads to excessive stator currents and flux distortion. The efficiency of this control method is high and the most used in industry. One of the other advantages of this control method is the constant torque that it can offer.

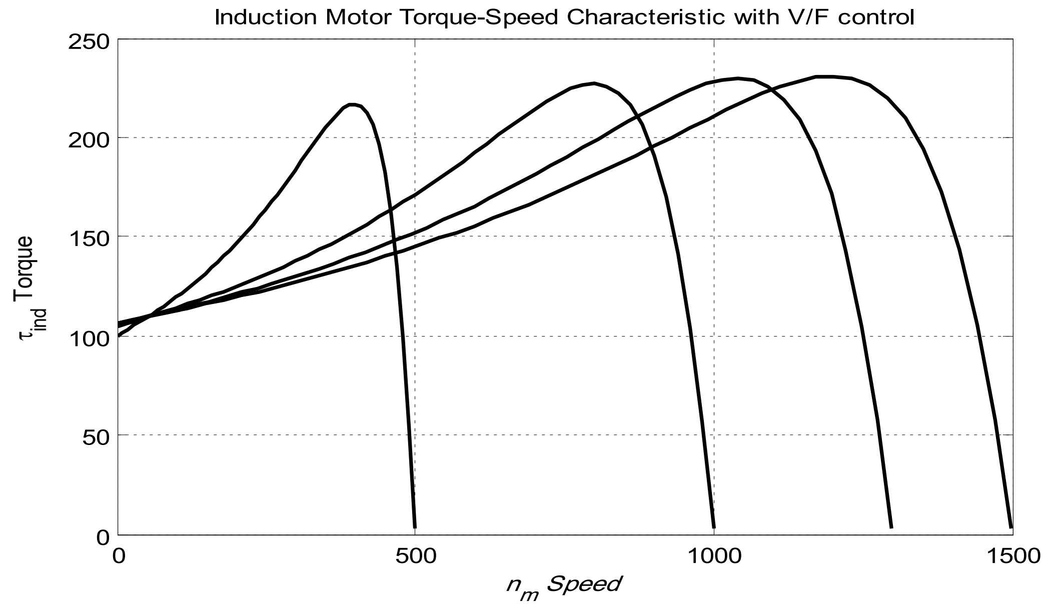


**Figure 3.3:** Torque speed characteristics with V/f control

The v/f control ensures very wide range of speed control where the speed can be varied between 2% and over 100% of its rated speed. Furthermore, the starting current of this method is reduced compared to the other control methods (Pujol, 2000). Figure 3.4 presents the speed torque curve of the induction motor with different V/F values. It’s clear that the maximum developed torque remains constant for wide range of speed in this control.

### 3.1.4 Rotor Rheostat Control

This method is the similar of the armature control rheostat of shunt DC machines. As its name indicates, it uses a series resistance with the rotor windings to reduce the currents of the rotor. The use of this method is possible for wound rotor induction motors and can’t be used with other types of AC machin.

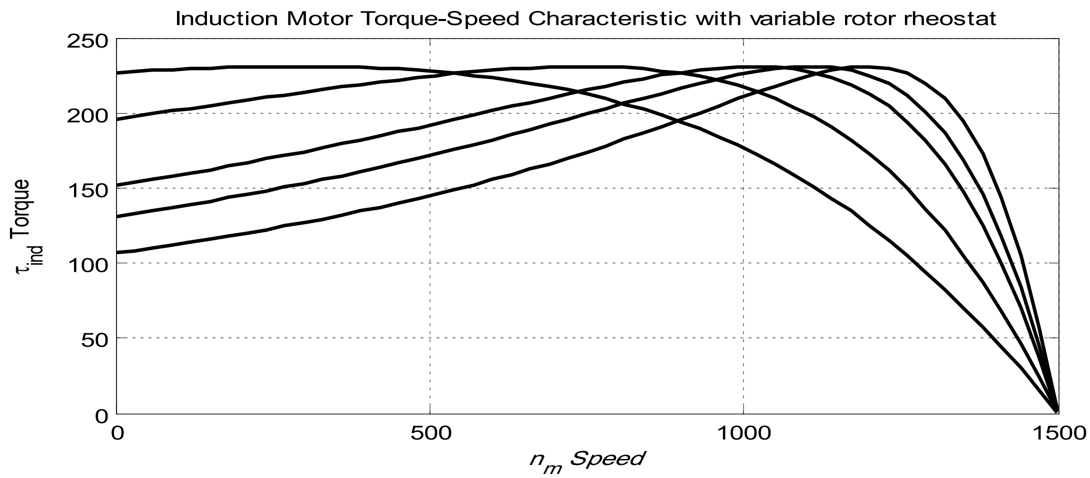


**Figure 3.4:** Torque speed characteristics with rotor rheostat control

### 3.1.5 Changing the Number of Stator Poles

As the synchronous speed is a function of the frequency and number of poles of the stator one of the methods used to change the speed of a motor is changing its pairs of poles. Different windings

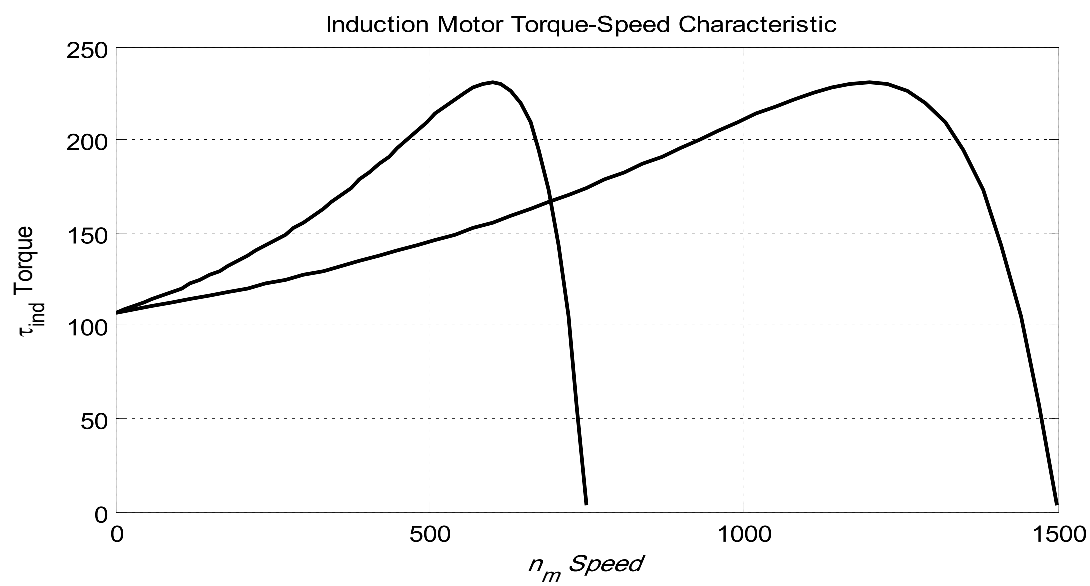


**Figure 3.5:** Speed control by changing stator number of poles

are wound in the stator such that the connection of these windings change the number of poles is applied. This method can give two or three different speeds and used in some applications where no need for too much speed variation.

### 3.1.6 Vector Control Method (Field Orientation Control)

This method was proposed three decades ago in Germany by Hasse, Blaske, and Leonhard (Ozturk, 2005). In this method, the equations of the motor are transformed into the synchronous dq coordinates rotating with the vector of rotor's flux. This method simplifies the control and makes it similar to the control of decoupled separate DC machine. This method of control has spread widely in the control of AC machines and is used widely worldwide.

### 3.1.7 Direct Torque Control

In this method, it is possible to control directly the stator flux and torque by applying suitable voltage via a voltage source inverter. The electromagnetic torque in a three phase induction motor can be given by:

$$\tau_e = \frac{3}{2} P \vec{\varphi}_s \times \vec{i}_s \tag{3.2}$$

Where, $\varphi_s$ is the stator flux, $i_s$ is the stator current and P the number of pairs of poles of stator. This equation can be simply written in the form:

$$\tau_e = \frac{3}{2} P \varphi_s . i_s \sin(\alpha_s - \delta_s) \tag{3.3}$$

Such that $\alpha_s, and\, \delta_s$ are the stator flux and current angles respectively referred to the direct axis of the stationary reference. The torque can be changed by controlling the angle of the flux while keeping constant its modulus. Direct torque control doesn't need any current controllers, no need for any transformations and heavy calculations to apply it, and able to control the torque in transients as like as in steady states. The main disadvantages of the DTC reside in its variable switching frequency, high current and torque ripples, in addition to the difficulty of control under low speeds.

The main fundamental elements of the control system model consists of a circuit for power supply, a three phase VSI (voltage source inverter), the induction motor, a controller to control speed and the torque in addition to the DTC controller. The DTC controller consists of torque and flux estimation blocks, sector determination table, and two hysteresis controllers. The output of the DTC controller represents the pulses controlling the voltage source inverter. In contrary to the other control methods of induction motors, DTC is not affected by motor parameters changes. It doesn't also need any mechanical sensors. Figure 3.6 shows the simplified scheme of direct torque control method. Two hysteresis comparators for flux and torque are used. The output of these hysteresis blocks is used to determine the optimum output voltage of the voltage inverter. A look table is used to accomplish this task as seen in the Figure.

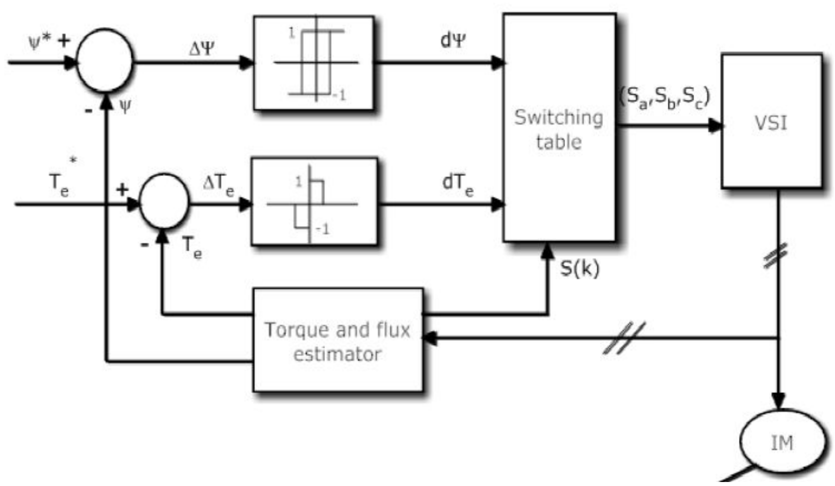


**Figure 3.6:** Simplified scheme of DTC control structure

As seen from the Figure, the motor's flux and torque are estimated from the externally measured values of the machine. After measuring the actual torque and flux, they are compared to the reference torque and flux and the error is fed to two hysteresis controllers. Each one of the hysteresis controllers is used to determine the sector where the error resides. The outputs of these controllers are fed to a block table to determine the suitable control voltage (Ozturk, 2005). The basic concept of DTC is to control separately and directly the torque and flux by using eight voltage vectors (Ozturk, 2005).

### 3.1.7.1 Estimation of Machine's Flux and Torque

The estimation of the actual flux and torque of the machine is the first step in the DTC method. It is based on the measured values of stator voltages and currents. These currents are then transformed into two phase stationary system. The two phase stationary coordinates can be given by:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{3.4}$$

The three phase current can also be transformed into two phase using the same matrix equation such that:

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{3.5}$$

As it is well known that the measured values of voltage are not the electromotive forces generated inside the stator unless the stator resistance is neglected. The measured voltages are equal to:

$$\begin{aligned} v_{qs} &= E_{qs} + R_s i_{qs} \\ v_{ds} &= E_{ds} + R_s i_{ds} \end{aligned} \tag{3.6}$$

As the induced voltage is equal to the derivative of the changing flux, Tte stator generated voltages (Electromotive forces) are given in function of the stator flux by:

$$E_{qs} = -\frac{d}{dt}\vec{\varphi}_{qs} = v_{qs} - R_s i_{qs}$$
$$E_{ds} = -\frac{d}{dt}\vec{\varphi}_{ds} = v_{ds} - R_s i_{ds} \tag{3.7}$$

Clearly, the stator flux can be found by integrating the equations 3.7 to give:

$$\vec{\varphi}_{qs} = \int (v_{qs} - R_s i_{qs})\, dt$$
$$\vec{\varphi}_{ds} = \int (v_{ds} - R_s i_{ds})\, dt \tag{3.8}$$

The estimated flux can then be transformed into modulus and angle preparing for hysteresis control. The modulus and angle of the flux are given by:

$$\varphi = \sqrt{\varphi_{qs}^2 + \varphi_{ds}^2}$$
$$\gamma = \tan^{-1}\left(\frac{\varphi_{ds}}{\varphi_{qs}}\right) \tag{3.9}$$

The developed torque of the machine can then be estimated using the next equations:

$$\tau_{me} = \frac{3}{2} P(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \tag{3.10}$$

The block diagram of the flux and torque estimation in Matlab/Simulink is shown in the Figure 3.7.

