بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

Sudan University of Science & Technology

College of Engineering

School of Electrical & Nuclear Engineering

Speed Control of Inductions Motor by Changing Applied frequency

التحكم في سرعة المحرك الحثي عن طريق تغير التردد

A project Submitted In Partial Fulfillment for The Requirements of The Degree of B.Sc.(Honor) In Electrical Engineering

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(Octaber,2015)

الآيــة

قــال تعــالى :

قَالَ الَّذِي عِنْدَهُ عِلْمٌ مِنَ الْكِتَابِ أَنَا آتِيكَ بِهِ قَبْلَ أَنْ يَرْتَدَّ إِلَيْكَ طَرْفُكَ فَلَمَّا رَآهُ مُسْتَقِرًّا عِنْدَهُ قَالَ هَٰذَا مِنْ فَضْلِ رَبِّي لِيَبْلُوَنِي أَأَشْكُرُ أَمْ أَكْفُرُ ۖ وَمَنْ شَكَرَ فَإِنَّمَا يَشْكُرُ لِنَفْسِهِ ۖ وَمَنْ كَفَرَ فَإِنَّ رَبِّي غَنِيٌّ كَرِيمٌ ﴿٤٠﴾ سورة النمل.

صدق الله العظيم

I

DEDICATION

To our parents, who look forward to the day they see us translating our education into work for the benefit of our nation.

ACKNOWLEDGEMENT

Due thanks together with a special word of appreciation and gratitude to our supervisor Mr. Ashraf Nour Eldin hasan for his continuous assistance and keen supervision, Mrs. Nehad Abdullah for guidance and coordination extended to us, Dr. Nagmel Din for his technical support and Mr. Ahmed Khalid for his generous help. The kind help we received from all the above mentioned in addition to the guidance of all the staff of the Electrical Engineering Department were extremely valuable to us in finalizing this project.

ABSTRACT

Speed Control means intentional change of the drive speed to a value required for performing the specific work process. speed control is a different concept from speed regulation where there is natural change in speed due to change in load on the shaft. Speed Control is either done manually by the operator or by means of some automatic control device. Widely used in many industrial applications, the induction motors represent the starting point when an electrical drive system has to be designed. According to the non-liner relation between the voltage and torque of induction motor changing applied frequency method is useful . A 3-phase induction motor is practically a constant-speed machine. The speed regulation of an induction motor is usually less than 5% at full-load. In induction motor speed reduction is accompanied by a corresponding loss of efficiency and good speed regulation.

المستخلص

معنى التحكم في السرعة التغير المتعمد في سرعة الدافع للحصول على السرعة المطلوبة لأداء عمل ما. مفهوم التحكم في السرعة يختلف عن تنظيم السرعة وهو تغير طبيعي في السرعة عند تغير الحمل على عمود الدوران. التحكم في السرعة اما يدوي ويتم عن طريق المشغل او آلي عن طريق بعض ادوات التحكم. ويستخدم على نطاق واسع في تطبيقات الصناعة. المحرك الحثي يمثل نقطة البداية عندما يراد تصميم النظام. بسبب العلاقة الغير خطية بين الجهد والعزم في المحرك الحثي استخدمت طريقة التحكم عن طريق تغير التردد. المحرك الحثي عمليا هو ماكينة ذات سرعة ثابتة. تنظيم السرعة في المحرك عادة اقل من 5% عند الحمل الكامل. في المحرك الحثي تخفيض السرعة يكون مصحوب بي نقص في الكفاءة ويكون تنظيم السرعة جيد.

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LIST OF SYMBOLS

Ns	Synchronous speed, R.P.M
Nr	Rotor speed, R.P.M
f	Frequency, HZ
P	Number of pole
S	Slip
Sb	breakdown or pull-out slip
E1	Stator induced e.m.f./phase,
E2	rotor induced e.m.f./phase,
R1	Stator resistance/phase,Ω
R2	rotor resistance/phase, Ω
X1	Stator reactance/phase,Ω
X2	Rotor reactance/phase ,Ω
T	Torque ,N*M
Tst	starting torque, N*M
Tb	Breakdown Torque, N*M
V2	stator voltage
Vs	voltage source
Id	direct current
Iq	quadrature current

LIST OF ABBREVIATIONS

DC	Direct current
AC	Alternator current
P	Proportional
I	Integral
D	Derivative
PID	Proportional Integral Derivative
E.M.F	electrical magnetic flax
R.M.S	root mean square
Kp	proportional gain
Ki	integral gain
Kd	derivative gain
IM	Induction motor
VFD	variable frequency drive
RPM	revolution per minuet

CHAPTER ONE

INTRODUCTION

1.1 General concepts:

In conjunction with advances in microelectronics technology and power semiconductor devices since the 1980s, rapid progress has been made in the field of inverters (a form of electrical conversion system) and the drive control systems that combine inverters with motors. Along with control functions that have made it possible to supply motors with operating characteristics tailored to specific system applications, it also seems likely that this progress was helped along by the desire for greater energy efficiency.

Induction motors are widely used in many residential, commercial, industrial and utility applications. This is because the low manufacturing cost, wide speed range, high efficiency and robustness .[1]

Previously, the variable speed drives had various limitations such as poor efficiencies, larger space, low speed and etc. The power electronics transformed the variable speed drive into a smaller size, high efficiency and high reliability .[2]

 The development of speed control system using frequency control has been designed by combinations of PWM control circuit, driver circuit and H-bridge inverter which makes the system simple, robust and compact open loop PWM controller, three phase induction motors are mainly used in residential appliances, farming and low power industrial applications.[3]

Then a modern speed Ac machine system is equipped with adjustable frequency drive for speed control of electric machine. The speed of machine is controlled by converting fixed voltage and frequency to adjustable values on machine side.

1.2 Problem:

In wide variety of industrial application there is multi-usage of several different of speeds of induction motors also there are some new industries that need specific speeds with high degree of accuracy that does not assume error. However, both of these problems can be solved by controlling the frequency of the source.

1.3 Objectives:

- Control the speed of the induction so that the true speed and desired speed could be almost equal (less possible error).
- Design a controller so that any change in the load does not affect the desired speed.
- Reduce the high starting current of the induction motor.
- Make the speed changes without a negative effect on the motor.

1.4 Methodology:

Design the technical block diagram of the project which can guide us through making the model and simulation of the project. Study the effect of the parameters of the control circuit in several ways, and make a comparison between these ways in speed and torque characteristics.

1.5 Page Layout:

The research is compromised from an abstract & five chapters.

Chapter one represents an introduction that include general concept, research problems, research objectives, research methodology and the research outlines.

Chapter two represents main components that include introduction to induction motor, rectifiers, capacitors, insulated-gate bipolar transistor (IGBT), inverter, pulse width modulation, and proportional integral derivative controller (PID).

Chapter three represents speed control of induction motor that includes introduction, control from rotor side and control from stator side.

Chapter four represents application include introduction, system components, system operation and results.

Chapter five represents conclusion and recommendations.

CHAPTER TWO

MAIN COMPONENTS

2.1 Induction Motor :

As a general rule, conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In DC motors, the electric power is conducted directly to the armature through brushes and commutator. Hence, in this sense, a DC motor can be called a conduction motor. However, in AC motors, the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary can see in figure (2.1) . That is why such motors are known as induction motors. In fact, an induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate .
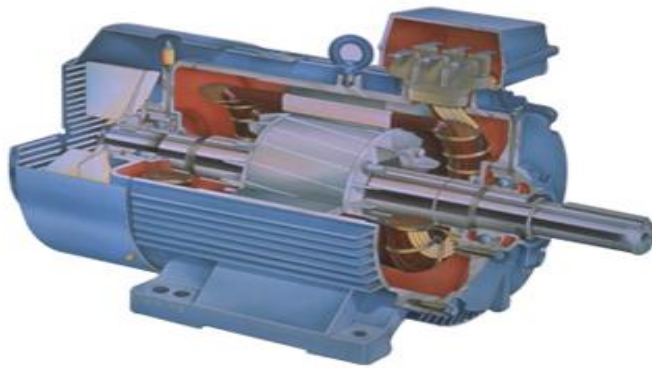
Figure 2.1 : AC induction motor opened to show the construction

2.1.1 Advantages and dis-advantage :

Of all the AC motors, the poly phase induction motor is the one which is extensively used for various kinds of industrial drives. It has the following main advantages and also some dis-advantages:

Advantages:

- It has very simple and extremely rugged, almost unbreakable construction (especially squirrel cage type).
- Its cost is low and it is very reliable.
- It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
- It requires minimum of maintenance.
- It starts up from rest and needs no extra starting motor.

Disadvantages:

- Its speed cannot be varied without sacrificing some of its efficiency.
- Just like a DC shunt motor, its speed decreases with increase in load.
- Its starting torque is somewhat inferior to that of a DC shunt motor.

2.1.2 Construction:

An induction motor consists essentially of two main parts :

(a) a stator and (b) a rotor.

(a) Stator :

The stator of an induction motor is, in principle, the same as that of a synchronous motor or generator.

It is made up of a number of stampings, which are slotted to receive the windings. The stator carries a 3-phase winding and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. Greater the number of

poles, lesser the speed and vice versa. It will be shown in Art. 34.6 that the stator windings, when supplied with 3-phase currents, produce a magnetic flux, which

is of constant magnitude but which revolves (or rotates) at synchronous speed is given by:

$$Ns= \frac{120 \times f}{p}$$ (2.1)

 This revolving magnetic flux induces an E.M.F. in the rotor by mutual induction.

(b) Rotor :

(i) Squirrel-cage rotor :

Almost 90 per cent of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminum or alloys can see in figure (2.2). One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short-circuiting end-rings, thus not possible to add any external resistance in series with the rotor circuit for starting purposes. This is useful in two ways, first it helps to make the motor run quietly by reducing the magnetic hum and second it helps in reducing the locking tendency of the rotor . Motors employing this type of rotor are known as squirrel-cage induction motors.
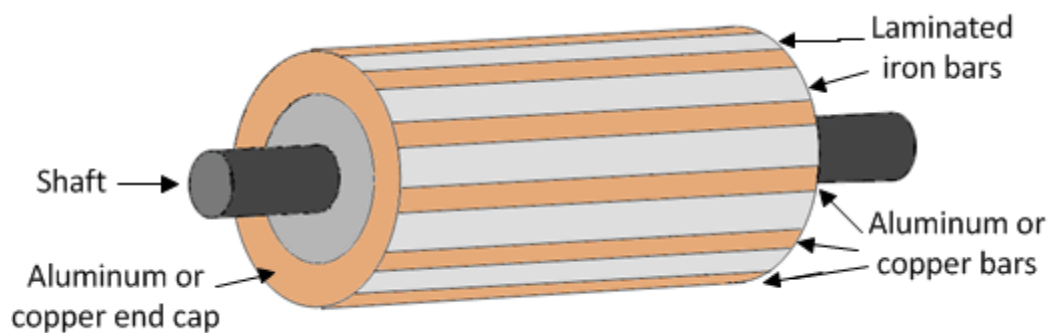

Figure 2.2: squirrel-cage rotor

(ii) Phase-wound or wound rotor :

This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils as used in alternators. The rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even when the stator is wound two-phase. The three phases are starred internally. The other three winding terminals are brought out and connected to three insulated slip-rings mounted on the shaft with brushes resting on them. These three brushes are further externally connected to a 3-phase star-connected rheostat. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor, and for changing its automatically short-circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip-rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel-case rotor. Motors employing this type of rotor are variously known as 'phase-wound' motors or 'wound' motors or as 'slip-ring' motors.

The reason the rotor of an induction motor is set into rotation is as follow, when the 3-phase stator windings, are fed by a 3-phase supply then, a magnetic flux of constant magnitude, but rotating at synchronous speed, is set up. The flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary. Due to the relative speed between the rotating flux and the stationary conductors, an E.M.F. is induced in the latter, according to Faraday's laws of electro-magnetic induction. The frequency of the induced E.M.F is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors and its direction is given by Fleming's Right-hand rule. Since the rotor bars or conductors form a closed circuit, rotor current is produced whose direction, as given by Lenz's law,

is such as to oppose the very cause producing it. In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux.

In practice, the rotor never succeeds in 'catching up' with the stator field. If it really did so, then there would be no relative speed between the two, hence no rotor E.M.F, no rotor current and so no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference between the synchronous speed Ns and the actual speed Nr of the rotor is known as slip.

$$\% \text{slip s} = \frac{Ns - Nr}{Ns} \times 100 \tag{2.2}$$

2.1.3 Starting torque :

The torque developed by the motor at the instant of starting is called starting torque. In some cases, it is greater than the normal running torque, whereas in some other cases it is somewhat less.

$$T_{st} = \frac{3}{2\pi Ns} \cdot \frac{E2^2 R2}{R2^2 + X2^2} \tag{2.3}$$

2.1.4 Maximum torque :

Torque under running condition is maximum at that value of the slip s which makes rotor reactance per phase equal to rotor resistance per phase. This slip is sometimes written as sb and the maximum torque as Tb. Slip corresponding to maximum torque is $s = R_2/X_2$

$$T_{max} = \frac{3}{2\pi Ns} \cdot \frac{E2^2}{2X2} \tag{2.4}$$

2.1.5 Rotor torque and breakdown torque :

The rotor torque at any slip s can be expressed in terms of the maximum (or breakdown) torque *Tb* by the following equation :

$$T=T_b \left[\frac{2}{\left(\frac{sb}{s}\right)+\left(\frac{s}{sb}\right)} \right]$$
$$(2.5)$$

2.1.6 Effect change in supply voltage on torque and speed :

Obviously, torque at any speed is proportional to the square of the applied voltage. If stator voltage decreases by 10%, the torque decreases by 20%. Changes in supply voltage not only affect the starting torque Tst but torque under running conditions also. If V decreases, then T also decreases. Hence, for maintaining the same torque, slip increases $i.e.$ speed falls.

2.1.7 Effect change in supply frequency on torque and speed :

The major effect of change in supply frequency is on motor speed. If frequency drops by 10%, then motor speed also drops by 10%. Machine tools and other motor-driven equipment meant for 50 Hz causes problem when connected to 60-Hz supply. Everything runs $(60 - 50) \times 100/50 = 20\%$ faster than normal and this may not be acceptable in all applications. In that case, we have to use either gears to reduce motor speed or an expensive 50-Hz source. A 50-Hz motor operates well on a 60-Hz line provided its terminal voltage is raised to $60/50 =$ 6/5 (i.e. 120%) of the name-plate rating. In that case, the new breakdown torque becomes equal to the original breakdown torque and the starting torque is only slightly reduced. However, power factor, efficiency and temperature rise remain satisfactory.

Similarly, a 60-Hz motor can operate satisfactorily on 50-Hz supply provided its terminal voltage is reduced to 5/6 (i.e. 80%) of its name-plate rating.

2.1.8 Torque and speed curve :

The torque developed by a conventional 3-phase motor depends on its speed but the relation between the two cannot be represented by a simple equation. It is easier to show the relationship in the form of a curve (Fig. 2.3). In this diagram, T represents the nominal full-load torque of the motor. As seen, the starting

torque (at $N = 0$) is 1.5 T and the maximum torque (also called breakdown torque) is 2.5 T.
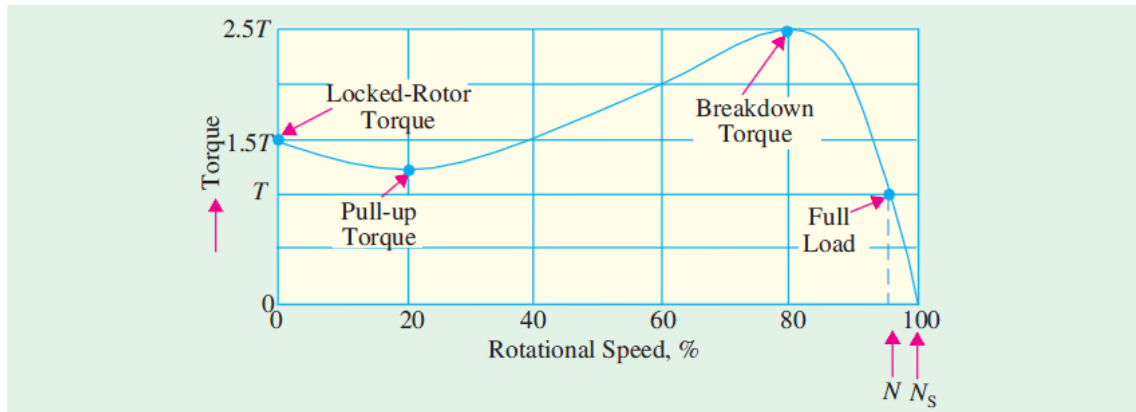
Figure 2.3 : Torque and speed curve

At full-load, the motor runs at a speed of N. When mechanical load increases, motor speed decreases till the motor torque again becomes equal to the load torque. As long as the two torques are in balance, the motor will run at constant (but lower) speed. However, if the load torque exceeds 2.5 T, the motor will suddenly stop. For a squirrel-cage induction motor (SCIM), shape of its torque/speed curve depends on the voltage and frequency applied to its stator. If f is fixed, $T \propto V2$ (figure 2.4). Also, synchronous speed depends on the supply frequency.[4]
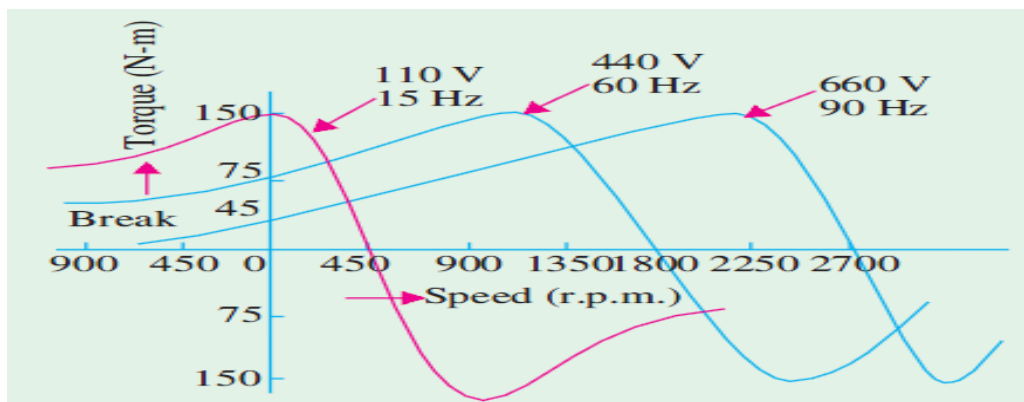
Figure 2.4 : torque and speed with change in supply voltage and frequency

2.2 Rectifiers :

A rectifier is an electrical device that <u>converts</u> (AC), which periodically reverses direction to (DC), which flows in only one direction. The process is known as rectification.

Diodes play an important role in rectification circuits. Rectification is performed by a diode that allows current to flow in one direction but not in the opposite direction. Direct current that has only been rectified, however, has various changes in voltage (ripples) lingering from the alternating current.[5]
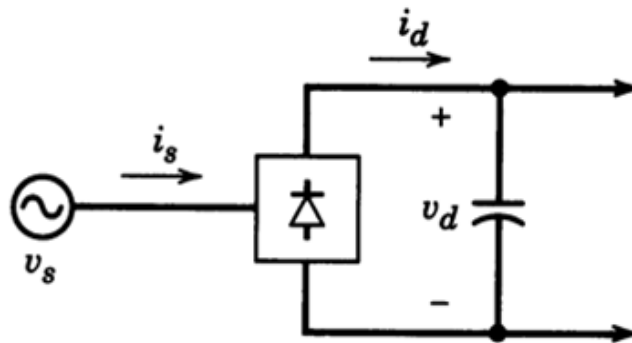
Figure 2.5 : Descriptive graph for rectifier circuit

2.2.1 Types of rectifiers:

Single-phase rectifiers:

- **Half-Wave Rectifier:**

The power diode in a half wave rectifier circuit passes just one half of each complete sine wave of the AC supply in order to convert it into a DC supply. Then this type of circuit is called a "half-wave" rectifier because it passes only half of the incoming AC power supply.
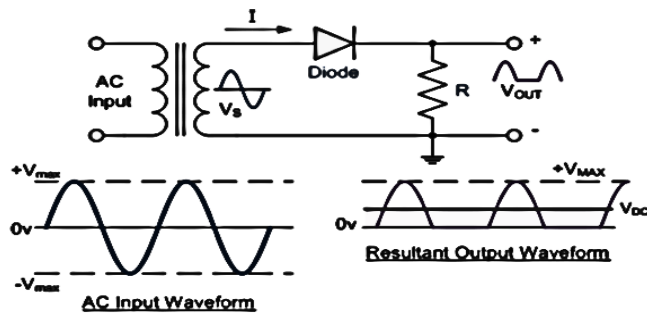
Figure 2.6 : Half-Wave Rectifier circuit and input, output waveforms

During each "positive" half cycle of the AC sine wave, Since the DC load is resistive (resistor, R), the current flowing in the load resistor is therefore proportional to the voltage (Ohm´s Law), and the voltage across the load resistor will therefore be the same as the supply voltage, V_s (minus V_f), that is the "DC" voltage across the load is sinusoidal for the first half cycle only so $V_{out} = V_s$. During each "negative" half cycle of the AC sine wave, the diode is in the blocking condition therefore, the output voltage is zero so $V_{out} = 0$.

The current on the DC side of the circuit flows in one direction only making the circuit Unidirectional and the value of the DC voltage V_{DC} across the load resistor is calculated as follows:

$$V_{dc} = \frac{V_{max}}{\pi} = 0.318 V_{max} = 0.4 V_{rms} \qquad (2.6)$$

- **Full-Wave Bridge Rectifier:**

This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special center tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side.
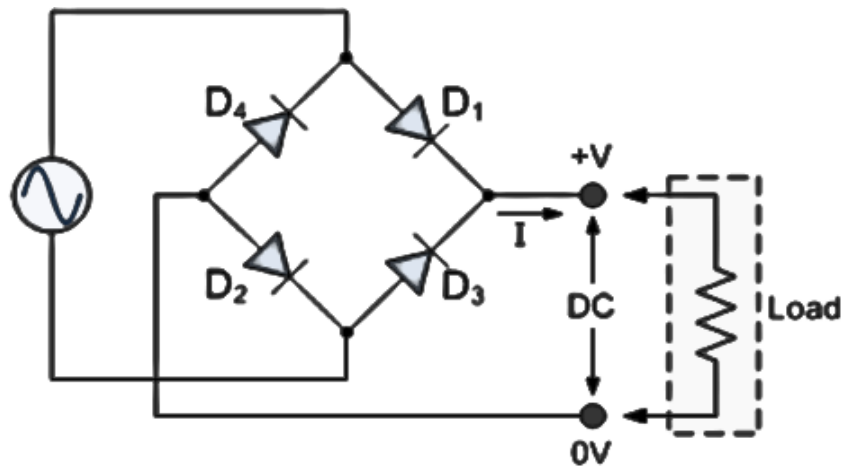
Figure 2.7 : Full-Wave Bridge Rectifier circuit and input, output waveforms

The four diodes labeled D_1 to D_4 are arranged in "series pairs" with only two diodes conducting current during each half cycle. During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown above.

As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional, therefore the average DC voltage across the load is.

$$V_{dc} = \frac{2V_{max}}{\pi} = 0.637V_{max} = 0.9V_{rms}$$ (2.7)

However in reality, during each half cycle the current flows through two diodes instead of just one so the amplitude of the output voltage is two voltage drops (2 x 0.7 =1.4v) less than the input V_{MAX} amplitude.

Three-Phase Rectifiers:

For larger power output and most industrial applications, three-phase rectifier circuits are the norm. As with single-phase rectifiers, three-phase rectifiers can take the form of a half-wave circuit, or a full-wave bridge circuit.

- **Half-wave circuit:**

A three-phase, half-wave circuit requires three diodes, one connected to each phase. This is the simplest type of three-phase rectifier but suffers from relatively

high harmonic distortion on both the AC and DC connections. This type of rectifier is said to have a pulse-number of three, since the output voltage on the DC side contains three distinct pulses per cycle of the grid frequency.

- **Full-Wave Bridge Rectifiers:**

These types of rectifiers are very common in high power applications and it shown in fig(2.8) . This rectifier gives six-pulse ripples on the output voltage. The pair of diodes which are conducting between that pair of supply lines having the highest amount of instantaneous line-to-line voltage will conduct. The line-to-line voltage is $\sqrt{3}$ times the phase voltage of the three-phase. The waveforms are shown in figure (2.9).[6]

The average output voltage is:

$$V_{dc} = \frac{2}{2\pi/6} \int_0^{\pi/6} \sqrt{3} V_m \cos \omega t \, d(\omega t) \tag{2.8}$$
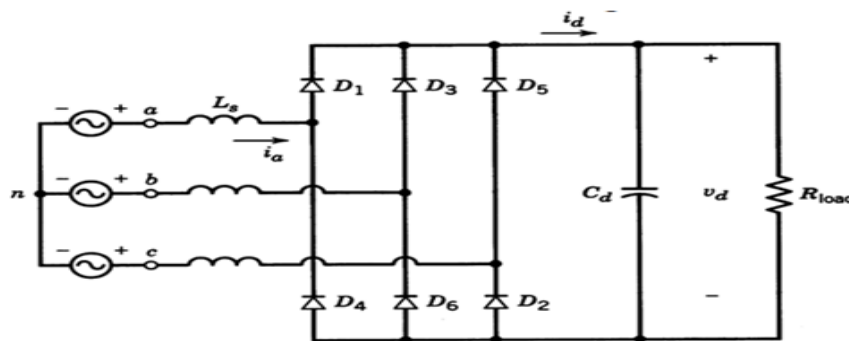
$$= \frac{3\sqrt{3}}{\pi} V_m = 1.6542 V_m \tag{2.9}$$

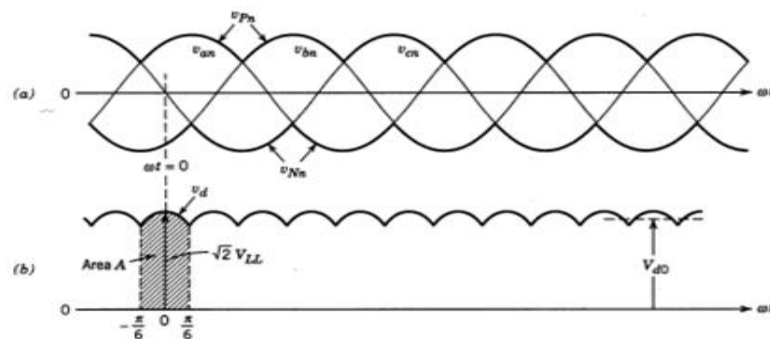Figure 2.8 : Three-Phase Full-Wave Bridge Rectifier circuit

Figure 2.9 : Three-Phase Full-Wave Bridge Rectifier waveform

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2.2.2 Rectifiers applications :

- Rectifiers are also used for detection of amplitude modulated radio signals. The signal may be amplified before detection. If not, a very low voltage drop diode or a diode biased with a fixed voltage must be used.

- Radio, television and computer equipment, require a steady constant DC current (as would be produced by a battery). In these applications the output of the rectifier is smoothed by an electronic filter (usually a capacitor) to produce a steady current.[7]

2.3 Capacitors :

Capacitor is a passive two-terminal electrical component used to store electrical energy temporarily in an electric field.

2.3.1 Construction :

All contain at least two electrical conductors (plates) separated by a dielectric. A dielectric can be glass, ceramic, plastic films, air, vacuum, paper, mica, oxide layer etc . Capacitors are widely used as parts of electrical circuits in many common electrical devices. An ideal capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates.