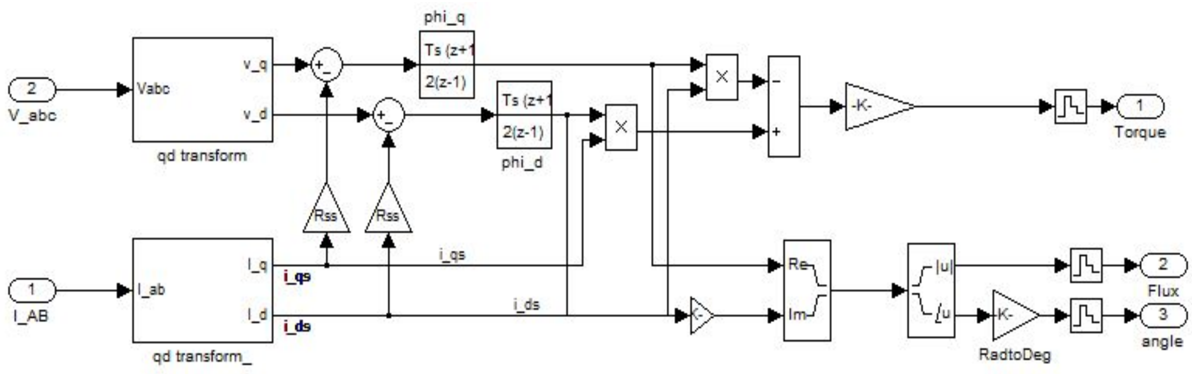


**Figure 3.7:** Estimation of torque and flux of an induction machine

### 3.1.7.2 Hysteresis Controller

Each one of the estimated flux and torque values will be compared with its reference. The error signal is to be generated and passed through a hysteresis controller that determines the suitable output based on the error value and direction. Two hysteresis controllers are used in the DTC control, one for the flux and the other for the torque hysteresis.

### 3.1.7.3 Torque Hysteresis

This is a three level hysteresis whose output can be one of three digital outputs. The input of this hysteresis is the torque error while its output is the status of the torque error dTe. A predetermined band is used to decide the output status. Whenever the torque error is out of the band limits, the output is not equal to zero. Figure 3.8 shows the principle of torque hysteresis controller. The three status of the output are determined by:

$$dTe = \begin{cases} 1, \ \Delta Te > \dfrac{B_T}{2} \\ 0, \ |\Delta Te| < \dfrac{B_T}{2} \\ -1, \Delta Te < -\dfrac{B_T}{2} \end{cases} \tag{3.11}$$

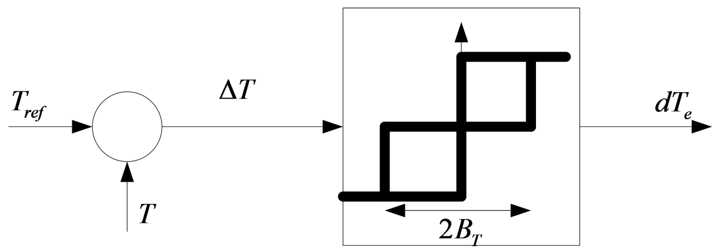


**Figure 3.8:** Principle of torque hysteresis control

### 3.1.7.4 Flux Hysteresis Controller

This is a two level controller based on the same principle of the torque hysteresis controller. The output of the controller can be either 0 or 1. Figure 3.9 shows the hysteresis controller of the flux error. The outputs of the controller are given by:

$$dPhi = \begin{cases} 1, & \Delta\varphi_s \leq B_\varphi \\ 0, & \Delta\varphi_s > B_\varphi \end{cases} \tag{3.12}$$

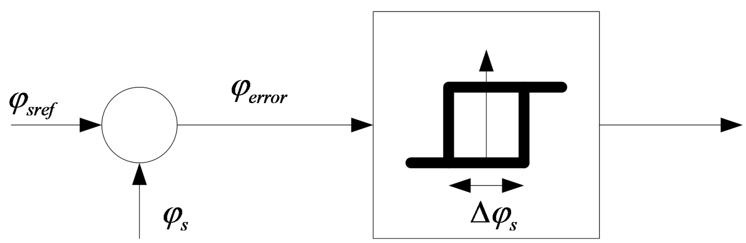


**Figure 3.9:** Flux hysteresis controller structure

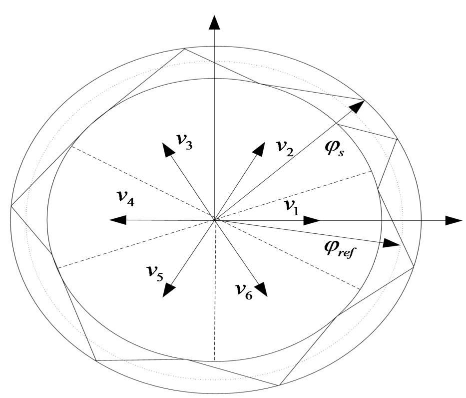


**Figure 3.10:** Incremental stator flux linkage space vector demonstration in DQ plane

The angle of the flux vector is also determined and the 360 degrees are divided into six sectors 60 degrees each. The control of the voltage source inverter is determined by using a look up table for the sector, flux status, and torque status. The look up table is as follow:

**Table 3.1:** Look up table for flux and torque hysteresis

| *dPhi* | *dTe* | S1-30<γ<=30 | S2 30< γ<=90 | S3 90<γ<=150 | S4 150<γ<=210 | S5 210<γ<=270 | S6 270<γ<=330 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | V2 | V3 | V4 | V5 | V6 | V1 |
| | 0 | V7 | V0 | V7 | V0 | V7 | V0 |
| | -1 | V6 | V1 | V2 | V3 | V4 | V5 |
| 0 | 1 | V3 | V4 | V5 | V6 | V1 | V2 |
| | 0 | V0 | V7 | V0 | V7 | V0 | V7 |
| | -1 | V5 | V6 | V1 | V2 | V3 | V4 |

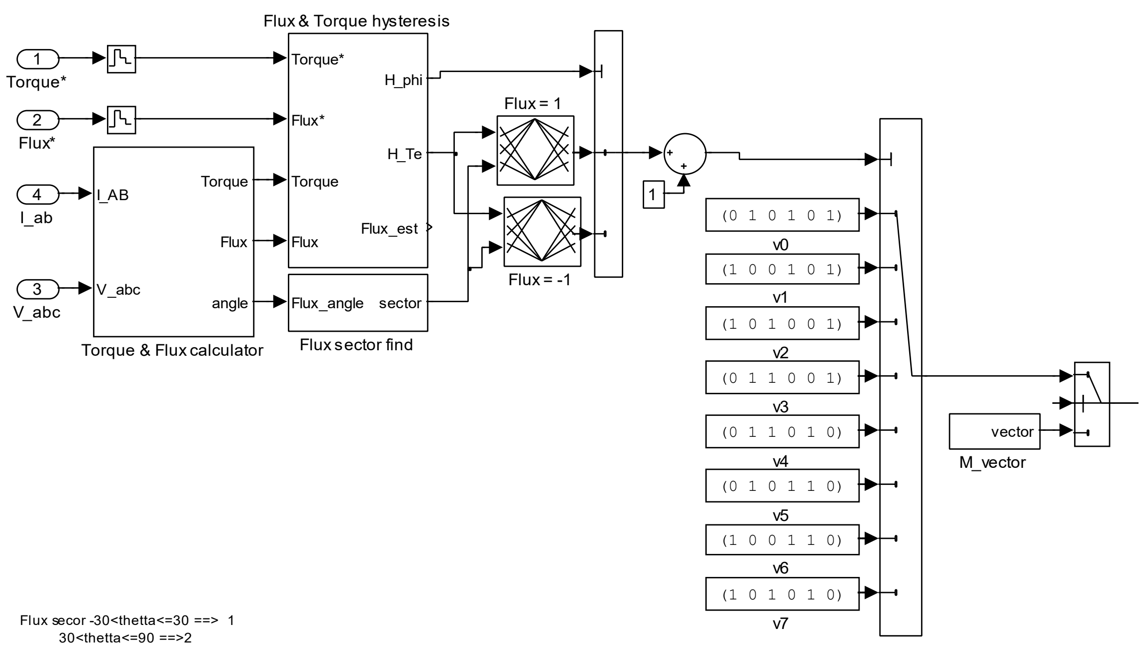


**Figure 3.11:** Block diagram of estimation and voltage determination

### 3.1.7.5 Torque and Flux Reference Generation

The control of induction motor speed implies the measurement of the speed. The measured speed is compared with the desired speed. The error between desired speed and actual speed is fed to a speed controller whose output determines the torque reference of the induction motor. Figure 3.12 shows the speed control of induction motor and torque reference generation.

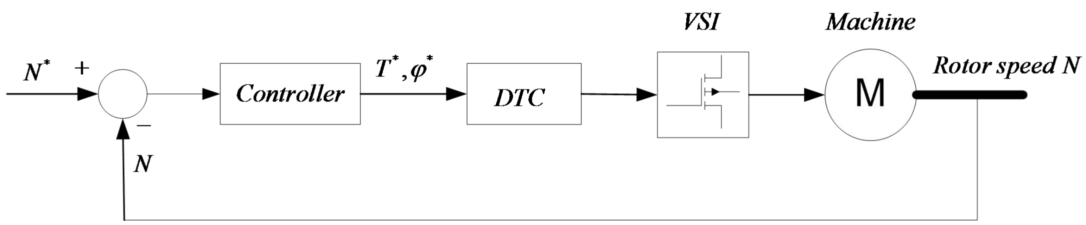


**Figure 3.12:** General structure of DTC control including the use of a controller

## 3.2 Voltage Source Inverter

The voltage source inverter produces voltage vectors controlled by the lookup table block. The idea of the VSI is to switch positive and negative voltages on and off in high frequency to produce the required AC voltage. It is used in generating AC voltage from DC source or apacitor bank. The VSI is composed mainly of six power switchs controller in openning and closing; these switches are connected in anti parallel with recovery diodes. Figure 3.13 presents the general structure of a simple voltage source inverter (Rashid, 2010).

Different controls are used to control the output voltage/current of VSI such as PWM and hysteresis control. The common thing is that each two switchs of the leg are complimentary to each other. That means they cant be on in the same time. The DTC method is a very simple method in terms of VSI control because it doesn’t need any PWM signal generation in general. The output voltage vector is kept constant during the sampling period with no need to apply other vectors. The phase output voltage of the VSI can be given in terms of DC source voltage and switches states as follow (Rashid, 2010):

$$
\begin{aligned}
v_a &= V_{Link}\frac{2S_a - S_b - S_c}{3} \\
v_b &= V_{Link}\frac{2S_b - S_c - S_a}{3} \\
v_c &= V_{Link}\frac{2S_c - S_b - S_a}{3}
\end{aligned} \tag{3.13}
$$

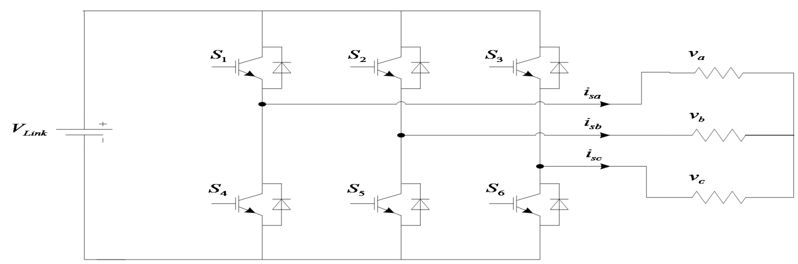


**Figure 3.13:** Voltage source Inverter general structure

### 3.2.1 Output Vector Table

As the switches of the same leg of the VSI can't be on at the same time, there will be 8 different output voltage vectors from the VSI. These 8 vectors are the most important parameters in the DTC control. Table 3 shows the different switches states and the correspondent vector. In Figure dd we can see the different vectors represented in a stationary reference plane (Bose, 2001).

**Table 3.2:** Output voltage vectors of VSI

| S1 | S2 | S3 | S4 | S5 | S6 | $\vec{V}_k$ |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 1 | 1 | 1 | $\vec{V}_0$ |
| 1 | 0 | 0 | 0 | 1 | 1 | $\vec{V}_1$ |
| 1 | 0 | 0 | 0 | 1 | 1 | $\vec{V}_2$ |
| 0 | 1 | 0 | 1 | 0 | 1 | $\vec{V}_3$ |
| 0 | 1 | 1 | 1 | 0 | 0 | $\vec{V}_4$ |
| 0 | 0 | 1 | 1 | 1 | 0 | $\vec{V}_5$ |
| 1 | 0 | 1 | 0 | 1 | 0 | $\vec{V}_6$ |
| 1 | 1 | 1 | 0 | 0 | 0 | $\vec{V}_7$ |

Finest switching vector selection is as shown in table 3.1 shows the best possible selection of the switching vectors in all sectors of the stator flux plane. This table is based on the value error statusof stator flux, error status of torque and course of stator flux for anti clockwise rotation of the shaft.

# CHAPTER 4
# FUZZY LOGIC CONTROL

Fuzzy logic is a soft computing tool for adopting human experience into algorithms. The first seed of fuzzy logic was invented by Dr. Lofti Zadeh in the 60s of the last century for modeling of uncertainty of natural languages (Zadeh, 1965). Fuzzy logic is a logical system that simulates a model for personal logic modes. The personal logic modes are approximate logic decisions and not exact. In contrary to the traditional logic systems that have two possible outputs, the fuzzy logic systems can have infinite number of uncertain outputs that can be developed based on their inputs. In binary logic, the system can give a decision weather an output is true or false with 100% certainty. The human reasoning system is designed to give decisions with degrees of certainty supporting the decisions. Fuzzy logic is similar to human brain because it also can give an output with a degree of certainty (or uncertainty) of a set or sets of inputs.

Fuzzy logic systems have been developed for systems where simple true false decisions are not enough to give a decision or produce an output. The fuzzy logic can be employed to build smart systems based on the knowledge expressed in human language. Fuzzy logic based systems have proven their efficiency over the other conventional systems such as binary logic. Recently, the employment of intelligent systems such as neural networks, fuzzy logic, and genetic algorithms has become very common. Such systems are more practical and able to simulate human reflections and decisions. They can in the small scale- replace the human in doing some processes that were until few years ago impossible to be achieved without human interact.

Fuzzy logic has been recently applied in process control, modeling, estimation, identification, stock market prediction, diagnostics, military science, agriculture and many other fields of science and industry. One of the important applications of fuzzy logic is the control systems (Cirstea and Dinu, 2002). In the past few years, fuzzy logic has been developed and used widely in various applications. The development of the personal computers and processing units has the main favor for the spread of fuzzy logic. It is now used in quality control systems, elevator controls, trains operation, planes, and many other processes.