When there is a potential difference across the conductors an electric field develops across the dielectric, causing positive charge +Q to collect on one plate and negative charge –Q to collect on the other plate. If a battery has been attached to a capacitor for a sufficient amount of time, no current can flow through the capacitor. However, if a time-varying voltage is applied across the leads of the capacitor, a displacement current can flow.

An ideal capacitor is characterized by a single constant value, its capacitance. Capacitance is defined as the ratio of the electric charge Q on each conductor to the potential difference V between them. The SI unit of capacitance is the farad (F), , which is equal to one coulomb per volt (1 C/V). Typical capacitance values range from about 1 pF (10^{-12} F) to about 1 mF (10^{-3} F).

2.3.2 Applications :

- Energy storage:

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery, or like other types of rechargeable energy storage system. Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

- Power conditioning:

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

- Power factor correction:

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load . Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (VAR). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to

make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

- Filters:

Filters are capacitors used for filtering of undesirable frequencies. They are common in electrical and electronic equipment .

- Motor starters

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary "start" winding has a series non-polarized starting capacitor to introduce a lead in the sinusoidal current. When the secondary (start) winding is placed at an angle with respect to the primary (run) winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. [8][9]

2.4 Insulated-Gate Bipolar Transistor (IGBT) :

The insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching.

2.4.1 Construction :

The IGBT combines the simple gate-drive characteristics of MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors.

Cross section of a typical IGBT showing internal connection of MOSFET and Bipolar Device, an IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor see in figure (2.10). This additional p+ region creates a cascade connection of a PNP bipolar junction transistor with the surface n-channel MOSFET.
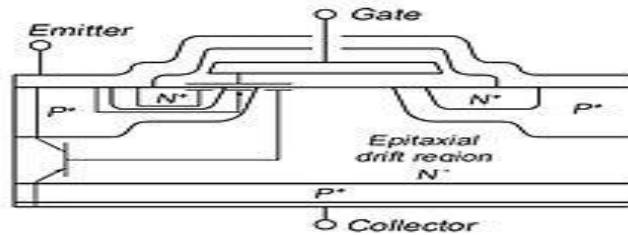

Figure 2.10 : Device structure

2.4.2 Application :

variable-frequency drives (VFDs), electric cars, trains, variable speed refrigerators, lamp ballasts, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to turn on and off rapidly, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters. In switching applications modern devices feature pulse repetition rates well into the ultrasonic range, frequencies which are at least ten times the highest audio frequency handled by the device when used as an analog audio amplifier.[10]

2.5 Inverter :

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static VAR compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According

to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as adjustable speed drives (ASDs).

Theory of operation in inverter can take from simple circuit in figure (2.11) that include two MOSFET (Q1,Q2) and two diodes (D1,D2) and load by resistance and two voltage sources Vs1,Vs2 ,when tarn on Q1 the current pass from Vs1 through Q1 to load ,and the voltage between load be (–Vs) , that throughout connect (T/2),then when Q2 tarn on the current pass from Vs2 through Q2 to load ,and the voltage between load be (–Vs) , that throughout connect (T/2) , on that the voltage and current sine wave's be in figure(2.12) that call half wave inverter .
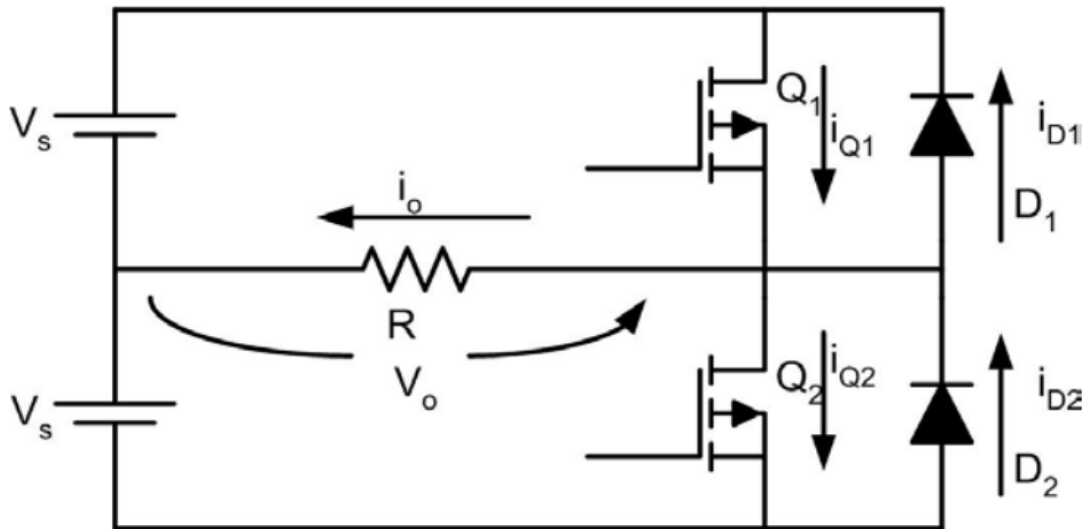
Figure 2.11 : half wave single phase inverter
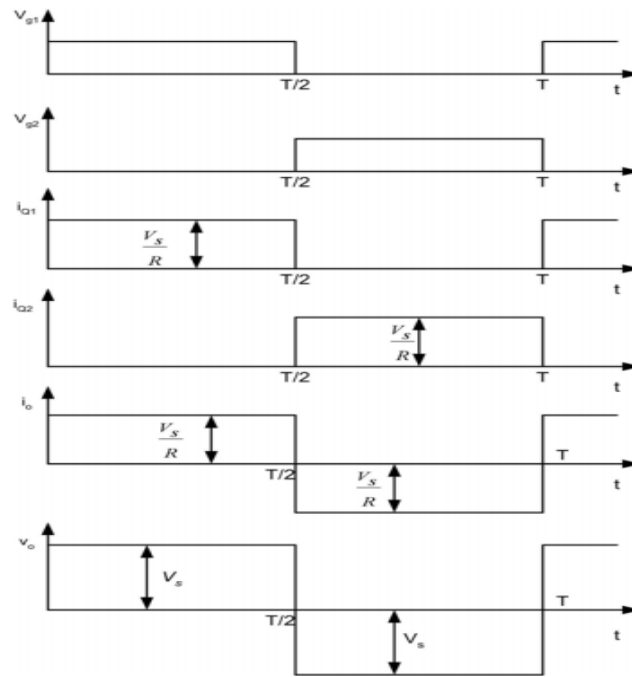
Figure 2.12 : voltage and current wave

- Single phase bridge inverter

The bridge inverter consists of four elements (MOSFET, IGBT ,est.) and four diodes they connect in bridge figure(2.13) ,where are turn on Q1.Q2 together the voltage between load be(2Vs) ,when turn on Q3,Q4 together the voltage in load be (-2Vs) figure(2.14),the D1,D2 used to pass the current when Q3,Q4 turn off until the current be zero .
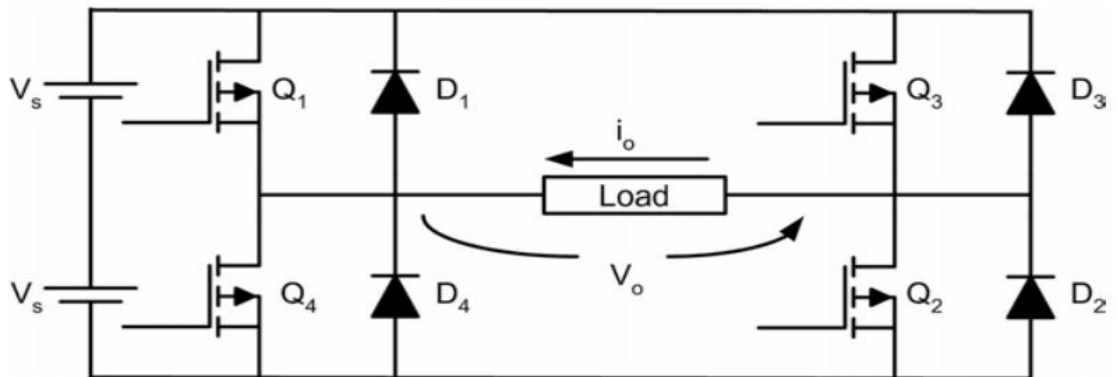
Figure 2.13: single phase bridge inverter
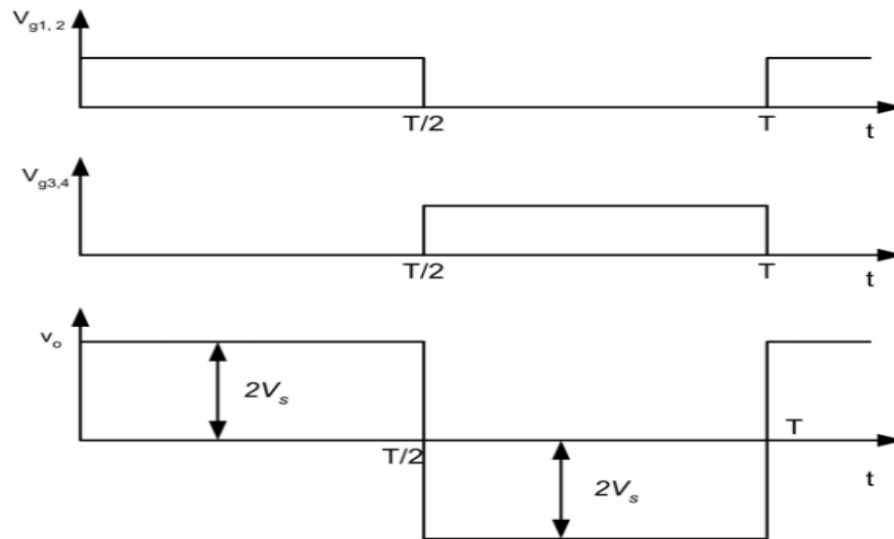
Figure 2.14: voltage and current wave for bridge inverter

- Three phase inverter

The three phases inverter use in many high power application ,there are many way to make three phases inverter but the most important three phase bridge inverter figure(2.15) consists of six (MOSFET or IGBT) and six diodes where are turn on each MOSFET to 180 then turn off it to 180 and that in cascade figure(2.16).[6]
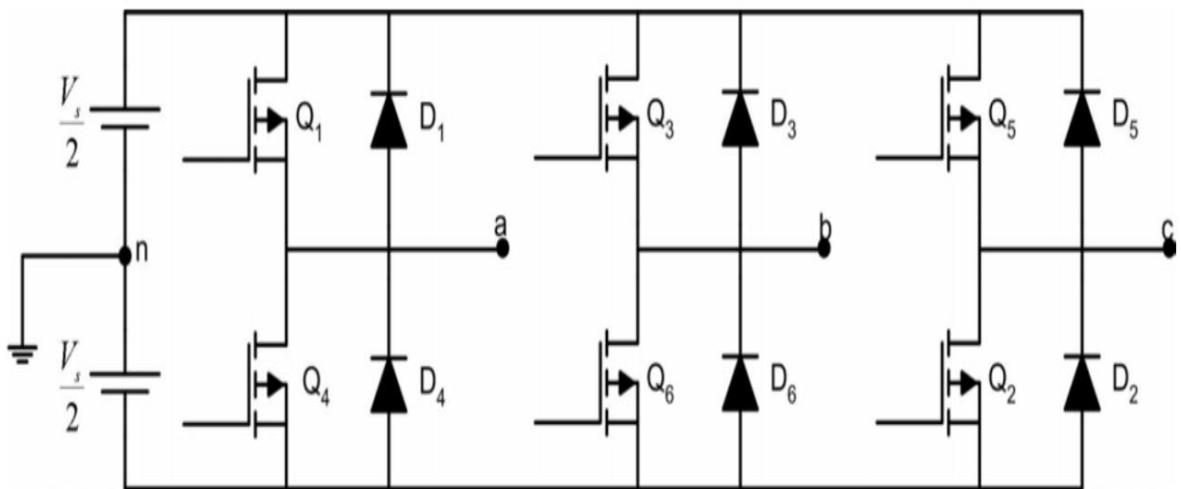
Figure 2.15 : three phase bridge inverter
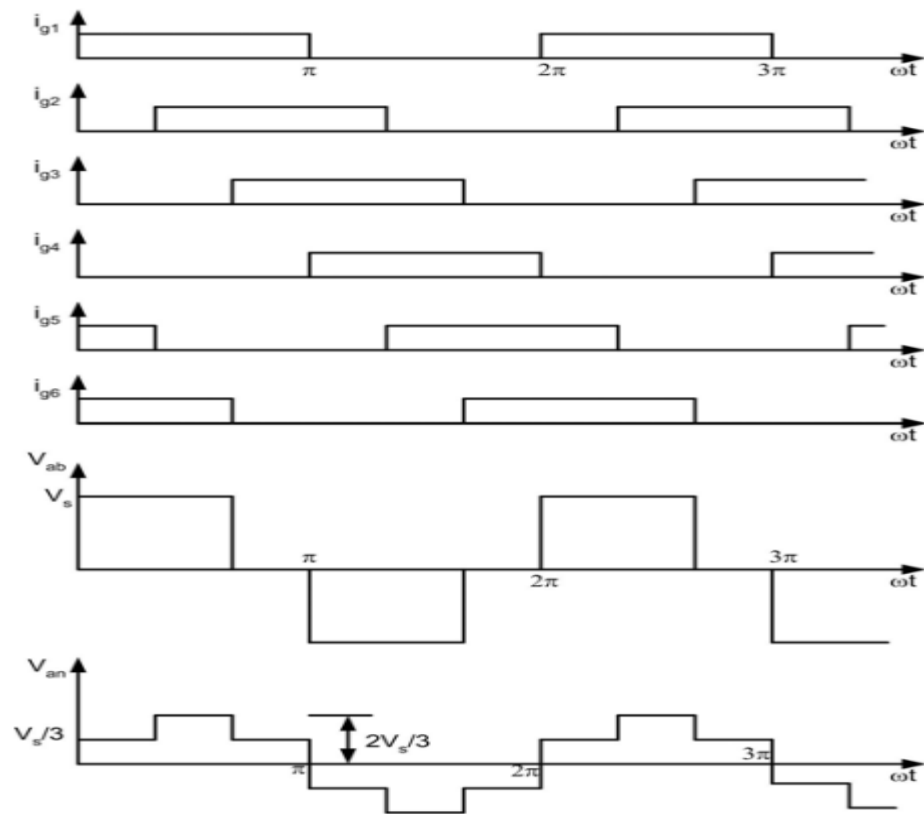
Figure 2.16: control pulse and voltage out in three phase inverter

2.6 Pulse width modulation :

Pulse-width modulation (PWM) is the basis for control in power electronics. The theoretically zero rise and fall time of an ideal PWM waveform represents a preferred way of driving modern semiconductor power devices. With the exception of some resonant converters, the vast majority of power electronic circuits are controlled by PWM signals of various forms. The rapid rising and falling edges ensure that the semiconductor power devices are turned on or turned off as fast as practically possible to minimize the switching transition time and the associated switching losses. The pulse frequency is one of the most important parameters when defining a PWM method and can be either constant or variable.

2.6.1 Types of PWM :

(a) 2-Level PWM :

The most common and popular technique of digital pure-sine wave generation is pulse-width-modulation (PWM). The PWM technique involves generation of a digital waveform, for which the duty-cycle is modulated such that the average voltage of the waveform corresponds to a pure sine wave. The simplest way of producing the PWM signal is through comparison of a low-power reference sine wave with a triangle wave (figure 2.17). Using these two signals as input to a comparator, the output will be a 2-level PWM signal (figure 2.18). This PWM signal can then be used to control switches connected to a high-voltage bus, which will replicate this signal at the appropriate voltage.
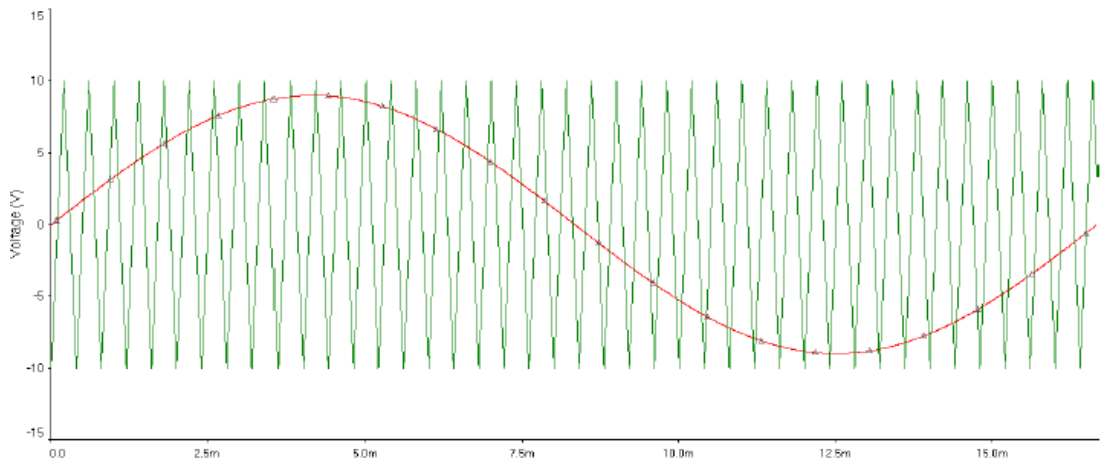

Figure 2.17 : 2-Level PWM Comparison Signals
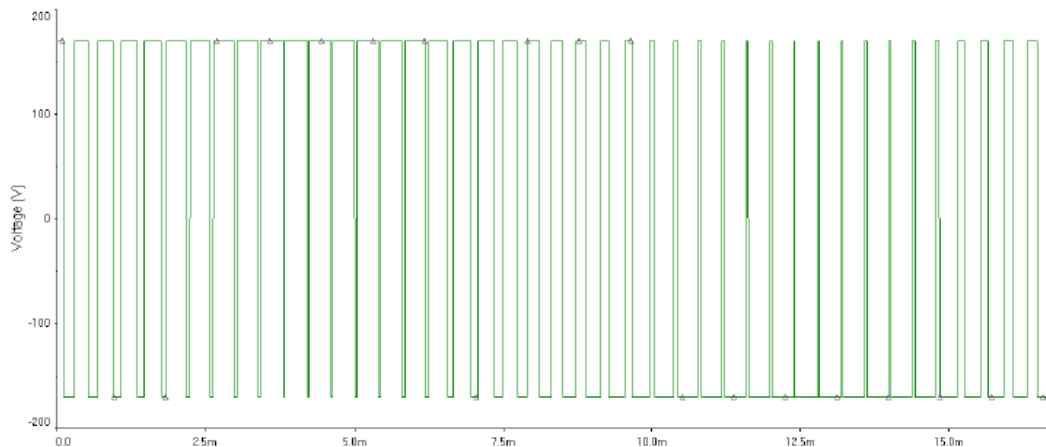
Figure 2.18 : 2-level PWM output

(b)3-Level PWM :

In order to create a signal which is closer to a true sine wave, a 3 level PWM signal can be generated with high, low, and zero voltage levels. For the resulting 3-level PWM signal to correspond to a sine wave, the signal comparison stage must also be 3-level (figure 2.19). A triangle wave is used as it is in the 2-level PWM comparison, but it half the amplitude and summed with a square wave to compare one half of the sine reference signal at a time. The resulting PWM signal is used to control one half of an H-bridge (figure 2.20), which controls how long the bus voltage is allowed through to the load. The other half of the H-bridge controls the polarity of the voltage across the load, and is controlled by a simple square wave of the same frequency and in phase with the sine signal. Generally, this square wave can simply be created in a stage of the sine wave generation circuit. The resulting 3-level high-voltage PWM signal (figure 2.21) It should be noted that the simulations we did for this technique utilized a very low switching frequency for the triangle wave, so the PWM switching frequency is also low. This was done so that the waveforms would be easy to view and understand. In reality, a switching frequency above 20 kHz would be used to keep inductance ringing outside the range of human hearing.
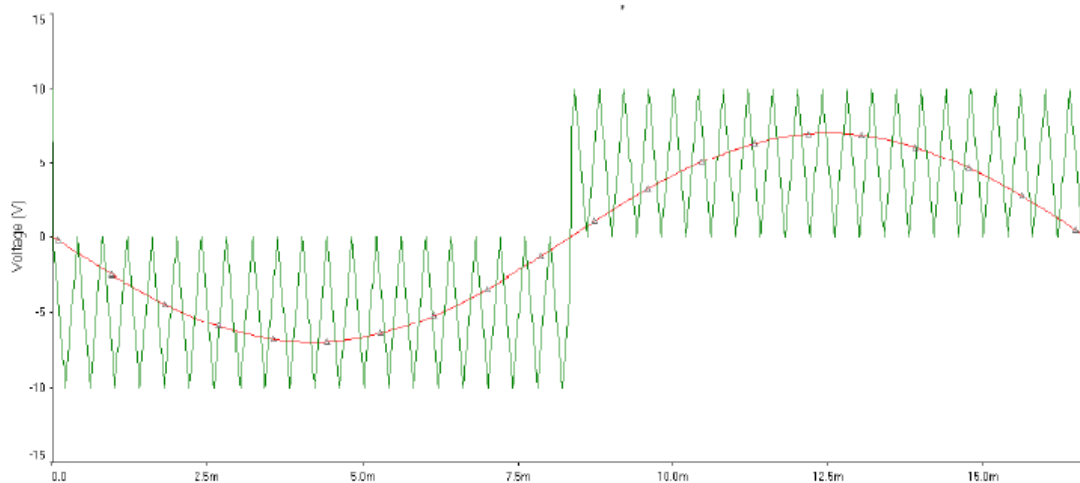
Figure 2.19 : 3-Level PWM Comparison Signals

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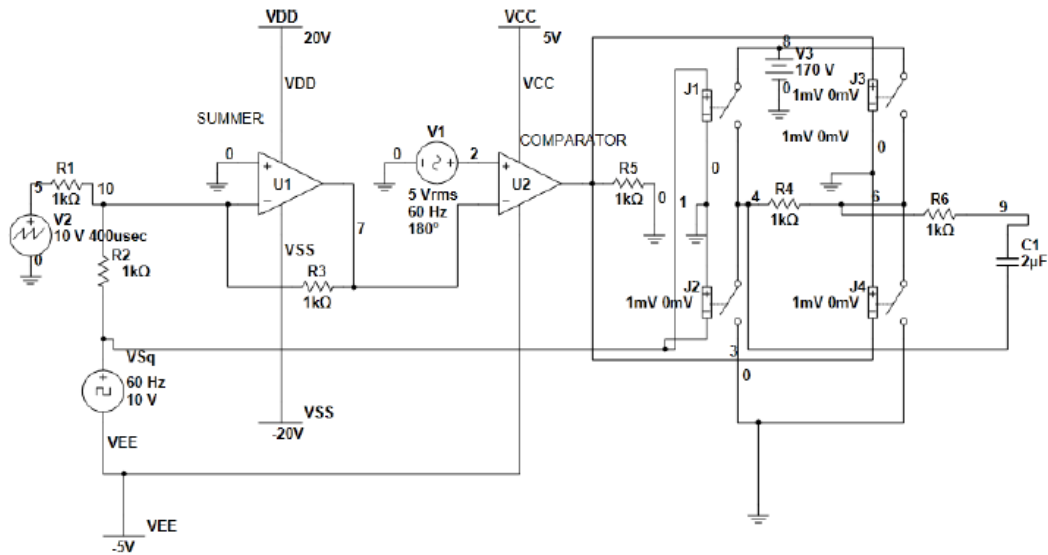
Figure 2.20 : 3-Level PWM Simulation Circuit
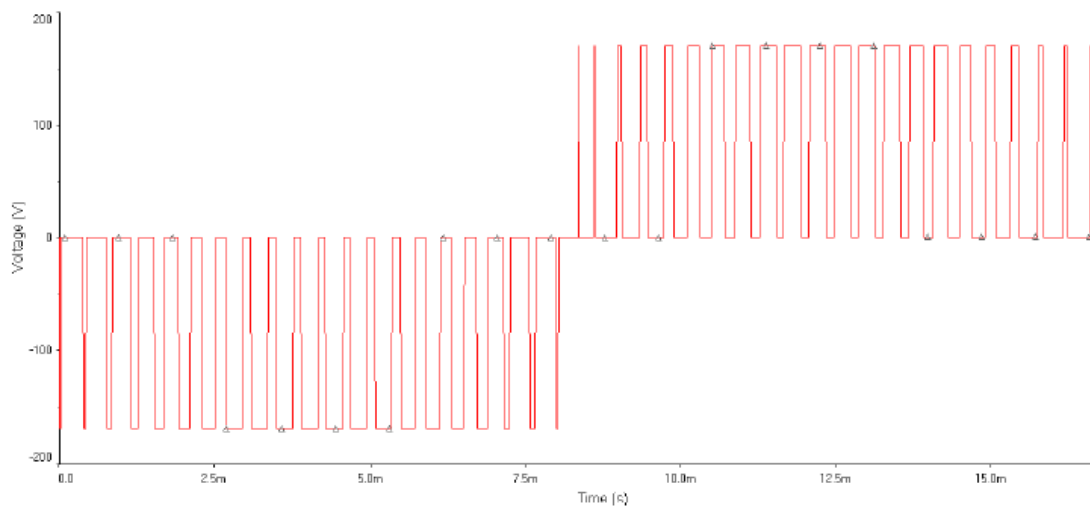
Figure 2.21: 3-level PWM output

(c) 5-Level PWM :

In order to create a PWM signal which more closely follows the desired sine wave output, the design described for the 3-level PWM technique can be expanded to 5-, 7- and 9+ level PWM. Each additional 2 levels added on top of the 3-level design adds an H-bridge (added in series), a comparator, and a summer. The added accuracy of the signal due to increasing the level therefore brings with it the addition of components, and the space, cooling, and power they