## 4.1 Basics of Fuzzy Logic Control

Fuzzy logic offers a non-analytical choice to avoid the classical analytical control systems. It offers a simple possibility for a powerful control of complex systems whose mathematical models are impossible to be developed. Fuzzy logic control systems are not based on the model of the controlled process. They are robust and doesn't need precise inputs or system parameters. They can be easily tuned to improve performance of controlled processes. Over more, they offer a suitable alternative for the control of multiple inputs multiple outputs systems. Data is stored in the fuzzy logic systems as membership functions and rules (Raviraj and Sen, 1997; Ross, 2005;Yu and Kaynak, 2009).

The general diagram of fuzzy logic system used in a closed loop process control is presented in Figure 4.1.

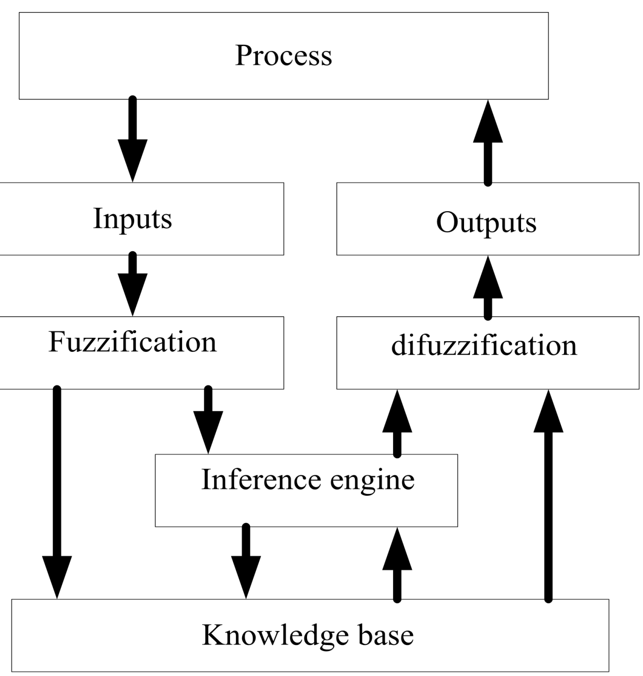


**Figure 4.1** Fuzzy logic Control structure

### 4.1.1 Fuzzy Sets and Subsets

The sets are one of the main notations of mathematics; the set theory has been created first by the German mathematician Georg Cantor. He defined the sets as collections of things. A set can be defined, discrete or continuous (Cirstea and Dinu, 2002). A set can be defined by one of the next methods.

1 By writing the list of its elements.

2 By giving a function describing the elements of the set.

In fuzzy logic, the function that describes the elements of a set is called membership function (Cirstea and Dinu, 2002).

### 4.1.2 Membership Functions

A membership function is a function that describes how much a point or an object in the universe of discourse is related to the universe by giving a degree of membership between 0 and 1. Membership functions can be arbitrary curves that are simple, confident, efficient, and provide enough speed (Ross, 2005). The linguistic variables are not real numbers or integers but they are fuzzy sets. Looking at Figure 4.2.a presenting a classic set of people classified based on the age. The variable η is the degree of membership of a person while x is the age. It is clear that in the classic sets the person can either belong to the set of age or not. Figure 4.2.b represents a fuzzy set where each age can be given a degree of membership to the set between 0 and 1.

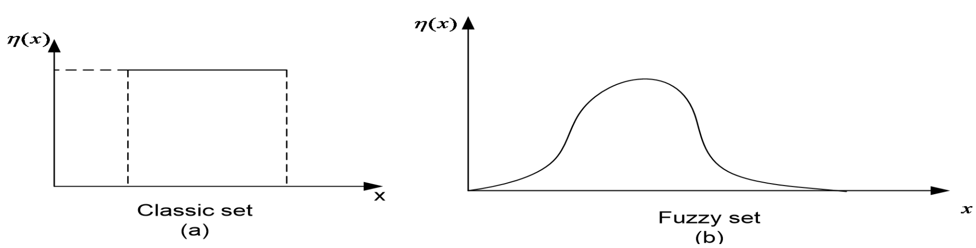


**Figure 4.2:** Classic set vs. fuzzy set

The membership degree or function is the description of how much a given variable belongs to a given set. The functions are designed to make mathematical calculations of linguistic rules and implement them in processing. For each linguistic variable we can assign a membership function η. The membership function will give a degree of membership for each value of a variable x. In the literature of fuzzy logic there are different types of membership functions such as (Cirstea and Dinu, 2002; Passino and Yurkovitch, 1998):

a  Triangular function defined by:

$$\mu(x) = \begin{cases} \dfrac{x-a}{b-a} & , a < x \leq b \\ \dfrac{c-x}{c-b} & , b < x \leq c \\ 0 & , otherwise \end{cases} \tag{4.1}$$

b  Trapezoidal function, the function of this membership degree is given by:

$$\mu(x) = \begin{cases} \dfrac{x-a}{b-a} & , a < x \leq b \\ 1 & , b < x \leq c \\ \dfrac{d-x}{d-c} & , c < x \leq d \\ 0 & , otherwise \end{cases} \tag{4.2}$$

c  Gaussian curve, its function is defined by:

$$\eta(x) = \exp\left(\left(\frac{x-m}{\delta}\right)^2\right) \quad , -\infty < x < \infty \tag{4.3}$$

Figure 4.3 shows the curves of the different main membership functions of the fuzzy logic. The choice of membership function in a fuzzy system is the preference of the user. There are no precise rules for the selection of defined membership function or others. The membership functions can be chosen to make simpler and more efficient the application (Kecman, 2001; Ross, 2005). However there are some general rules that must be respected to improve the efficiency of a fuzzy logic system. The main rule is that a membership function should overlap just with the nearest membership function. Also, the sum of any membership value of an input must be always 1 (Passino and Yurkovitch, 1998).

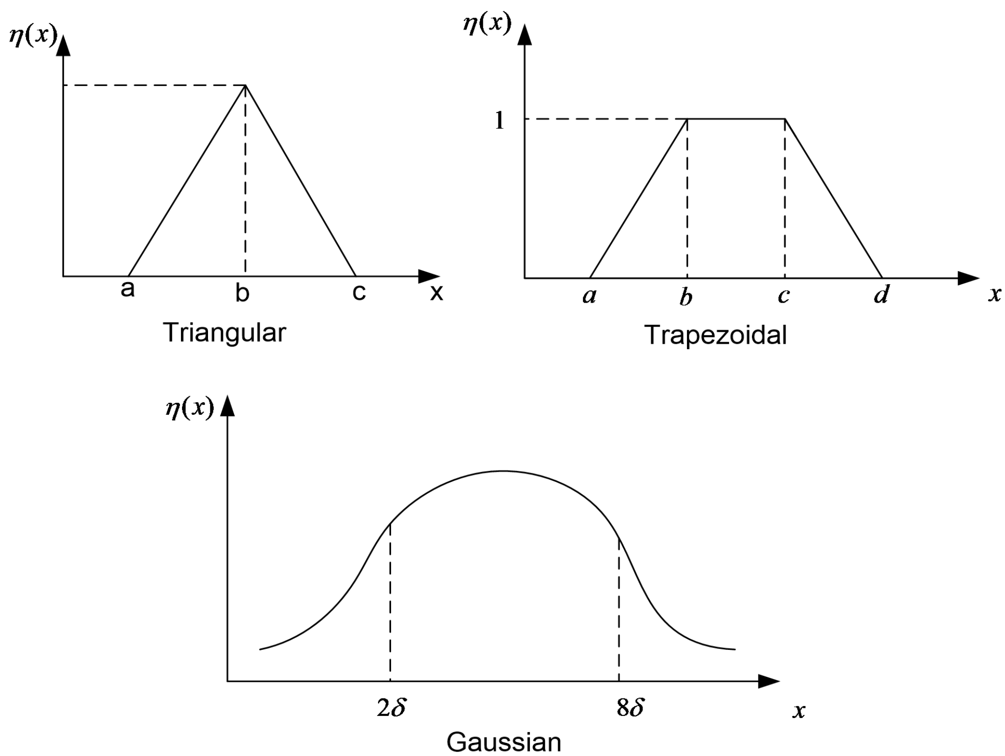


**Figure 4.3:** Different membership functions

### 4.1.3 Linguistic Variables

Linguistic variable is a term used to describe the inputs and outputs of a fuzzy logic controller. Conventional variables are exact numerical variables that can't support the dummy concept of fuzzy logic. Linguistic variables are built of words and sentences that are less precise. It provide the possibilities of describing events that are complex or difficult to be described numerical (Cirstea and Dinu, 2002). An example of that is the age of humans. Age is a linguistic value whose fuzzy sets can be child, young, old, and very old. Another example can be the error of an output process, the set of linguistic variables cab be negative, zero, and positive. In other cases this set can be extended into positive large, positive small, zero, negative small, and negative large.

## 4.2 Fuzzification of Inputs

The term fuzzification is used to describe the process of expressing the deterministic input variables into linguistic variables. This process is done by choosing suitable membership functions for the different input variables. The input variables are to be normalized to fit into the range of linguistic variables by using suitable gains. The input variable can be either discrete or continuous. In a continuous world of discourse; the number of linguistic variables describing the inputs can vary. It can contain 2, 3, 5, or more membership functions. The linguistic variables can be described by membership functions like:

NL: Negative Large

NM: Negative medium

NS: Negative Small

Z: Zero

PS: Positive Small

PM: Positive Medium

PL: Positive Large

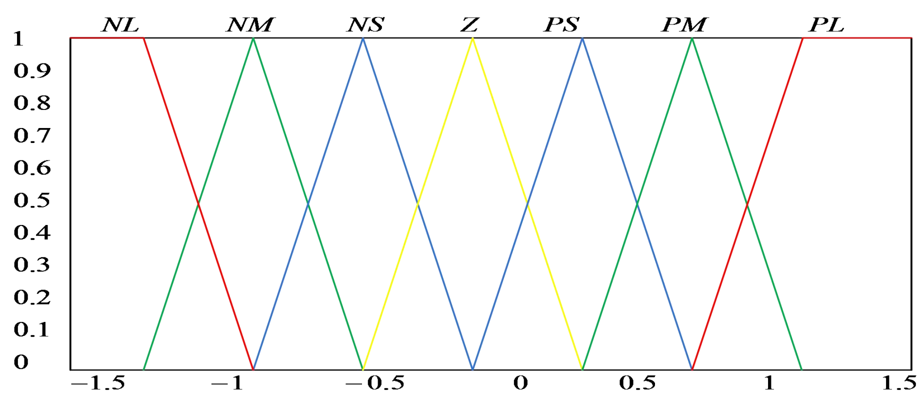


**Figure 4.4:** Fuzzification of inputs with seven membership functions

The fuzzification is done using different operators of fuzzy logic. These operators change dependent on the application and the preference of the user. The main operators of fuzzy logic are:

OR operator, the membership function of this operator can be defined for the two variables A and B by:

$$\mu_{A\cup B} = \mu_A(u) + \mu_B(u) - \mu_A(u) * \mu_B(u) \tag{4.4}$$

AND operator, the membership function of this operator can be defined for the two variables A and B by:

$$\mu_{A \cap B} = \mu_A(u) * \mu_B(u) \tag{4.5}$$

NOT operator, the membership function can be defined by:

$$\mu_{\bar{A}} = 1 - \mu_A(u) \tag{4.6}$$

The fuzzification interface engine consists of different processes, these processes can be resumed in:

- Measurement of numerical values of input variables.
- Projecting these values into the universe of discourse by scaling them into a defined period.
- Transforming these numerical values into linguistic functions that can be fed to the knowledge base.

**4.3 Knowledge Base**

The knowledge base is the part of fuzzy logic where the database of the process control and the control rules of the designed controller. It can be divided into two parts; Data Base and Rule Base. The data base is the data need to fuzzify the inputs and difuzzfy it after processing is done to generate outputs. All membership functions of the variables of controller are contained in this block. The rule base is the rules formulated from the knowledge of experts to give the best response. Typically, the rule base is consisted of states like "if variable x has the value d then variable y of output has a value of e". Rules can also be complex or compound of different relations with logic OR, AND or any other logic relation. The next part contains a type of fuzzy inference like Mamdani type. The knowledge base is the brain of the fuzzy system that must be designed carefully with a lot of experience (Raviraj and Sen, 1997; Yu and Kaynak, 2009).

**4.4 Fuzzy Inference Engine**

Fuzzy inference is the operation of generating fuzzy logic outputs of given inputs according to the rules in the base of knowledge. There are three types of fuzzy inference engines that are mostly used. These are Mamdani inference engine, Sugeno inference engine, and Tsukamoto inference engine.

### 4.4.1 Mamdani-Type Systems

In Mamdani-type systems, or it can be called max-min systems the operator "and" with minimum or "OR" with maximum formula is used. If the antecedent of a rule has only one input, membership value of the input in the corresponding set gives the value of the rule. If it has more than one input, the fuzzy operator ("min" with "and", "max" with "or") is applied for the membership values to obtain the value of the rule. This truth value is then applied to the output fuzzy set (Ross, 2005).

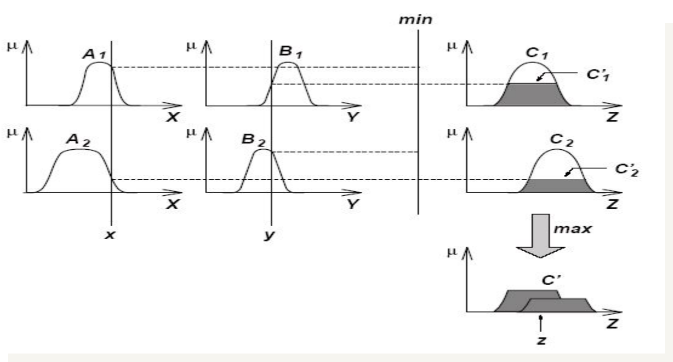


**Figure 4.5:** Mamdani-type Inference (Ross, 2005)

### 4.4.2 Sugeno-Type Inference

A Sugeno-type system differs from a Mamdani-type system in the nature of inference rules. Unlike Mamdani-type system, this method uses fuzzy sets only for input variables, but not for output variables and the consequent part of each rule of Sugeno-type system contains a linear or aquadratic function of the input variables. If the previous part of a rule has more than one input, the fuzzy operator ("min" if the connective is "and", "max" if the connective is "or") is applied for the membership values to obtain truth value of the rule (Ross, 2005).