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require. Control signals must be created separately for each H-bridge (figure 2.22), each of which correspond to one layer of the sine voltage (figure 2.23). Higher level PWM also requires multiple isolated voltage buses. For example, the 5-level PWM circuit requires two isolated buses at 1/2 the voltage of the corresponding 3-level circuit. The buses must be isolated, as they need to be connected in series. In the 5-level PWM circuit, one half of each H-bridge is controlled by the square wave from the 3-level circuit, and simply controls polarity across the bridge. The other half of each bridge is controlled by the PWM output of each respective comparator. The resulting PWM signal is shown in (figure 2.23). One of the advantages of higher level PWM generation is that there is less of a voltage swing from the minimum and maximum of each step, which results in less power loss due to the slope up and down for each step . This reduced power loss results in higher efficiency for the inverter. This increased efficiency must be considered in balance with the addition of components and frequency effects which must be filtered out.
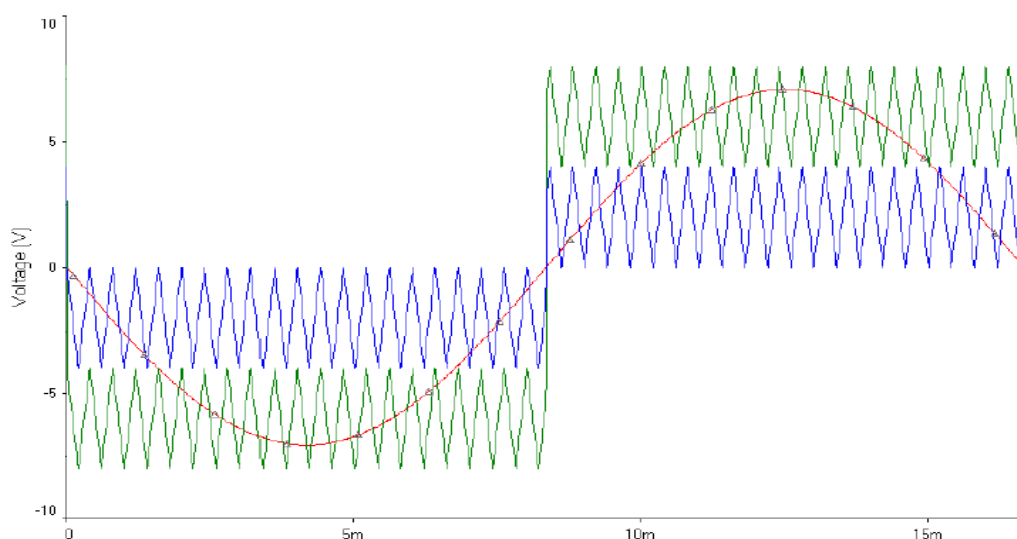
Figure 2.22 : 5-Level PWM Comparison Signals
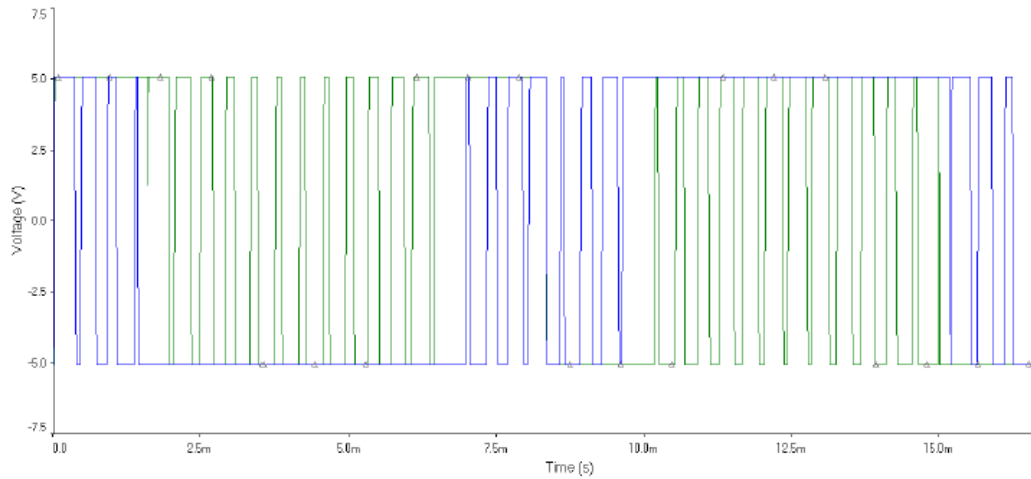
Figure 2.23 : 5-level PWM output

2.6.2 Amplitude Modulation :

In PWM generation, two very important characteristics are ma and mf, where mf is the ratio between the frequency of the triangle wave to the sine wave signal, and is generally an odd integer. This number is significant in that it determines the frequency of the harmonics in the PWM output signal. The significant components of this output are the primary, the harmonic at frequency mf*fc where fc is the frequency of the sine wave control (as well as the primary output), and the harmonics at mf+2*fc and mf-2*fc. Mf, therefore, determines the frequency of the harmonics of the output, which of course affects how easily they can be filtered out.

The ratio of the amplitudes of the sine wave and the triangle wave is ma, and is always kept between 0 and 1, as a value above 1 will result in clipping and non-linear amplitude relationships. Between 0 and 1, though, the amplitude of the primary is linearly related to ma. As the ma ratio decreases, the amplitude of the primary also decreases. At the same time, though, the amplitude of the harmonics increase, and the mf harmonic actually becomes larger than the primary just above 0.8 ma.[11]

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2.7 Proportional Integral Derivative Controller (PID) :

Feedback control is a control mechanism that uses information from measurements. In a feedback control system, the output is sensed. There are two main types of feedback control systems: (1) positive feedback (2) negative feedback. The positive feedback is used to increase the size of the input but in a negative feedback, the feedback is used to decrease the size of the input. The negative systems are usually stable.

the PID controller can be understood as a controller that takes the present, the past, and the future of the error into consideration. After digital implementation was introduced, a certain change of the structure of the control system was proposed and has been adopted in many applications. But that change does not influence the essential part of the analysis and design of PID controllers.

2.7.1 Role of a Proportional Controller :

The role of a proportional depends on the present error, I on the accumulation of past error and D on prediction of future error. The weighted sum of these three actions is used to adjust Proportional control is a simple and widely used method of control for many kinds of systems. In a proportional controller, steady state error tends to depend inversely upon the proportional gain (if the gain is made larger the error goes down). The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain. The proportional term is given by:

$P=K_p.Error (t)$ (2.10)

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is very high, the system can become unstable. In contrast, a small gain results in a small output response to a large

input error. If the proportional gain is very low, the control action may be too small when responding to system disturbances.

2.7.2 Role of an Integral Controller :

An Integral controller is proportional to both the magnitude of the error and the duration of the error. The integral in in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. Consequently, an integral control (Ki) will have the effect of eliminating the steady state error, but it may make the transient response worse. The integral term is given by:

$$I = Ki \int_0^t Error(t) \qquad (2.11)$$

2.7.3 Role of a Derivative Controller :

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The derivative term slows the rate of change of the controller output. A derivative control (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. The derivative term is given by:

$$D = Kd \frac{dErorr}{dt} \qquad (2.12)$$

2.7.4 PID controller :

A typical structure of a PID control system is shown in Figure (2.24) shows a structure of a PID control system. The error signal e(t) is used to generate the

proportional, integral, and derivative actions, with the resulting signals weighted and summed to form the control signal u(t) applied to the plant model.
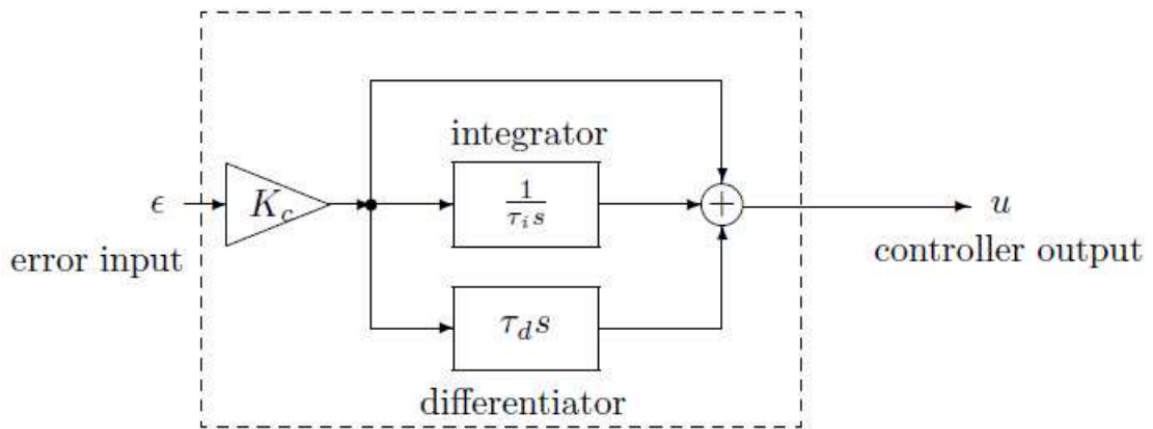
Figure 2.24 : PID control system

$$G(s) = Kp(1 + \frac{1}{Ti*s} + Td*s) \tag{2.13}$$

where K_p is the proportional gain, T_i is the integral time constant, T_d is the derivative time constant, $K_I = K_P/T_i$ is the integral gain and $K_d = K_p/T_d$ is the derivative gain. The ''three term'' functionalities are highlighted below. The terms K_p, T_i and T_p definitions are:

- The proportional term: providing an overall control action proportional to the error signal through the all pass gain factor.
- The integral term: reducing steady state errors through low frequency compensation by an integrator.
- The derivative term: improving transient response through high frequency compensation by a differentiator.[12]

CHAPTER THREE

MOTOR SPEED CONTROL

3.1 Introduction:

Whenever the term electric motor or generator is used, we tend to think that the speed of rotation of these machines are totally controlled only by the applied voltage and frequency of the source current. But the speed of rotation of an electrical machine can be controlled precisely also by implementing the concept of drive .

The main advantage of this concept is, the motion control is easily optimized with the help of drive. In very simple words, the systems which controls the motion of the electrical machines, are known as electrical drives. A typical drive system is assembled with a electric motor (may be several) and a sophisticated control system that controls the rotation of the motor shaft. Now a days, this control can be done easily with the help of software. So, the controlling becomes more and more accurate and this concept of drive also provides the ease of use. This drive system is widely used in large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc. Drives are employed as prime movers for diesel or petrol engines, gas or steam turbines, hydraulic motors and electric motors.

Electric motors are of various types. The dc motors can be divided in four types – shunt wound dc motor, series wound dc motor, compound wound dc motor and permanent magnet dc motor. And AC motors are of two types – induction motors and synchronous motors. Now synchronous motors are of two types – round field and permanent magnet. Induction motors are also of two types –

squirrel cage and wound motor. Besides all of these, stepper motors and switched reluctance motors are also considered as the parts of drive system.

Therefore, there are various types of electric motors, and they are used according to their specifications and uses. When the electrical drives were not so popular, induction and synchronous motors were usually implemented only where fixed or constant speed was the only requirement. And for variable speed drive applications, dc motors were used. But as we know that, induction motors of same rating as a dc motors have various advantages like they have lighter weight, lower cost, lower volume and there is less restriction on maximum voltage, speed and power ratings. For these reasons, the induction motors are rapidly replaced the dc motors. Moreover induction motors are mechanical stronger and requires less maintenance.

Electrical drives are readily used these days for controlling purpose but this is not the only the advantage of Electrical drives. There are several other advantages the drives are available in wide range torque, speed and power, the control characteristics of these drives are flexible. According to load requirements these can be shaped to steady state and dynamic characteristics. As well as speed control, electric braking, gearing, starting many things can be accomplished, and they are adaptable to any type of operating conditions, no matter how much vigorous or rough it is.

Because of the above mentioned advantages of electrical drives, they are getting more and more popular and are used in a wider range of applications.[13]

3.2 Control from Rotor Side:

a) Rotor rheostat control.

b) By operating two motors in concatenation or cascade.

c) By injecting an E.M.F. in the rotor circuit.

3.2.1 Rotor Rheostat Control:

The motor speed is reduced by introducing an external resistance in the rotor circuit. For this purpose, the rotor starter may be used, provided it is continuously rated.

Speed can be decrease by increasing the rotor resistance R_2.

$$T \propto \frac{s}{R2} \qquad\qquad (3.1)$$

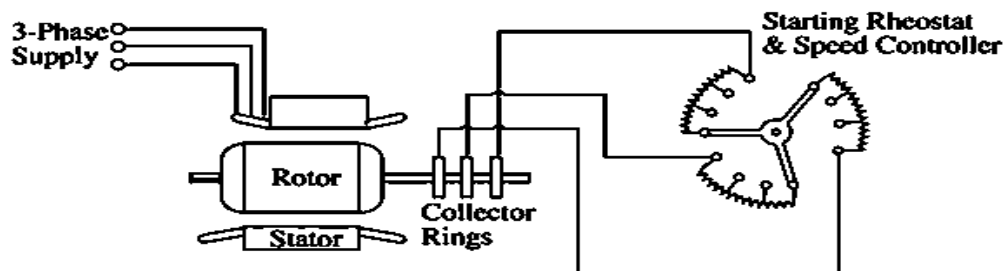Figure 3.1: Rotor rheostat control circuit

Advantages of this method:

- The rotor resistance is changed
- The maximum torque point shifts to higher slip values, while retaining a constant torque.

Disadvantage of this method:

- Applicable to slip-ring motors alone.
- With increase in rotor resistance iron losses ($I^2 * R_2$) also increase which decrease the operating efficiency of the motor.

- Double dependence of speed, not only on R_2 but on load as well. Because of the wastefulness of this method, it is used where speed changes are needed for short periods only.

3.2.2 Operating Two Motors in Concatenation or Cascade:

In this method, two motors are used and are ordinarily mounted on the same shaft, so that both run at the same speed.

The stator winding of the main motor A is connected to the mains in the usual way, while that of the auxiliary motor B is fed from the rotor circuit of motor A. For satisfactory operation, the main motor A should be phase-wound i.e. of slip-ring type with stator to rotor winding ratio of 1:1, so that, in addition to concatenation, each motor may be run from the supply mains separately. There are at least three ways in which the combination may be run:

1. Main motor A may be run separately from the supply. In that case, the synchronous speed is:

$$N_{sa} = 120 \times \frac{f}{P_a} \qquad (3.2)$$

where P_a = Number of stator poles of motor A.

2. Auxiliary motor B may be run separately from the mains (with motor A being disconnected). In that case, synchronous speed is:

$$N_{sb} = 120 \times \frac{f}{P_b} \qquad (3.3)$$

Where P_b = Number of stator poles of motor B.

3. The combination may be connected in cumulative cascade i.e. in such a way that the phase rotation of the stator fields of both motors is in the same direction. The synchronous speed of the cascaded set, in this case, is

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$$N_{sc} = 120 \times \frac{f}{(Pa+Pb)} \hspace{5cm} (3.4)$$

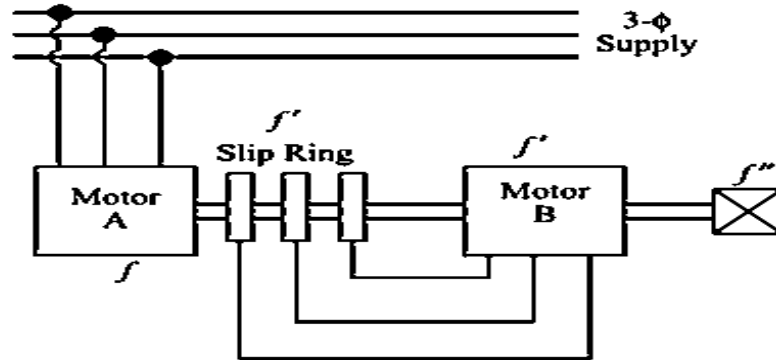Disadvantage of this method is motor A must be slip-ring.

figure 3.2:Operating two motors in concatenation or cascade

3.2.3 Injecting an E.M.F. in The Rotor Circuit:-

In this method, the speed of an induction motor is controlled by injecting a voltage in the rotor circuit, it being of course, necessary for the injected voltage to have the same frequency as the slip frequency. There is, however, no restriction as to the phase of the injected E.M.F. .