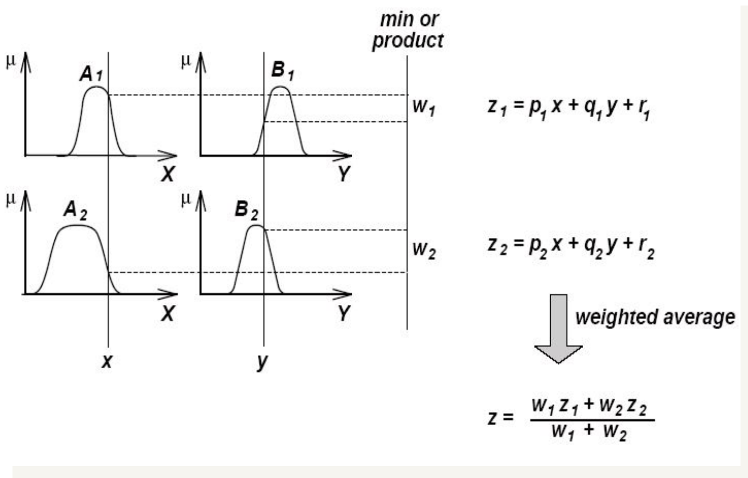


**Figure 4.6:** Sugeno-type Inference (Ross, 2005)

Sugeno-type systems are less complex in term of processing needs, and give bettr performance with linear systems and adaptive cases.

### 4.4.3 Tsukamoto-Type Inference

In Tsukamoto system, the fuzzy operator ("min" operator if the connective is "and", "max" operator if the connective is "or") is applied for the membership values to obtain the truth value of the rule. This truth value is then applied to the output fuzzy set.

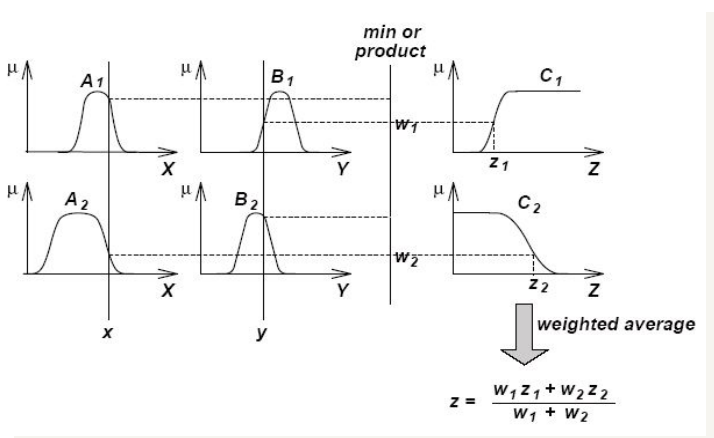


**Figure 4.7:** Tsukamoto-type Inference (Ross, 2005)

The crisp values processed using different rules are combined in one output to form the final result. The weighted average of the crisp values is found to generate the truth degree of output.

Figure 4.7 shows an example of this method of inference engine.

**4.5 Defuzzification**

The outputs from the inference engine are not numerical and need to be treated befor sending them to the process. The treatment of a fuzzy set or value to generate an output value is called difuzzification. There are many difuzzification methods like centroid method, Center of largest area method, Height method, First of maxima method, Last of maxima method, Mean of maxima method, and the weighted average method and Center of sums method are based on individual output fuzzy sets (Ross, 2005). Center of gravity method is the most used method due to its accuracy and smooth output. It consists of calculating the gravity center of the membership function. The defuzzified value is can be given by:

$$U = \frac{\sum_{i=1}^{n} z_i \mu(z_i)}{\sum_{i=1}^{n} \mu(z_i)} \tag{4.7}$$

Where, n is the number of outputs of a controller. If the membership functions are continuous we obtain:

$$U = \frac{\int z\,\mu(z)}{\int \mu(z)} \tag{4.8}$$

This method calculates the center of gravity of the space contained in the combined membership functions as shown in Figure 4.8.

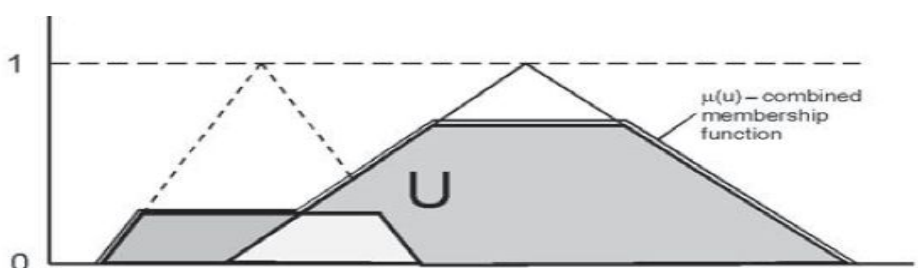


**Figure 4.8:** center of gravity and combined membership function

In the method of center of largest area, the subsets of memberships are not overlapping. It finds the convex fuzzy set and calculates the output to be the center of this set.

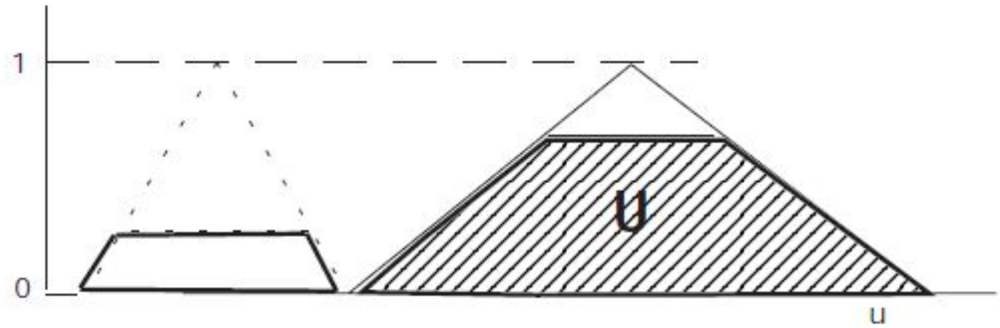


**Figure 4.9:** Center of largest area

First of maxima method finds the smallest value of the domain u with the maximal membership degree. Same way, last of maxima method finds the largest value of the domain u with maximum membership degree in it. Average of maxima method finds the average of smallest and largest values of the domain that has the maximum membership degree.

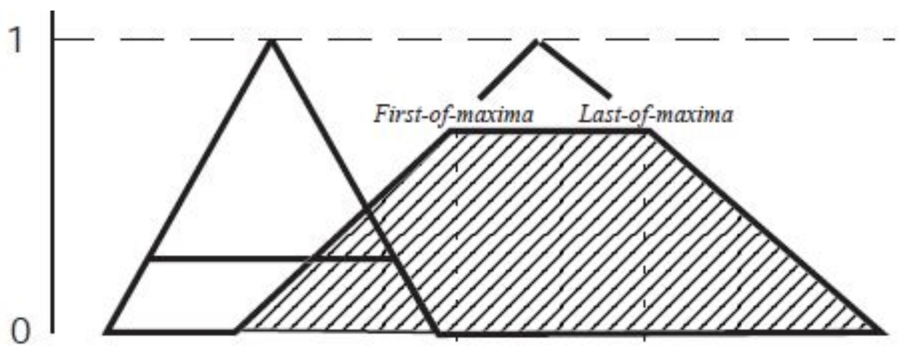


**Figure 4.10:** First and last of maxima method

Weighted average method is widely used in fuzzy logic applications due to its efficiency of calculation. Its main disadvantage is its limitation to symmetric membership distributions. It function can be given by the expression.

$$\frac{\sum \mu_c(\overline{z}).\overline{z}}{\sum \mu_c(\overline{z})} \tag{4.9}$$

Where $\bar{z}$ is the center of gravity of each membership function and $\mu_C(\bar{z})$ is the membership degree of $\bar{z}$.

## 4.6 Structure of Fuzzy Logic Controller

The general structure of fuzzy logic controller has two inputs. The two inputs are usually the error of output of the process to be controlled and the variation of that error. The derivative of the error can help for more stable transients of the process. The error and its derivative are to be scaled with factors $K_e$ and $K_{\Delta e}$, these two factors are used to limit the inputs of the fuzzy logic controller to two defined values. The next step is to choose fuzzification membership functions for each one of the inputs. The inference engine type is then designed and all the control rules are chosen and linguistic rules are built. After finishing all the last steps, the last thing to do is to choose suitable memberships of the output control. The output of fuzzy controller must then be scaled up to fit the controlled process. The scheme of the proposed controller is shown in Figure 4.11.

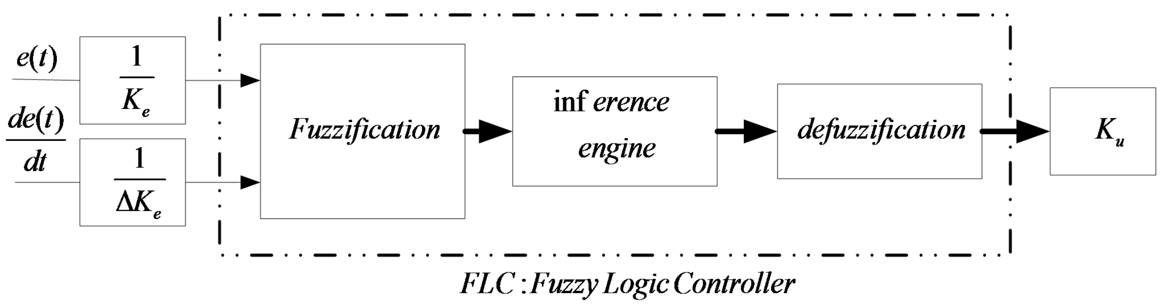


**Figure 4.11:** Structure of fuzzy logic controller

This structure is used to build the controller using the membership functions shown in the next Figure. Nine triangular functions were used to cover an error range between -50 and 50. Figure 4.12 presents the membership functions of the variations of error. These functions are divided into three parts, one for the negative derivative, one for the null derivative and the last for the positive derivative of error. The output membership functions are shown in Figure 4.13. Nine membership function were also used in the output to cover the control range of [-1000, 1000]. Table 4.1 presents the resume of all rules used in this fuzzy controller. Implementation of these rules was done using Matlab and results were obtained. Discussions of results and comparison with classic PI controller results will be presented.

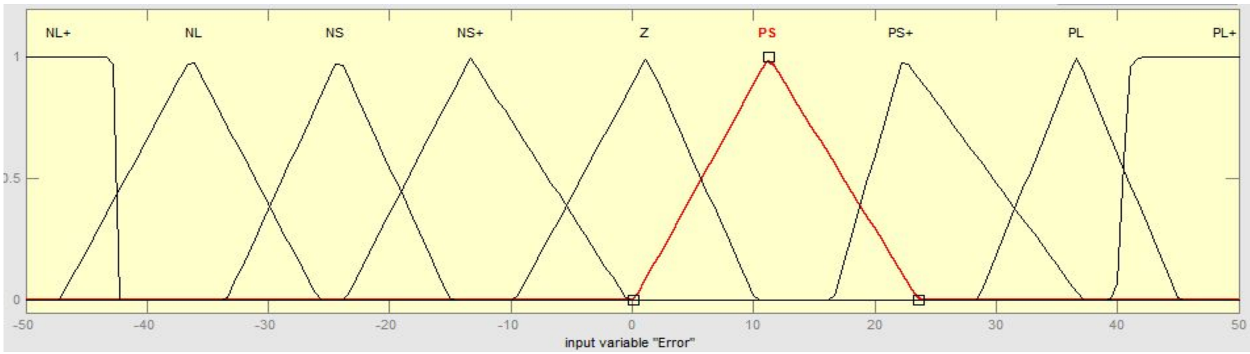


**Figure 4.12:** Membership functions of input 1 (Error)

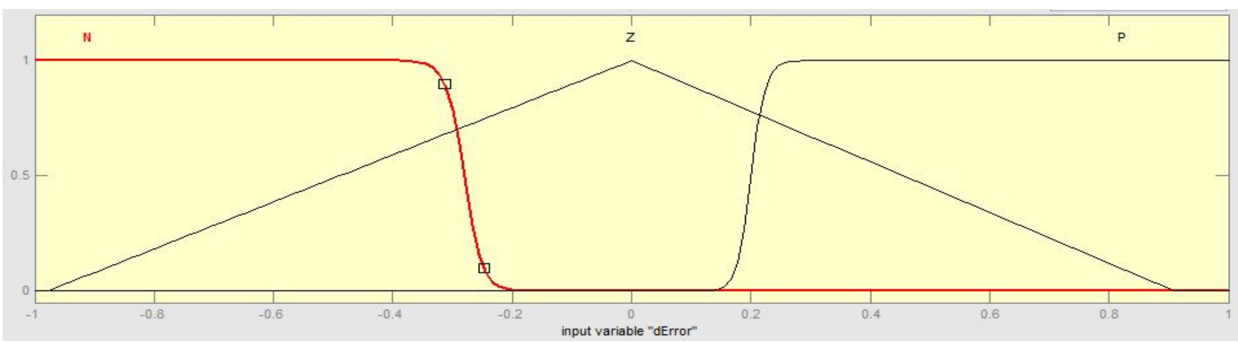


**Figure 4.13:** Membership functions of input 2 (derivative of Error)

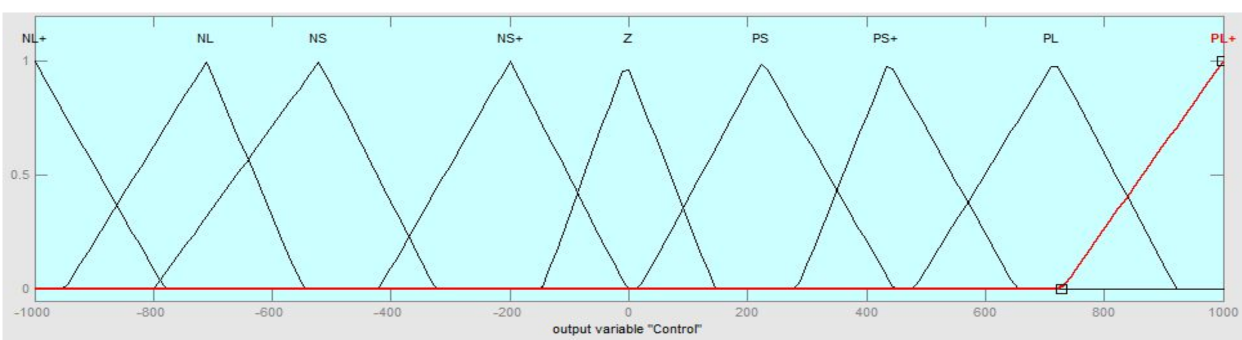


**Figure 4.14:** Membership functions of the output (control variable)

**Table 4.1:** The controller learning rules of FLC

| E / dE | NL+ | NL | NS | NS+ | Z | PS | PS+ | PL | PL+ |
|---|---|---|---|---|---|---|---|---|---|
| N | NL | NS | NS+ | Z | Z | Z | PS | PS+ | PL |
| Z | NL | NL | NS | NS+ | Z | PS | PS+ | PL | PL |
| P | NL+ | NL | NL | NS | NS+ | PS+ | PL | PL | PL+ |

The next List presents the fuzzy rules used in the fuzzy logic controller:

1.IF (Error is NL+) and (DError is N) then (Ctrl is NL) (1).
2.IF (Error is NL+) and (DError is Z) then (Ctrl is NL) (1).
3.IF (Error is NL+) and (DError is P) then (Ctrl is NL+) (1).
4.IF(Error is NL) and (DError is N) then (Ctrl is NS) (1).
5.IF (Error is NL) and (DError is Z) then (Ctrl is NL) (1).
6.IF (Error is NL) and (DError is P) then (Ctrl is NL) (1).
7.IF (Error is NS) and (DError is N) then (Ctrl is NS+) (1).
8.IF (Error is NS) and (DError is Z) then (Ctrl is NS) (1).
9.IF (Error is NS) and (DError is P) then (Ctrl is NL) (1).
10. IF (Error is NS+) and (DError is N) then (Ctrl is Z) (1).
11. IF (Error is NS+) and (DError is Z) then (Ctrl is NS+) (1).
12. IF (Error is NS+) and (DError is P) then (Ctrl is NS) (1).
13. IF (Error is Z) and (DError is N) then (Ctrl is Z) (1).
14. IF (Error is Z) and (DError is Z) then (Ctrl is Z) (1).
15. IF (Error is Z) and (DError is P) then (Ctrl is NS+) (1).
16. IF (Error is PS) and (DError is N) then (Ctrl is Z) (1).
17. IF (Error is PS) and (DError is Z) then (Ctrl is PS) (1).
18. IF (Error is PS) and (DError is P) then (Ctrl is PS+) (1).
19. IF (Error is PS+) and (DError is N) then (Ctrl is PS) (1).
20. IF (Error is PS+) and (DError is Z) then (Ctrl is PS+) (1).
21. IF (Error is PS+) and (DError is P) then (Ctrl is PL) (1).
22. IF (Error is PL) and (DError is N) then (Ctrl is PS+) (1).
23. IF (Error is PL) and (DError is Z) then (Ctrl is PL) (1).

24. IF(Error is PL) and (DError is P) then (Ctrl is PL) (1).
25. IF(Error is PL+) and (DError is N) then (Ctrl is PL) (1).
26. IF(Error is PL+) and (DError is Z) then (Ctrl is PL) (1).
27. IF(Error is PL+) and (DError is P) then (Ctrl is PL+) (1).

# CHAPTER 5
# RESULTS AND DISCUSSIONS

In this work, the construction of the induction machine, the structure of fuzzy logic controller and the direct torque control method for the speed control of induction machine have been discussed. The direct torque control method as one of the most important and simple control methods of induction machines has been discussed and presented. A fuzzy logic controller will be used instead of the traditional PI controller to increase the stability of system in transient and steady states of the machine.

This chapter of the work is sacrificed for the study and discussion of the proposed control methods and the comparison between the obtained results. All results will be presented, tabulated and discussed throughout this chapter.

## 5.1 Description of System

During this work, a Matlab/Simulink standard three phase induction motor was used. The parameters of the motor are all given in table 5.1. Three phase power source, three phase bridge rectifier, breaking chopper, and a three phase voltage source inverter were used to supply the induction motor with the need power. General model of the simulation circuit is presented in Figure 4.1. The rectifier is used to supply with DC voltage that is fed to a chopper. The chopper makes sure that the voltage at the DC side of the rectifier/inverter doesn't exceed certain limit. The inverter is responsible to generate three phase AC control voltages.

**TABLE 5.1:** Parameters of the controlled three-phase machine

| | | | | | |
|---|---|---|---|---|---|
| Motor Type | Squirrel cage | Stator L | 0. 3mH | Inertia | 3.1 kg.m^2 |
| Power | 150 kw | Rotor R | 0.0093 Ω | friction | 0.08 N.m.s |
| voltage | 420 v | Rotor L | 0. 3 mH | poles | 4 |
| frequency | 50 Hz | Mutual L | 10 mH | Stator R | 0.148Ω |

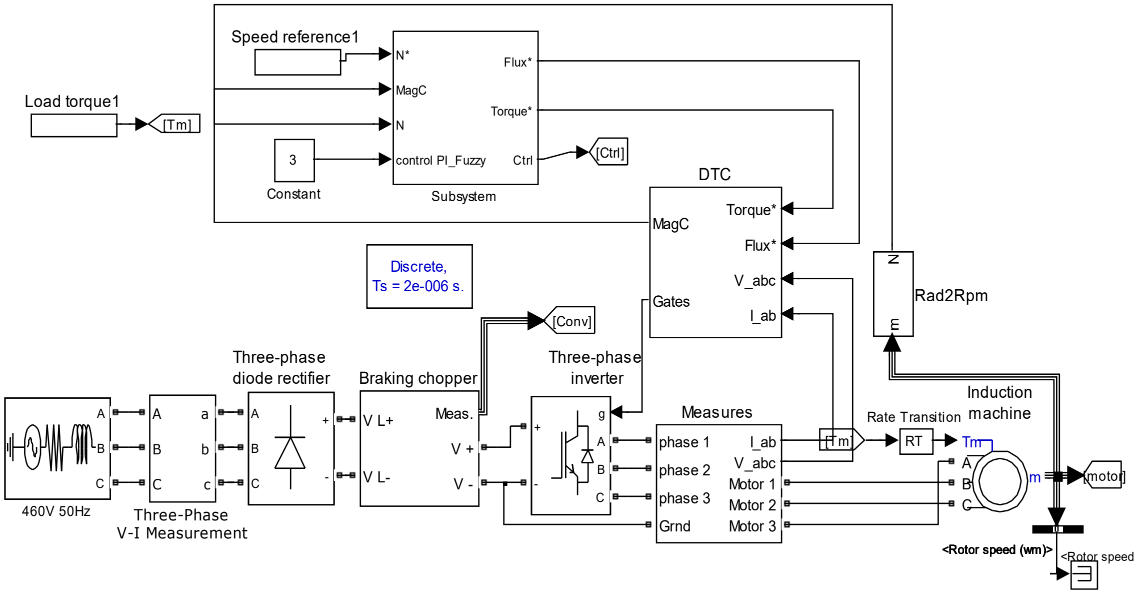


**Figure 5.1:** General structure of the Simulink model

In this work, two controller types were used namely PI controller and fuzzy logic controller. These two controllers are used as seen from Figure 5.2 to control the speed of the induction motor. The reference speed slope is firstly adjusted to avoid any sudden changes in the speed. Sudden speed changes can’t be obeyed due to the slow response of motors compared to the other electronic devices. The reference speed is then compared with the measured actual speed of the motor to generate the input of the controller. The error is then fed to the controller to generate the suitable torque value that the motor should

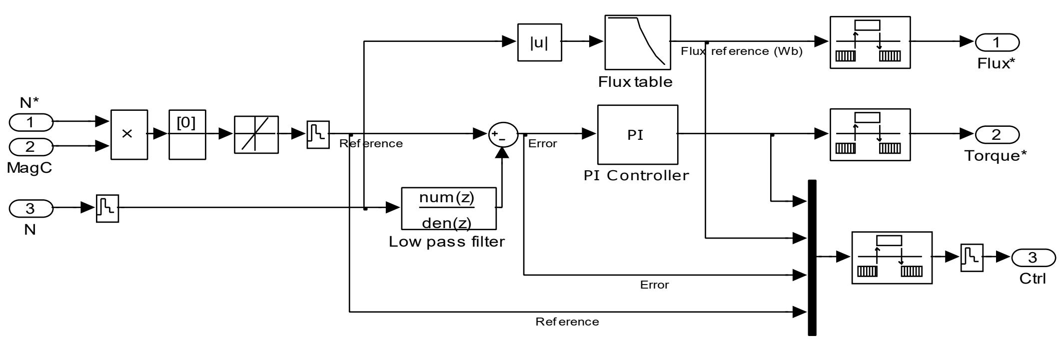


**Figure 5.2:** Block diagram of the PI controller and its structure

generate to make the error zero. For the PI controller, the values of kp=30 and ki=200 were found satisfactory.

The construction and parameters of fuzzy logic controller were discussed earlier in the fourth chapter of this work. Figure 5.3 presents the Simulink model of the fuzzy logic controller used.

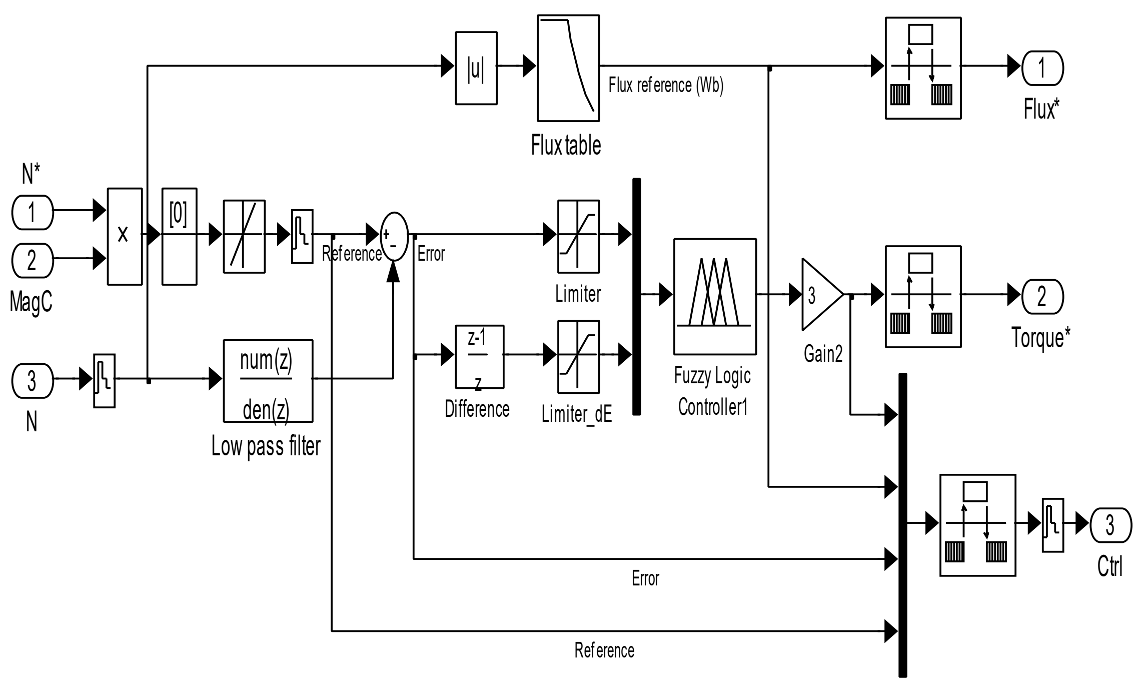


**Figure 5.3:** Simulink model of fuzzy logic controller.

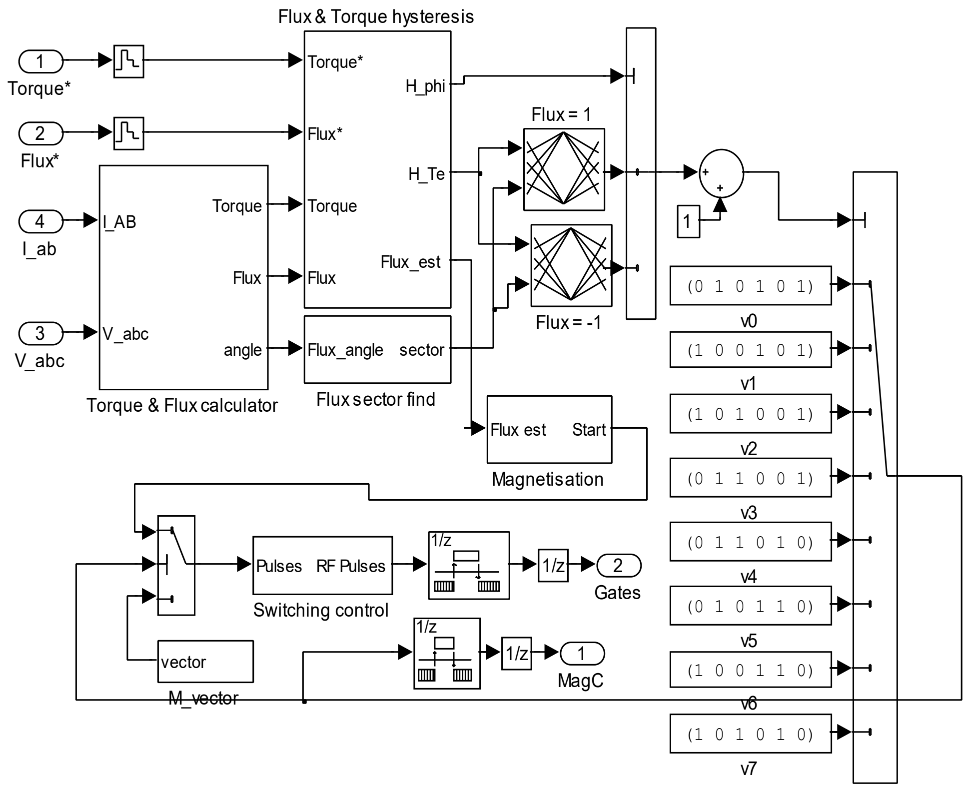


**Figure 5.4:** Model of the DTC control simulink block diagram

Figure 5.4 presents the Simulink model of the Direct Torque Control. It contains blocks for torque and flux calculation, hysteresis of torque and flux, output voltage vector decision block, and the gate pulse generation block. The contents of hysteresis block are presented in Figure 5.5. It generates 3 different output levels for the torque and two levels for the flux. In Figure 5.6 the transformations, torque, and flux calculation are presented.