When we insert a voltage which is in phase opposition to the induced rotor E.M.F., it amounts to increasing the rotor resistance, whereas inserting a voltage which is in phase with the induced rotor E.M.F., is equivalent to decreasing its resistance. Hence, by changing the phase of the injected E.M.F. and hence the rotor resistance, the speed can be controlled.

There are two types of this method:

- Kramer system:

Is used in the case of large motors of 4000 kW or above. It consists of a rotary converter C which converts the low-slip frequency A.C power into D.C power,

which is used to drive a D.C shunt motor D, mechanically coupled to the main motor M.

The main motor is coupled to the shaft of the D.C shunt motor D. The slip-rings of M are connected to those of the rotary converter C. The D.C output of C is used to drive D. Both C and D are excited from the D.C bus-bars or from an exciter. There is a field regulator which governs the back E.M.F. E_b of D and hence the D.C potential at the commutator of C which further controls the slip-ring voltage and therefore, the speed of M.

Advantage of this method:

 ❖ Any speed, within the working range, can be obtained instead of only two or three, as with other methods of speed control.
 ❖ If the rotary converter is over-excited, it will take a leading current which compensates for the lagging current drawn by main motor M and hence improves the power factor of the system.
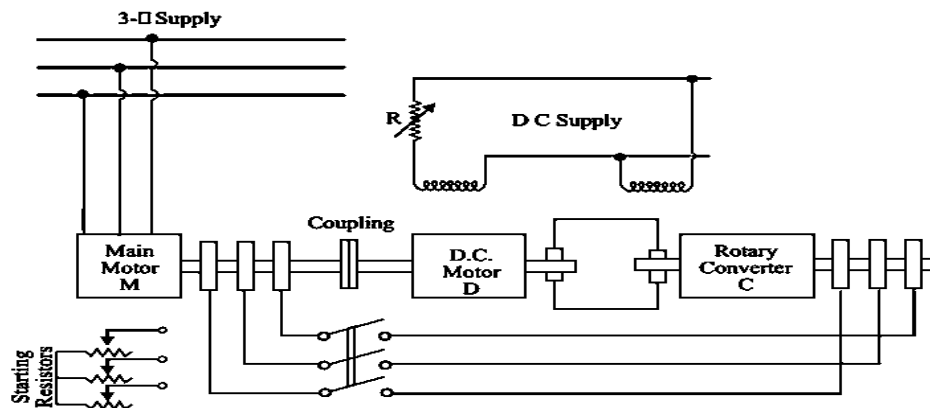

figure 3.3: Kramer system

 • Scherbius system:

For controlling the speed of large induction motors, the slip energy is not converted into DC and then fed to a DC motor, rather it is fed directly to a

special 3-phase (or 6-phase) DC commutator motor-called a, Scherbius machine. The poly phase winding of machine C is supplied with the low-frequency output of machine M through a regulating transformer. The commutator motor C is a variable-speed motor and its speed (and hence that of M) is controlled by either varying the tapings on regulating transformer or by adjusting the position of brushes on C.
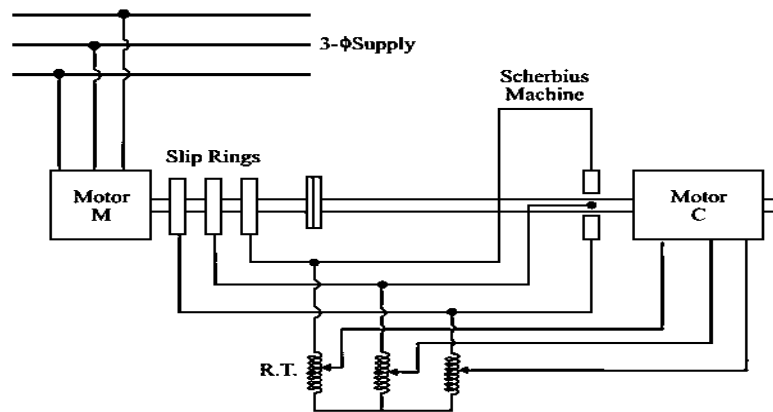

figure 3.4: Scherbius system

3.3 Control from Stator Side:

a) By changing the applied voltage.

b) By changing the number of stator poles.

c) By changing the applied frequency.

3.3.1 Changing Applied Voltage:

A very simple and economical method of speed control is to vary the stator voltage at constant supply frequency. The three-phase stator voltage at line frequency can be controlled by controlling the switches in the inverter. As seen from the equation below the developed torque is proportional to the square of the stator supply voltage and a reduction in stator voltage will produce a reduction in speed.

Torque equation of induction motor is:

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_s} \frac{s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$ (3.5)

This method though is the cheapest and the easiest, is rarely used because:

❖ A large change in voltage is required for a relatively small change in speed.

❖ This large change in voltage will result in a large change in the flux density thereby seriously disturbing the magnetic conditions of the motor.

Rotor resistance R_2 is constant and if slip s is small then sX_2 is so small that it can be neglected. Therefore, $T \propto sE_2^2$ where E_2 is rotor induced E.M.F. and $E_2 \propto V$ and hence $T \propto V^2$, thus if supplied voltage is decreased, torque decreases and hence the speed decreases.

One may note that if the applied voltage is reduced, the voltage across the magnetizing branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production.
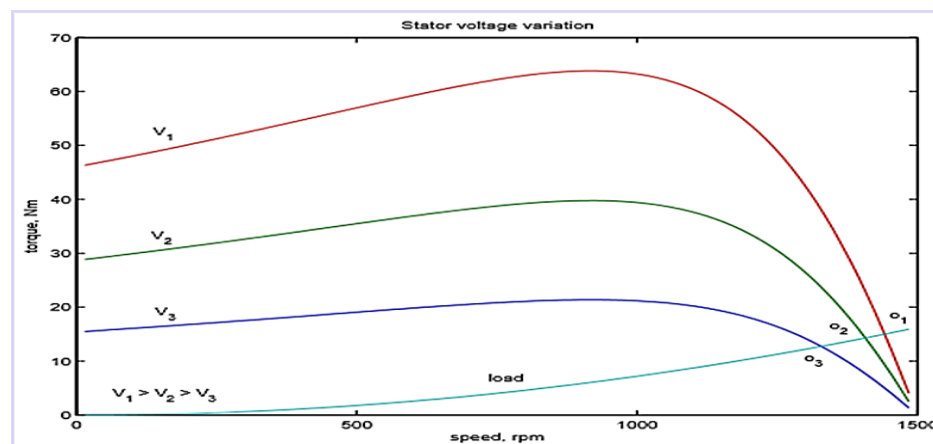

Figure 3.5: Speed-Torque characteristics with variable stator voltage

This figure shows if, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such

conditions, reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved

Voltage control may be achieved by adding series resistors or a series inductor / autotransformer or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper.

The salient features of stator voltage control method are:

- For low-slip motor, the speed range is very low.

- Not suitable for constant-torque load.

- Poor power factor.

Used mainly in low power applications, such as fans, blowers, centrifugal pumps, etc.

3.3.2 Changing the number of stator poles:

This method is easily applicable to squirrel-cage motors because the squirrel-cage rotor adopts itself to any reasonable number of stator pole.

$$Ns = \frac{120 \times f}{P} \tag{3.6}$$

From the above equation it is also clear that the synchronous speed of an induction motor could also be changed by changing the number of stator poles. This change of number of poles is achieved by having two or more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different synchronous speed.

Motors with four independent stator winding are also in use and they give four different synchronous speeds. Of course, one winding is used at a time, the others being entirely disconnected.

This method has been used for elevator motors, traction motors and also for small motors driving machine tools. Speeds in the ratio of 2:1 can be produced by a single winding if wound on the consequent-pole principle. In that case, each of the two stator windings can be connected by a simple switch to give two speeds, each, which means four speeds in all.

Advantages and disadvantages:

Dahlander motors have advantages compared to other speed control systems like variable frequency drives, as there is less power loss. This is because most of the power is used to drive the motor and no electrical pulse switching is done. The system is much simpler and easier to use compared to other speed control methods available. However, the Dahlander motor has the disadvantage of fast mechanical wear and tear due to changing speeds in such a drastic ratio; this type of connection also produces high harmonic distortion during the shifting of poles as the angular distance between the power generated increases as the poles are decreased in the motor.

3.3.3 Changing the Applied Frequency:

This method is also used very rarely. We have seen that the synchronous speed of an induction motor is given by Ns = 120 f/P. Clearly, the synchronous speed (and hence the running speed) of an induction motor can be changed by changing the supply frequency f. However, this method could only be used in cases where the induction motor happens to be the only load on the generators, in which case, the supply frequency could be controlled by controlling the speed of the prime movers of the generators. But, here again the range over which the motor speed may be varied is limited by the economical speeds of the prime movers. This method has been used to some extent on electrically- driven ships.

If the frequency is decreased keeping voltage constant, then saturation of air-gap flux takes place. At low frequency, the reactance will decrease and the motor

current may be too high. If the frequency is increased above its rated value, then the air gap flux and rotor current decreases correspondingly, the developed torque also decreases. Due to these reasons this method of control is rarely used.[4]
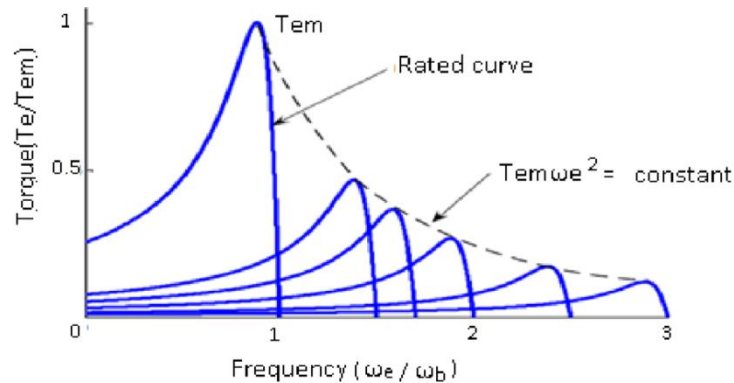

Figure 3.6 : Speed-Torque characteristics with variable frequency control

i. Volts Hertz (V/F) Control Method:

The constant V/F control method is the most popular method of Scalar control. If an attempt is made to reduce the supply frequency at the rated supply voltage, the air gap flux will tend to saturate, causing excessive stator current and distortion of flux wave. Therefore, the region below the base or rated frequency should be accompanied by the proportional reduction of stator voltage so as to maintain the air gap flux constant. If the ratio of voltage to frequency is kept constant, the flux remains constant. By varying the voltage and frequency the torque and speed can be varied. The torque is normally maintained constant while the speed is varied. This arrangement is widely used in the locomotives and industrial applications. The purpose of the volts hertz control scheme is to maintain the air-gap flux of AC Induction motor constant in order to achieve higher run-time efficiency. The magnitude of stator flux is proportional to the ratio of stator voltage & the frequency. If ratio is kept constant the stator flux remains constant & motor torque will only depends upon slip frequency. In

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variable-frequency, variable-voltage operation of a drive system, the machine usually has low slip characteristics (i.e low rotor resistance), giving high efficiency. In spite of the low inherent starting torque for base frequency operation, the machine can always be started at maximum torque as indicated in Fig 3.8.The absence of high in-rush starting current in a direct-start drive reduces stress and therefore improves the effective life of the machine. By far the majority of variable-speed ac drives operate with a variable frequency, variable-voltage power supply.

Other than the variation in speed, the torque-speed characteristics of the V/F control reveal the following:

- ❖ The starting current is low.

- ❖ The stable operating region of the motor is increased. Instead of simply running at its base/ rated speed, the motor can be run typically from 5% of the synchronous speed (NS) up to the base speed. The torque generated by the motor can be kept constant throughout this region.

- ❖ Since almost constant rated torque is available over the entire operating range, the speed range of the motor becomes wider. User can set the speed as per the load requirement, thereby achieving the higher efficiency.

- ❖ One of the most advantages is soft start capability in which motors are ramped up to speed instead of being abruptly thrown on line. This useful feature reduces mechanical stresses on the motor and leads to lower maintenance cost as well as a longer motor life. Because of above reasons V/F control method is proposed in this work.
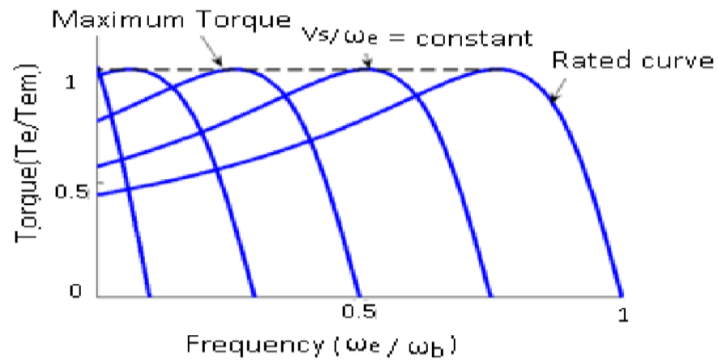
Figure 3.7:Speed-Torque curves with constant V/F ratio

ii. Algorithm of Vector Control:

induction motors have been run at a single speed, which was determined by the frequency of the main voltage and the number of poles in the motor.

The technique called vector control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973). In the vector control scheme, a complex current is synthesised from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor.