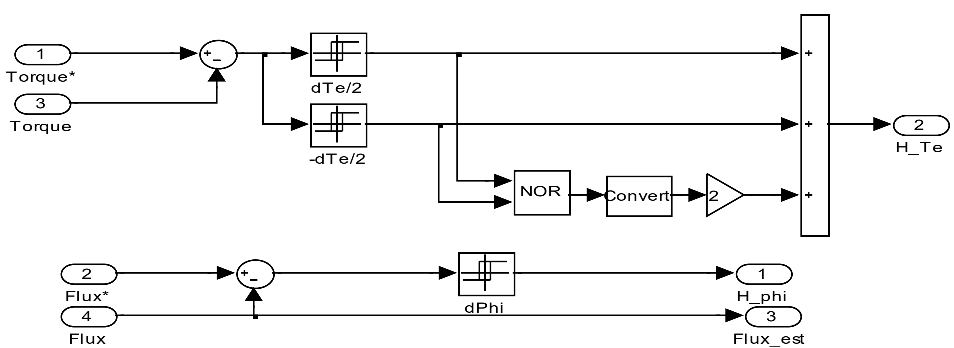


**Figure 5.5:** Flux and torque hysteresis block

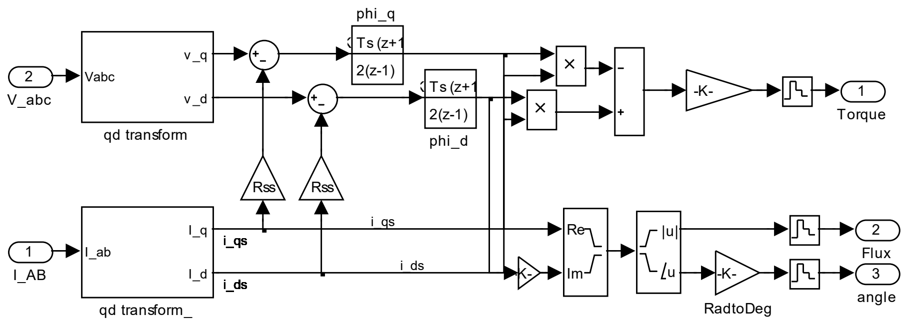


**Figure 5.6:** Torque and flux calculation bloc

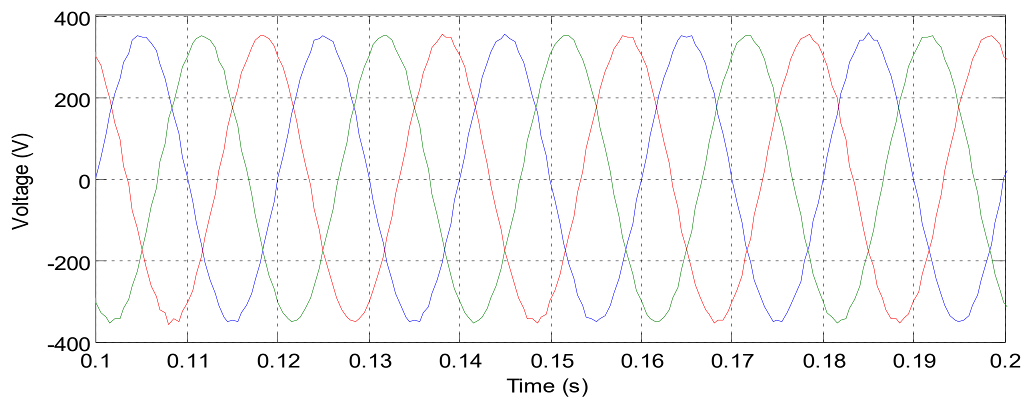


**Figure 5.7:** Three phase input voltage

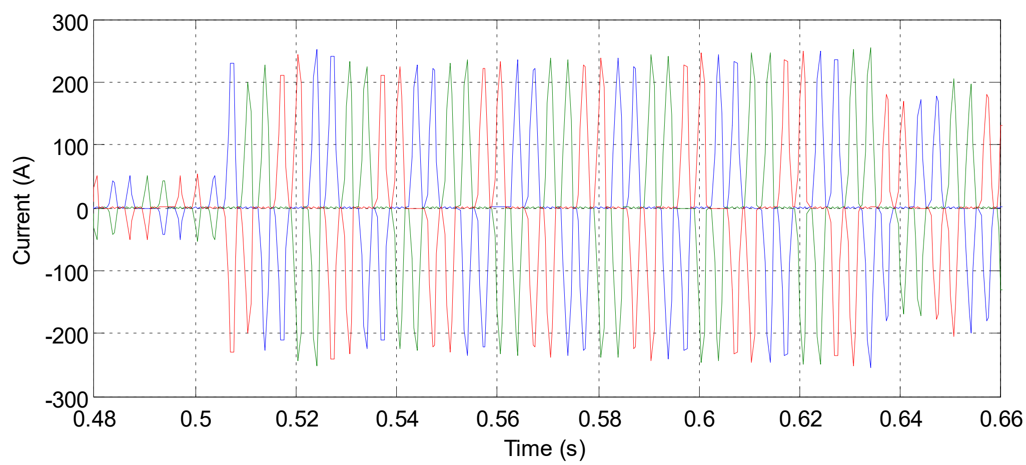


**Figure 5.8:** Three phase input current

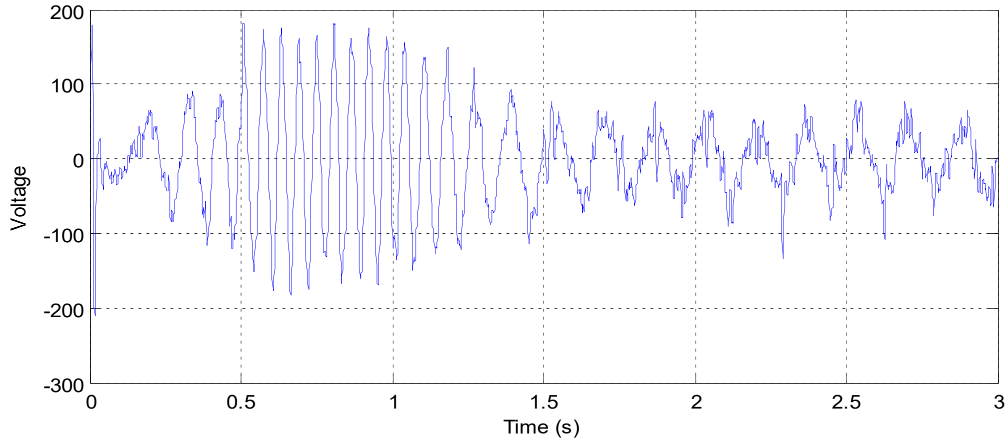


**Figure 5.9:** Output voltage of VSI

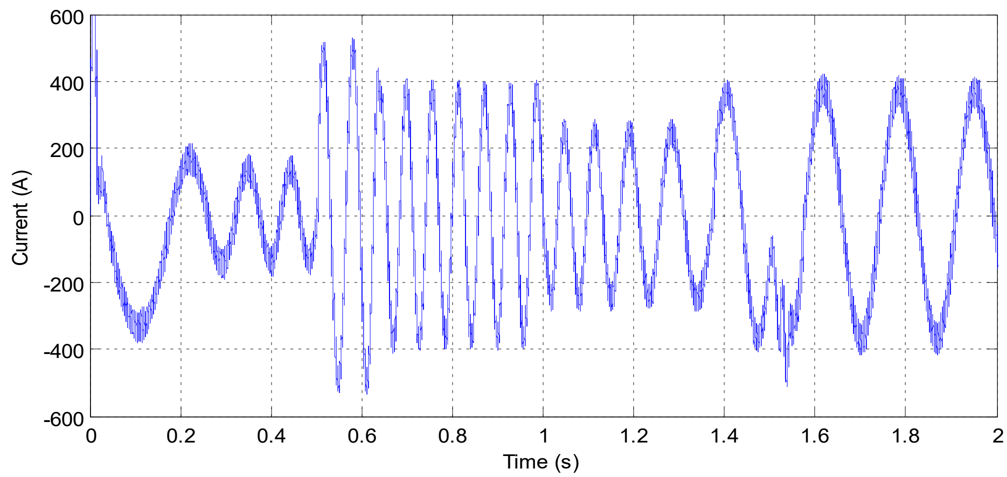


**Figure 5.10:** Stator current of phase A

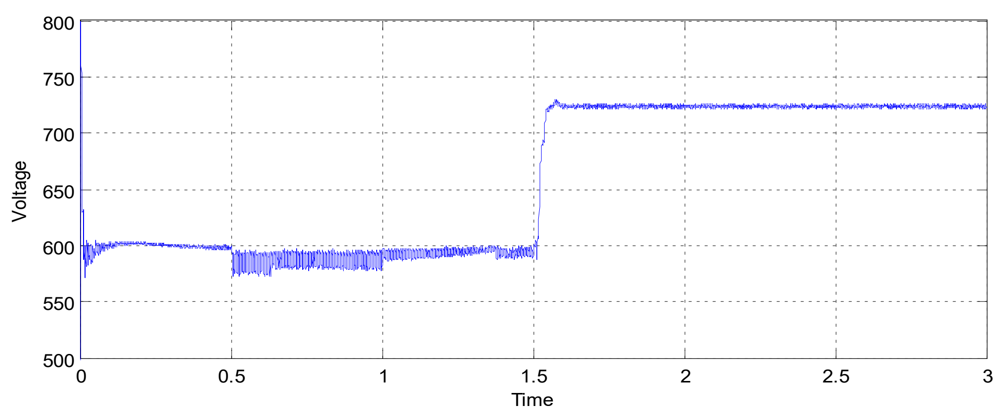


**Figure 5.11:** Voltage of DC link capacitor

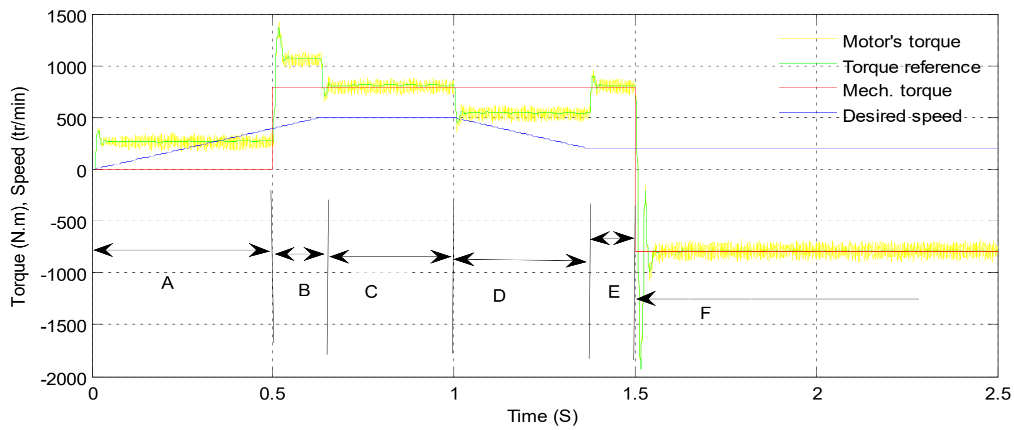


**Figure 5.12:** Applied mechanical torque on the motor, reference torque generated by the controller, and the torque developed by the motor

Figure 5.11 presents the different torques applied on the motor, generated by motor and the reference torque. In zone A, the motor is in start mode and no mechanical torque is applied. The reference torque is not zero as we can see and also the generated torque. This torque is developed to ensure the acceleration of motor from zero to the maximum desired speed and to compensate the mechanical losses due to friction and inertia. In zone B a torque of 800 is applied on the shaft of the motor. The motor develops higher torque to keep the acceleration because it's still in start mode. In zone C, the motor reaches its desired speed and acceleration is now zero. The generated torque is slightly higher than mechanical torque applied on the shaft. In Zone D although the mechanical torque didn't change, the desired speed is reduced. As a result, the motor needs to decelerate and less torque must be developed. The mechanical torque of the load is responsible to decelerate the motor speed in this case. In zone E the motor reaches its constant desired speed. The developed torque is again slightly higher than applied load torque. Finally, in zone F an inverse load torque is applied. The motor works in brake mode to keep speed in its desired values.

Figure 5.12 presents the speed and torque of the motor with no external control. Different values of load torque were applied. The nominal torque of the motor can be found by:

$$\tau_n = \frac{p_n}{\omega_n} = \frac{150\,kw}{1500 * \frac{2\pi}{60}} = 955\ N.m \tag{5.1}$$

For that nominal value, the values of 200, 500, and 900 Nm were applied on the motor. It is seen from the Figure that the increase in applied load torque causes a decrease in the speed of an induction motor. The speed of the motor is slightly less than 1500 tr/min and no other possible speeds without external control of the motor.

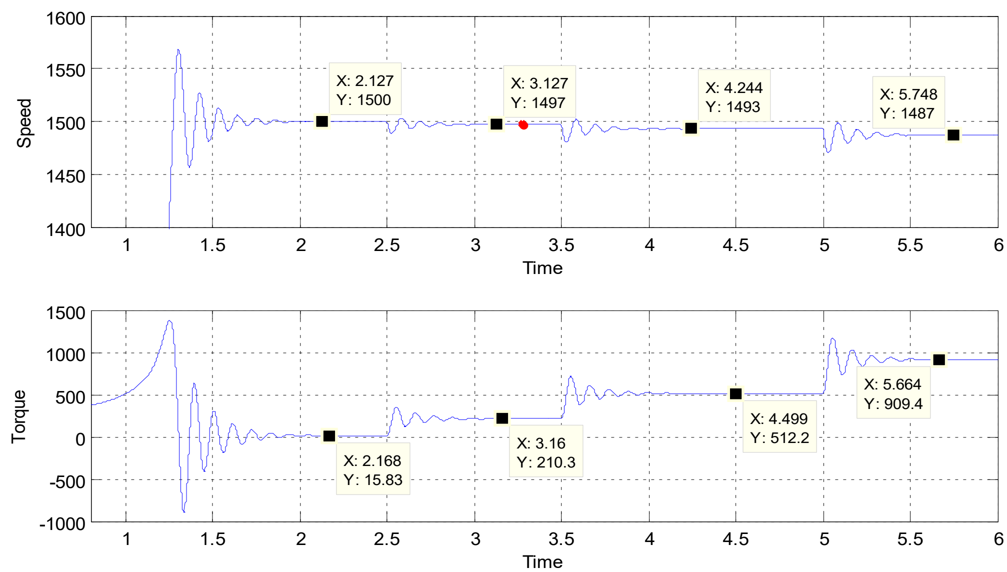


**Figure 5.13:** Speed and torque of induction motor with no control under different loads

In order to study the efficiency and robustness of both PI and fuzzy logic controller two different cases were applied. The first case included the application of speed of 500 tr/min initially, this speed is then changed to 200 tr/min at the time of 1 second. At the time of 0.5 second a load torque of 790 Nm was applied on the shaft of the motor and simulation results were recorded. In the time of 1.5 second the load torque was directly inversed and results were recorded.

In the second case , the motor was initially set to its full speed under its full load torque. At the moment 1.5s the applied torque was directly inversed. The set speed was changed to 1000 tr/min at the time 2.3s. all results were recorded and will be discussed in the next part of this work.

### 5.2 Case 1

As mentioned earlier different set speeds and different load torques were applied on the motor in this case. Figure 5.13 shows the desired speed and obtained speed curve of the motor using PI controller. We can see a slow response time with some static error in the starting moment of the motor and in the moments of speed or torque variations. PI controller is still able to show good results and small errors. Figure 5.14 presents the torque developed by the motor during the control. Figures 5.15 and 5.16 present the stator current and line voltage generated by the VSI. The results obtained by using a FLC controller are presented in Figures 5.17, 5.18, and 5.19. It's clear from Figure 5.17 that the rotor follows its desired speed perfectly with minimum error and faster response time in case of speed or torque variation. The generated torque and absorbed currents are also presented in Figure 5.18 and 5.19.

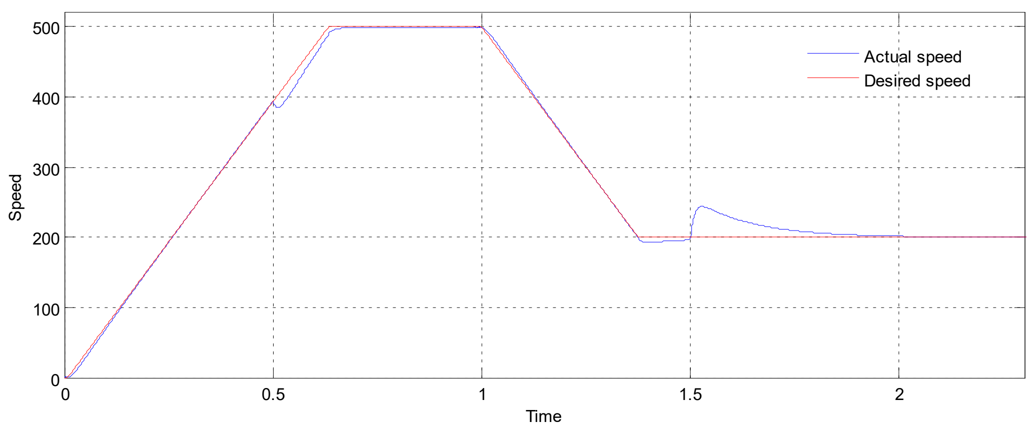


**Figure 5.14:** Desired and actual rotor speed in case of PI controller.

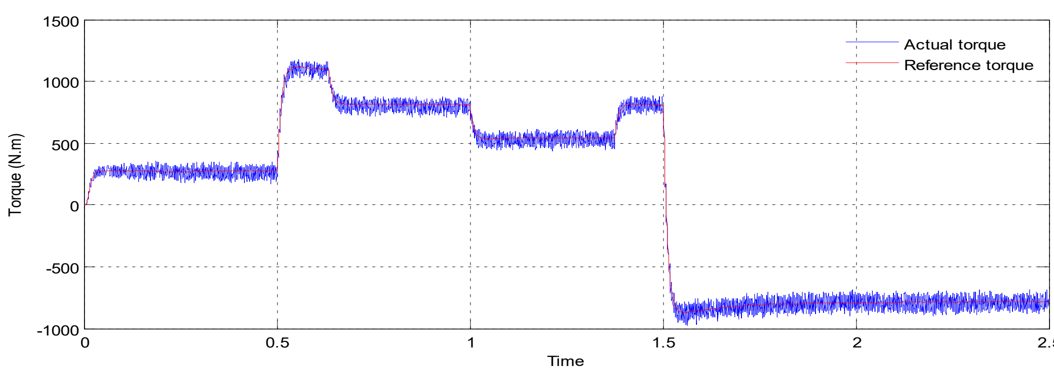


**Figure 5.15:** Reference and actual torque of the motor

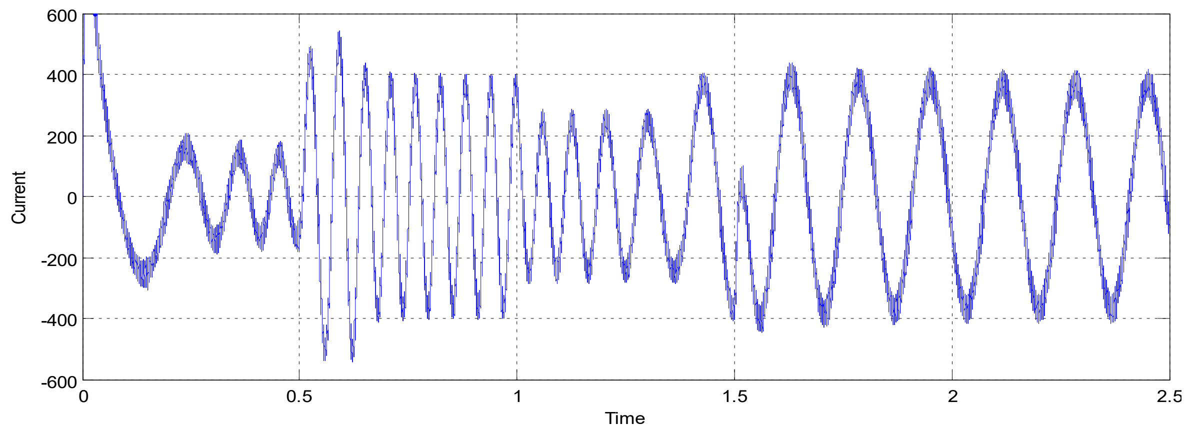


**Figure 5.16:** Current of the motor under different speed values

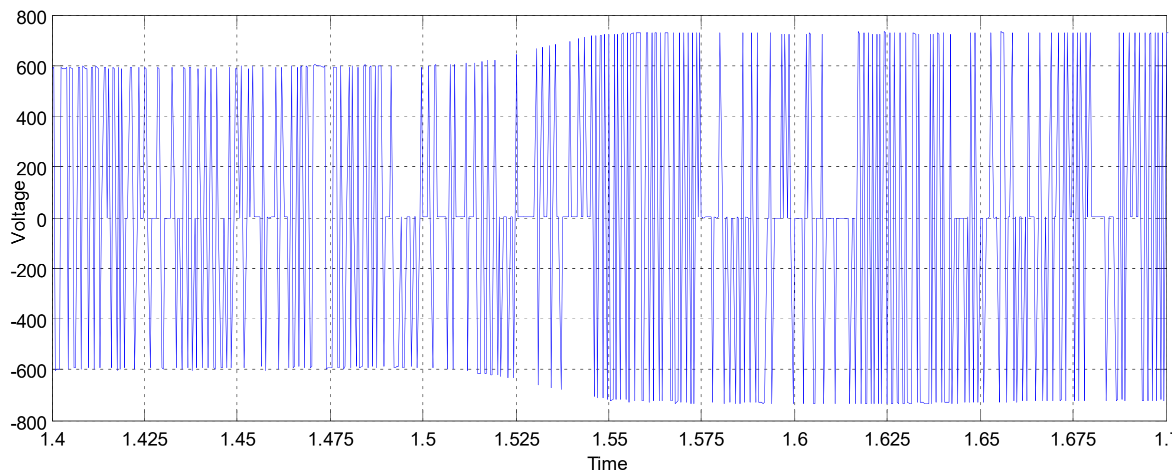


**Figure 5.17:** Output voltage of VSI to the motor

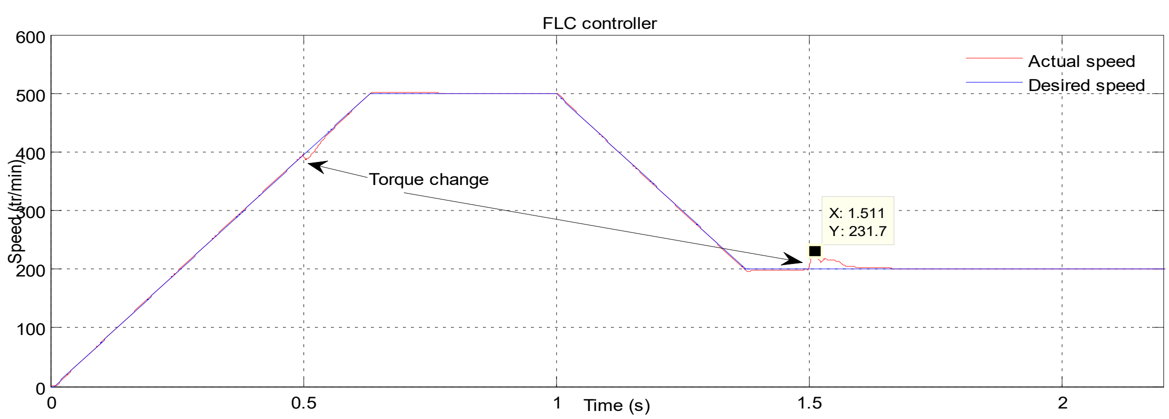


**Figure 5.18:** Actual vs. desired speed of motor after using FLC controller

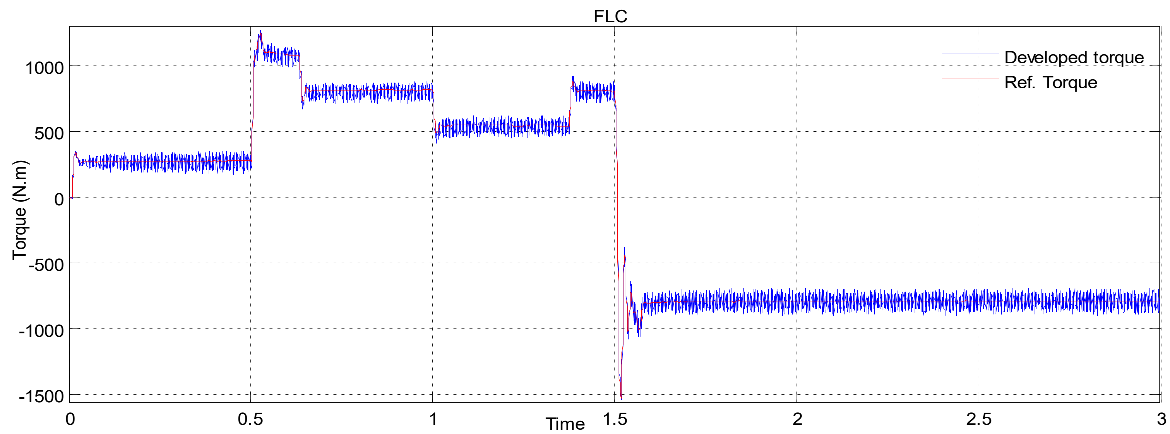


Figure 5.19: Reference torque and motor torque

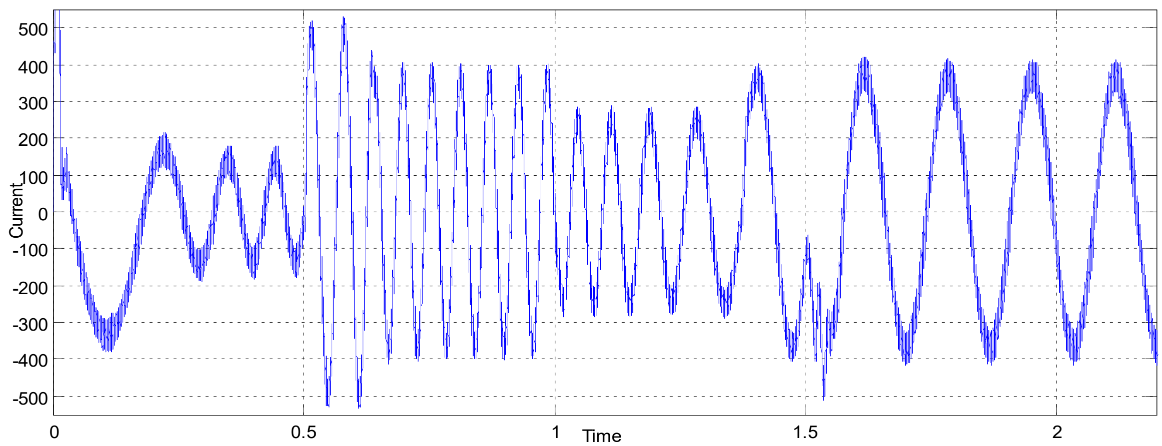


**Figure 5.20:** Stator current

### 5.3 Case 2

In this case , full load torque under full speed was applied on the motor. Load torque is presented in Figure 5.20. Figure 5.22 presents the desired and actual speed of the motor controlled using fuzzy logic with DTC controller. Speed is following its desired value fast with minimum error. The developed torque is presented in Figure 5.23. The results obtained using PI controller are presented in Figures 5.24 and 5.25. Figure 5.24 shows the speed of the motor compared to its desired value. We can see that the PI controller has limited capability to keep track of the desired speed in case of fast changes in reference speed. A speed error of more than 200 was detected at full speed. Over more, very slow response was achieved using this controller.