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents. An induction motor can be modeled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct (I_d) and quadrature (I_q) are responsible for producing flux and torque respectively in the motor. By definition, the I_q current is in phase with the stator flux, and Id is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system. The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control. The second fundamental idea is that of reference frames. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a

reference frame, which is rotating at the same frequency. Once a sinusoidal quantity is transformed to a constant value by careful choice of reference frame, it becomes possible to control that quantity with traditional proportional integral (PI) controllers.[13]

CHAPTER FOUR

SPEED CONTROL APPLICATION

4.1 Introduction:

Other names of VFD method are variable speed drive, adjustable speed drive, adjustable frequency drive, AC drive, micro drive and inverter, and it is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor.

Frequency is directly related to the speed of the motor. In other words the faster the frequency is the faster the RPM goes. If an application does not require an electric motor to run at full speed, the controller can be used to ramp down the frequency and voltage to meet the requirements of the electric motor speed and the requirements of the electric motor's load. As the application's motor speed requirements change, the controller can simply turn up or down the motor speed to meet the required speed.

The variable frequency drive is Should use to reduce energy consumption and energy costs. If you have an application that does not need to be run at full speed, then you can cut down energy costs by controlling the motor with a variable frequency drive, which is one of the benefits of Variable Frequency Drives. VFDs allow you to match the speed of the motor-driven equipment to the load requirement. There is no other method of AC electric motor control that allows you to accomplish this. Electric motor systems are responsible for more than 65% of the power consumption in industry today. Optimizing motor control systems by installing or upgrading to VFDs can reduce energy consumption in your facility by as much as 70%. Additionally, the utilization of VFDs improves product quality, reduces production costs and increases production through

tighter process control by operating your motors at the most efficient speed for your application. Moreover, fewer mistakes will occur and thus production levels will increase, particularly where flow control is involved. Conveyors and Belts eliminate jerks at start-up allowing high throughput, extending equipment Life and reducing maintenance. Your equipment will last longer and will have less downtime due to maintenance when it's controlled by VFDs ensuring optimal motor application speed. Because of the VFDs optimal control of the motor's frequency and voltage, the VFD will offer better protection for your motor from issues such as electro thermal overloads, phase fault, under voltage, overvoltage, etc.. When you start a load with a VFD you will not subject the motor or driven load to the "instant shock" of across the line starting, but can start smoothly, thereby eliminating belt, gear and bearing wear.

Applying a VFD to a specific application is no mystery when you understand the requirements of the load. the VFD must have ample current capability for the motor so that the motor can produce the required torque for the load. You must remember that machine torque is independent of motor speed and that load horsepower increases linearly with rpm.

4.2 Circuit:

The circuit include three divisions

4.2.1 Power Circuit Component:

The components of the power circuit is consisting :

- **AC Source:**

3-phase , 230 volt/phase generally it supplies electric energy to the system.

- **Rectifier:**

3-phase Full wave bridge rectifier which contains six diodes, it's also named a six pulse bridge.

This device converts alternating current (AC) to direct current (DC)

- **Capacitor:**

The output signal of the rectifier has various changes in voltage (ripples) lingering from the AC. This capacitor is used to filter the DC voltage from rectifier to provide extremely pure DC voltage and also smooth the current and make it even. It has a value of 4 F.

- **Inverter:**

It is an insulated-gate bipolar transistor (IGBT) which is a three-terminal power semiconductor device primarily used as an electronic switch. The input of inverter is the smoothed DC signal from rectifier. The inverter is pulse-width modulated (PWM) to produce the three-phase sinusoidal voltage.

- **Induction motor:**

The type of the motor is squirrel cage induction motor having the following parameters:

Voltage: 400 V/line.

Frequency: 50 Hz.

Power: 3Ph.

Inertia: 0.2 J(kg.m^2)

Friction factor: 0.005752 F(N.m.s)

Pole pairs: 2

-Stator: -Rotor:

Resistance: 1.115 ohm.   Resistance: 1.083 ohm.

Inductance: 0.005974 H.   Inductance: 0.005974 H.

4.2.2 Control Circuit Component:

The components of the control circuit is consisting :

- **Pulse-width modulation (PWM):**

The pulse width modulation device contains a comparator that compares the Triangle Carrier signal with a reference signal from the control circuit and turns IGBT's on or off depending on the results of the test.

- **Three Phase Sine Generator :**

Used to generate a three phase balanced sinusoidal signal (positive sequence), this vectorized signal usually represents a set of three phase voltages, three input let control the amplitude, phase and frequency of the three phase output signal.

- **Proportional-Integral controller (PI):**

P-I controller is mainly used to eliminate the steady state error resulting from P controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I guarantees set point overshoot.

- **Gain:**

The Gain block multiplies the input by a constant value (gain).The input and the gain can each be a scalar, vector or matrix.

- **Saturation:**

The Saturation block imposes upper and lower limits on an input signal.

- **Summation:**

The Sum block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector or matrix inputs. It can also collapse the elements of a signal.

- **Ramp Function:**

The ramp function is a unary real function, easily computable as the mean of the independent variable and its absolute value.

4.2.3 Measurement :

Measures the instantaneous voltage between two electric nodes, the voltmeter in simulink is the voltage measurement block. Measures the actual speed, physically called tachometer.

4.3 Operation :

The first stage of a Variable Frequency AC Drive, is the rectifier. The rectifier is comprised of six diodes, which are similar to check valves used in plumbing systems. They allow current to flow in only one direction; the direction shown by the arrow in the diode symbol. For example, whenever A-phase voltage (voltage is similar to pressure in plumbing systems) is more positive than B or C phase voltages, then that diode will open and allow current to flow. When B-phase becomes more positive than A-phase, then the B-phase diode will open and the A-phase diode will close. The same is true for the 3 diodes on the negative side of the bus. Thus, we get six current "pulses" as each diode opens

and closes. This is called a "six-pulse VFD", which is the standard configuration for current Variable Frequency Drives.
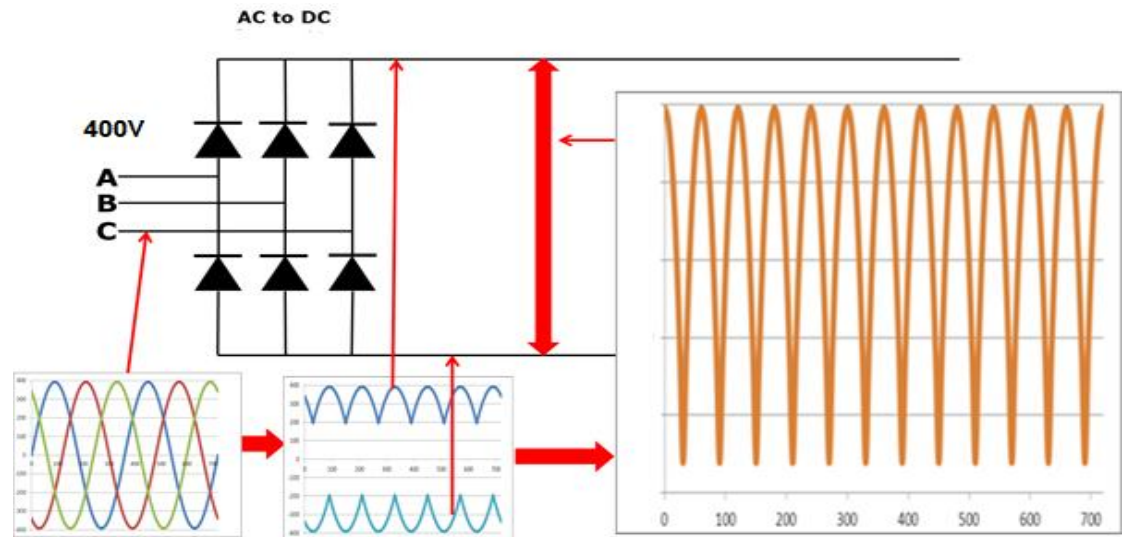
Figure 4.1: output from rectifier

let us assume that the drive is operating on 400V power system. The 400V rating is "RMS" or root-mean-squared. The peaks on a 400V system are 565.86V. As you can see, the VFD dc bus has a dc voltage with an AC ripple.

AC ripple on the DC bus can cancel by adding a capacitor. This capacitor absorbs the ac ripple and delivers a smooth dc voltage. Thus, the voltage on the DC bus becomes "approximately" $565.86V_{DC}$. The actual voltage will depend on the voltage level of the AC line feeding the drive, the level of voltage unbalance on the power system, the motor load, the impedance of the power system and any reactors or harmonic filters on the drive.

The diode bridge rectifier that converts AC-to-DC, is sometimes just referred to as a converter. The converter that converts the dc back to ac is also a converter, but to distinguish it from the diode converter, it is usually referred to as an "inverter". It has become common in the industry to refer to any DC-to-AC converter as an inverter.
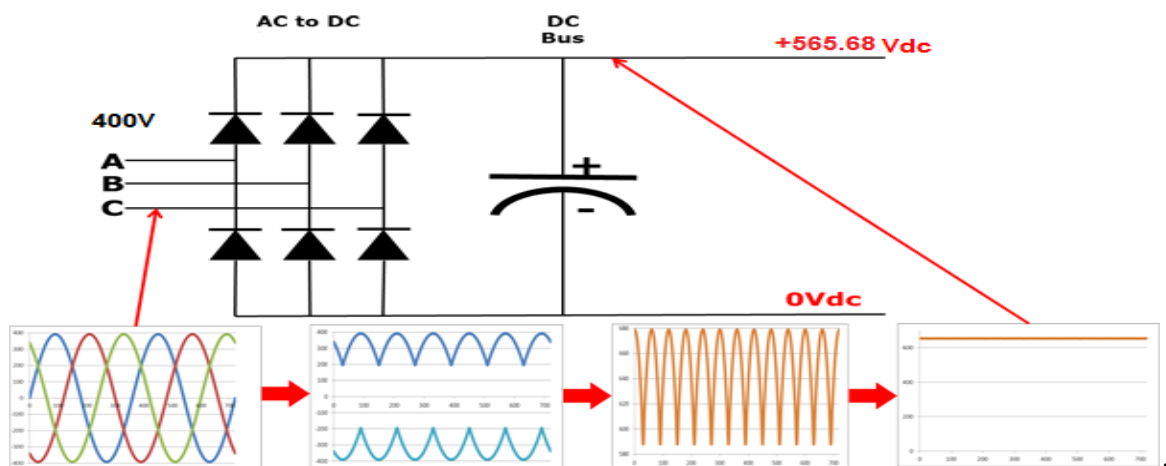
Figure 4.2: DC Voltage after clear the ripple

When we close one of the top switches in the inverter, that phase of the motor is connected to the positive dc bus and the voltage on that phase becomes positive. When we close one of the bottom switches in the inverter , that phase is connected to the negative dc bus and becomes negative. Thus, we can make any phase on the motor become positive or negative at will and can thus generate any frequency that we want. So, we can make any phase be positive, negative, or zero.
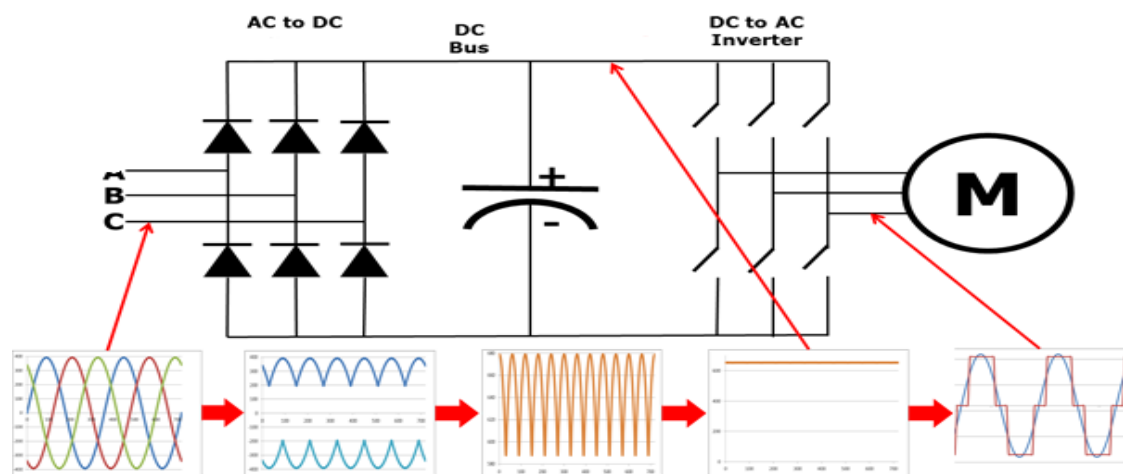
Figure 4.3:DC to AC inverter

In a real VFD, the switches shown would actually be transistors.

Notice that the output from the VFD is a "rectangular" wave form. VFD's do not produce a sinusoidal output. This rectangular waveform would not be a good choice for a general purpose distribution system, but is perfectly adequate for a motor.

If we want to reduce the motor frequency to 30 Hz, then we simply switch the inverter output transistors more slowly. But, if we reduce the frequency to 30Hz, then we must also reduce the voltage to 240V in order to maintain the V/f ratio.

This is called Pulse Width Modulation or PWM. Imagine that we could control the pressure in a water line by turning the valve on and off at a high rate of speed. While this would not be practical for plumbing systems, it works very well for VFD's. Notice that during the first half cycle, the voltage is ON half the time and OFF half the time. Thus, the average voltage is half of 400Vrms. By pulsing the output, we can achieve any average voltage on the output of the VFD.

The blue sine-wave is shown for comparison purposes only. The drive does not generate this sine wave.