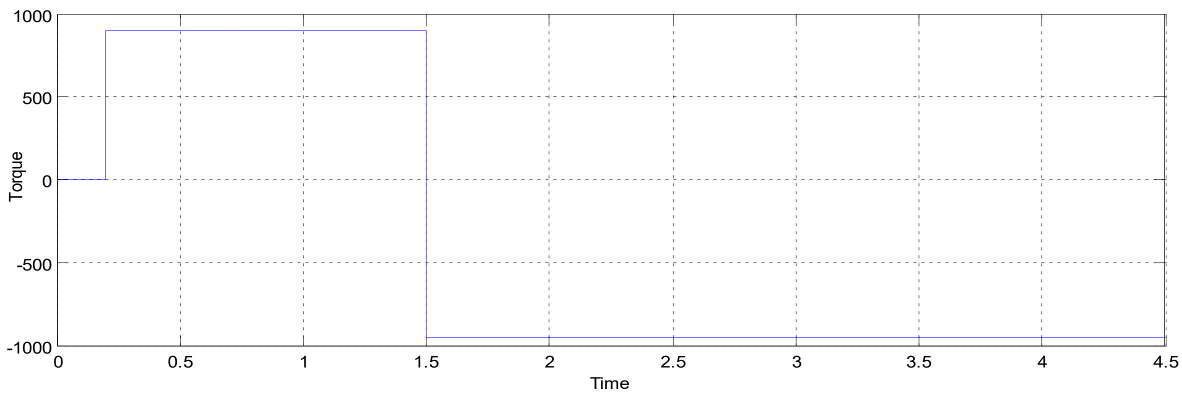


**Figure 5.21:** Applied load torque in case 2

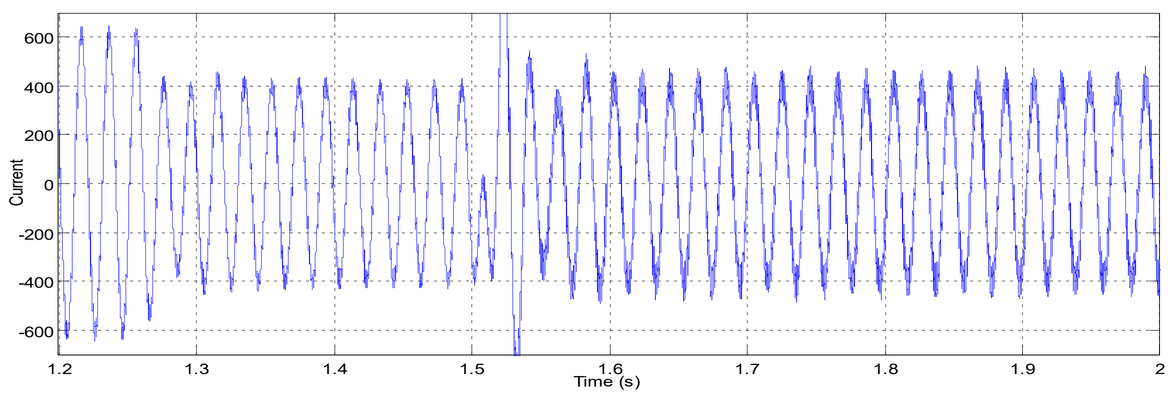


**Figure 5.22:** Stator current in the case of fuzzy controller

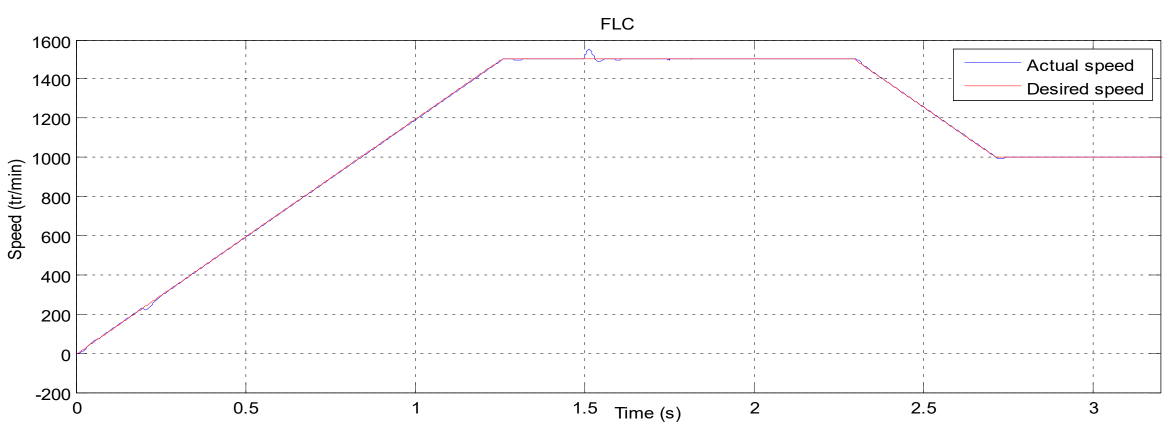


**Figure 5.23:** Rotor Speed under FLC control

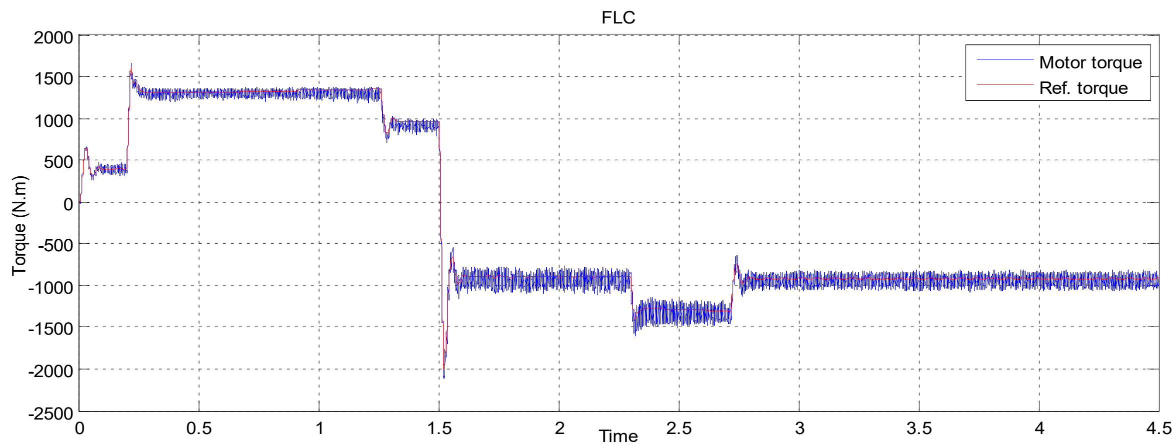


**Figure 5.24:** Motor torque

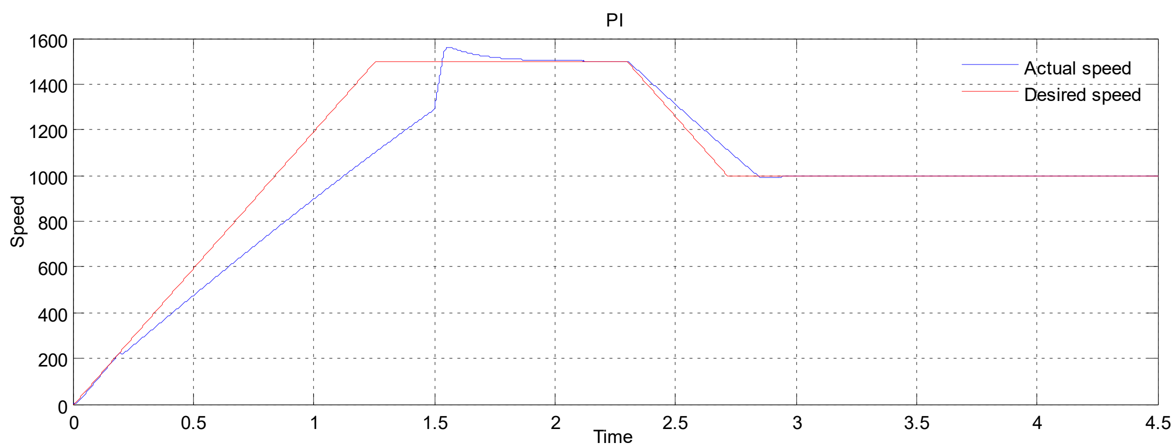


**Figure 5.25:** Rotor speed using PI controller

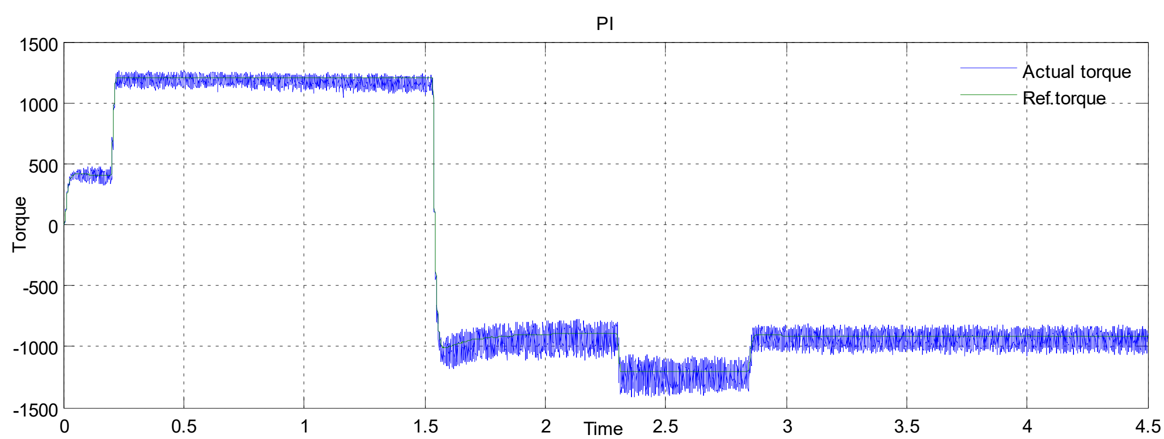


**Figure 5.26:** Torque of the motor

The table below presents a comparison between the results obtained by using a PI and FLC controller in the two studied cases. The comparison includes the static, dynamic error, and the transient time before the motor speed reaches its dynamic phase. We can notice that the fuzzy logic controller is faster in response with less transient fluctuations.

**Table 5.2:** Comparison between PI and FLC performance

| | Case 1 | | Case 2 | |
|---|---|---|---|---|
| | PI | FLC | PI | FLC |
| Static error | 0 | 0 | 0 | 0 |
| Dynamic error | 20% | 15% | 3% | 1% |
| Transient (s) | 0.4 | 0.2 | 0.5 | 0.1 |

# CHAPTER 6
# CONCLUSINS

## 6.1 Conclusions

The work and study done in this work have discussed the control of induction motors using DTC method with fuzzy logic controller.  The obtained results have shown that the use of DTC control method is simple, efficient, and output the desired values of speed and torque. DTC method has been proposed and used widely in industrial applications as well as in literature studies. In most of studies, the DTC was combined with PI controller for speed regulation. PI controllers are considered the most commonly applied controllers in industry due to their simple functional principles and the ease of their implementation. The use of fuzzy controller was proposed in this work to increase the accuracy of speed results in addition to the ability of fuzzy logic controller to react against sudden changes and non linearity of the system. Fuzzy controller has proved its efficiency and good results when used with DTC control scheme. DTC control has also proved its ability to keep track of desired speed values with minimum costs and efforts in addition to simple implementation. The method is an easy method with light amount of calculations and no need for any reference transformation or synchronization. The method implies no closed loop control of the voltage source inverter. Only two current sensors and three voltage sensors in addition to a speed sensors are need to implement the method. From the obtained results we can conclude that fuzzy logic controller with DTC method is a very excellent choice for the control of induction machines in term of low cost, simplicity, and efficiency. The control has shown the ability of this method to track different speed values with perfect response away from very low speeds.

In this work, an improvement in the control of induction motor control using DTC control method was achieved. Improved results with sudden changes in the desired speed were achieved by replacing the traditional PI controller by a non linear fuzzy logic controller. That is, higher stability of the control system and the machine is achieved in addition to fast and exact system response. That makes this method more suitable for systems that require high accuracy of speed and impose continuously variable speed drive.

As future plans, this work opens the doors widely for better understanding of different control schemes and comparative studies between these schemes. The use of different intelligent controller types such as neural networks and genetic algorithms in the control of induction motors. More deep studies of the induction motors and their controls are to be carried out and also discussed.

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