The speed error generates the slip frequency which controls the inverter frequency, where speed commands to adjust the speed, we have error in the steady state and imperfection in the system components. Using closed loop control employs a feedback signal to the drive to compensate for filter loading conditions. Two control loops, the inner loop have PI controller when the error signal is used to generate the proportional and integral action to the plant, the proportional control function determines how quickly an output reacts to process variation, and integral control determines a reaction based on a sum of variation. The out loop takes the PI action and sums up with the actual frequency. The function saturation has limit output depending on drive parameter. The

Volt/frequency (constant value) multiplies by frequency to create the voltage reference and the frequency reference to PWM. Voltage reference is the input reference to PWM and will be adjusted automatically to the plant.
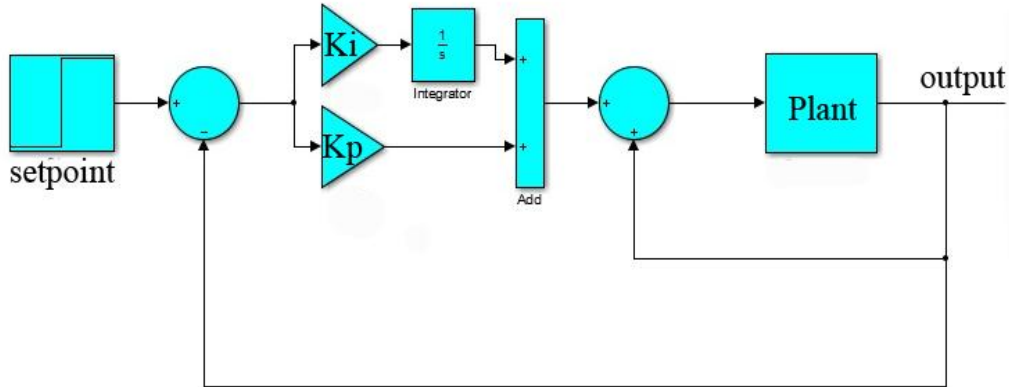

Figure 4.4: closed loop of the system

For controlling the speed of the motor frequency should reprocess by the PI controller, but to get the rated frequency that verifies the motor run condition can get by transfer the speed generated by traducer from (rad/sec) to (R.P.M), then transform to frequency by the relation :

$$Ns = \frac{120 \times f}{P} \tag{4.1}$$

$$f = \frac{P \times Ns}{120} \tag{4.2}$$

From equation (4.2) get the actual frequency from the plant and transform the reference speed from set point to frequency by the last equation.

The speed required to run the plant is increased or decreased progressively by using the ramp function for protecting the motor from high starting current.

The ramp function has two terminals (1800,-1800) where speed increases or decreases by one (R.P.M) during 557.97 µsec, so to rise to the maximum speed we need 0.83 sec.

If error found between the actual frequency and reference frequency, the error will be processed by the PI controller and the action of the controller added to speed output(actual speed transfer to actual frequency), by that practice we generate the new frequency to the machine, but the drive need value of reference voltage to block saturation of flux. So the new frequency multiplies by ratio (V/f) to transfer to voltage value. by that method the new value of the voltage and frequency is generated, This value affects the plant through the three phase sine wave generated.

The output of the three phase sine wave generator is proportional to the input of PWM.

PWM has two inputs the triangle wave(carrier) and sine wave(reference) produced by the three phase sine generator. The triangle wave has amplitude($2*\pi$) and the sine wave has information of the frequency and voltage. After that the output of PWM is sent to inverter to control the plant by putting off and on (suitable hatch) the transistor.

The parameter of induction motor has 50Hz and 400V to keep these values as the maximum input value of the motor from controller by putting a function called saturation.

All been mentioned of operations previous been simulated by MATLAB simulation shows in following figure.
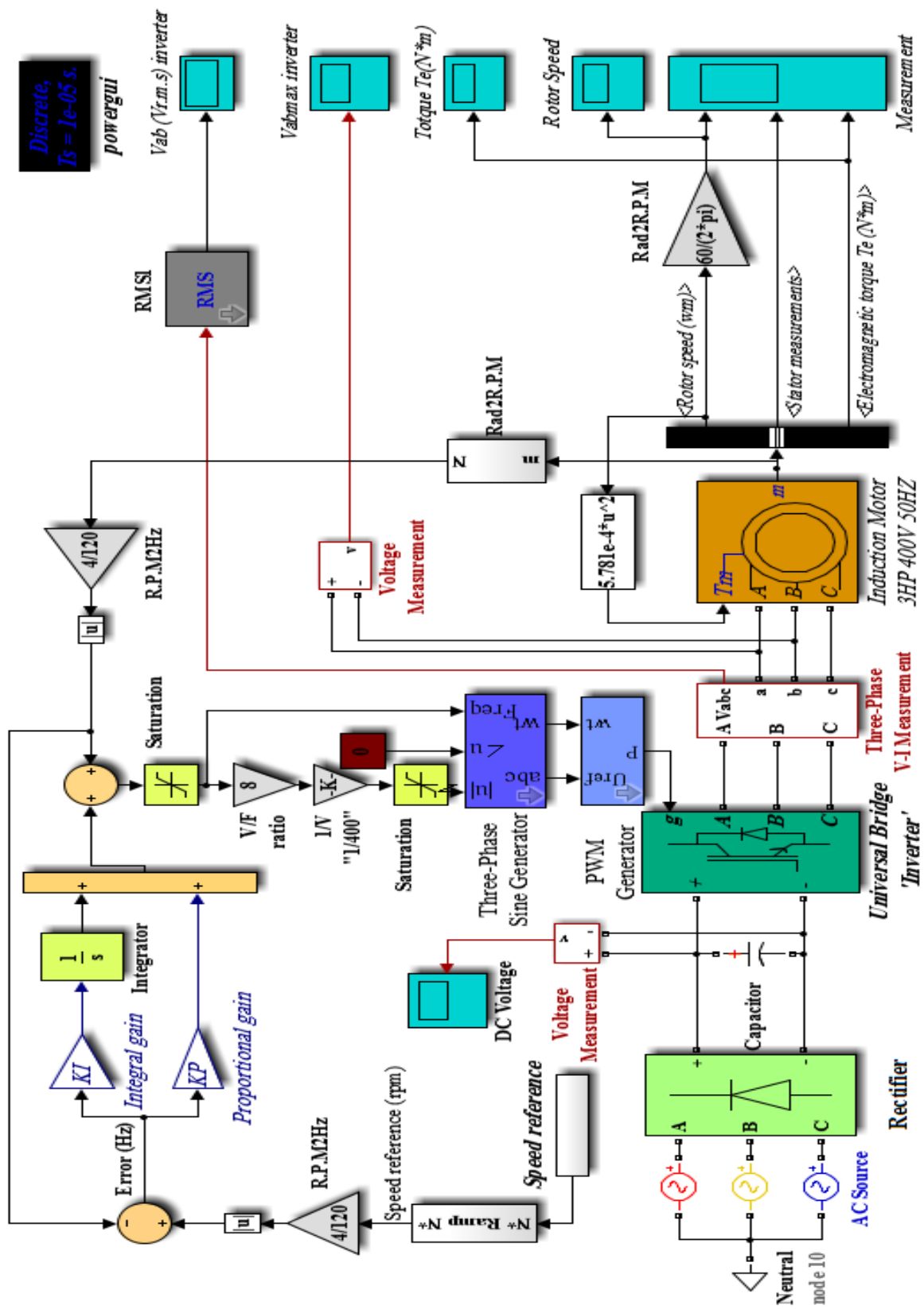
Figure 4.5: MATLAB/SIMULINK block diagram speed control of IM using frequency

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In this project two methods are used for tuning the parameter of PI controller: K_p and K_i. The first method is application of try and error method on a random value. Set the K_p=1 and K_i=1 then increase the k_p to improve the response of the system and increase K_i to make the error zero.

The value get from first method to fast response time plus it eliminates residual error:

K_p=9, K_i=10

The second method by calculation PI constant K_p and K_i, an electric motor can be represented by a second order equation :

$$\frac{Vm}{ei}=\frac{1/ke}{s^2+2\delta\omega ns+\omega^2} \tag{4.3}$$

An index of performance can be written to equate with the characteristic equation of eq (4.3) such that :

$$\frac{(\left(\frac{Kp}{J}\right)s+\left(\frac{Ki}{J}\right))}{[s^2+\left(\frac{Kp}{J}\right)s+\left(\frac{Ki}{J}\right)]} \tag{4.4}$$

Equating coefficients of eq(4.3) and eq(4.4):

$$2\delta\omega n=\frac{Kp}{J} \tag{4.5}$$

$$\text{And } \omega n^2=\frac{Ki}{J} \tag{4.6}$$

It can be assumed that the drive will be damped, thus δ=1.[14]

Therefore, substituting these approximations into eq (4.5) and eq (4.6)

$$K_p=2\omega nJ \tag{4.7}$$

$$\text{and } K_i=\omega n^2 J \tag{4.8}$$

Therefore

Jtotal at motor= 0.18 lb in sec^2

ωn=157.08

K_p= 2*157.08*0.18= 56.54

K_i=157.08^2 * 0.18= 4441.3

- **Matlab and Simulink:**

The name MATLAB stands for Matrix Laboratory, MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects.

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming environment. Furthermore, MATLAB is a modern programming language environment, it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. These factors make MATLAB an excellent tool for teaching and research.

Simulink is an environment for simulation and model-based design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.

4.4 Results:

The output of the Dc voltage from the Rectifier after the capacitor clears the ripple see in figure (4.6).
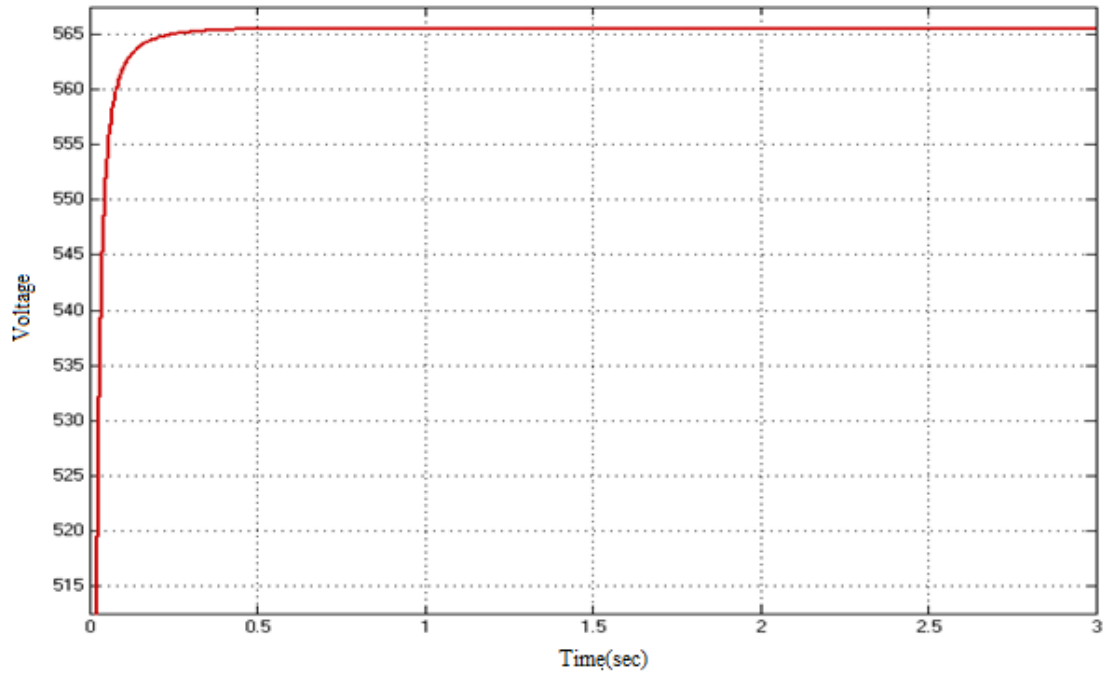
Figure 4.6 : Output Dc voltage from Rectifier

The Dc voltage transferred to inverter will be transferred to Ac voltage and we can see the shape of the voltage in Figure (4.7).
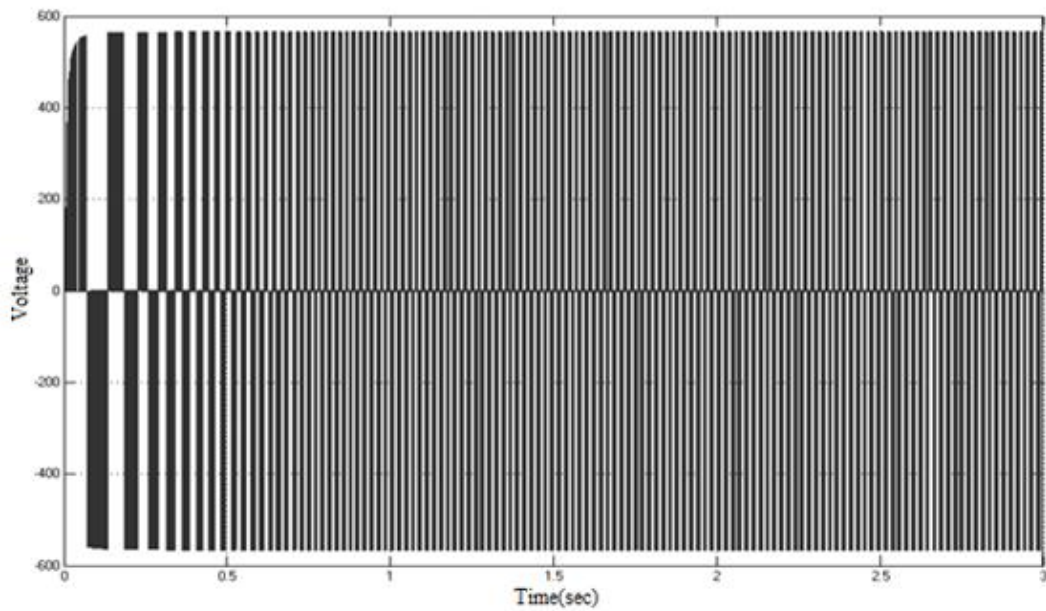
Figure 4.7: Output from Inverter Vab.max

Next figure shows the response of the system without PI controller :
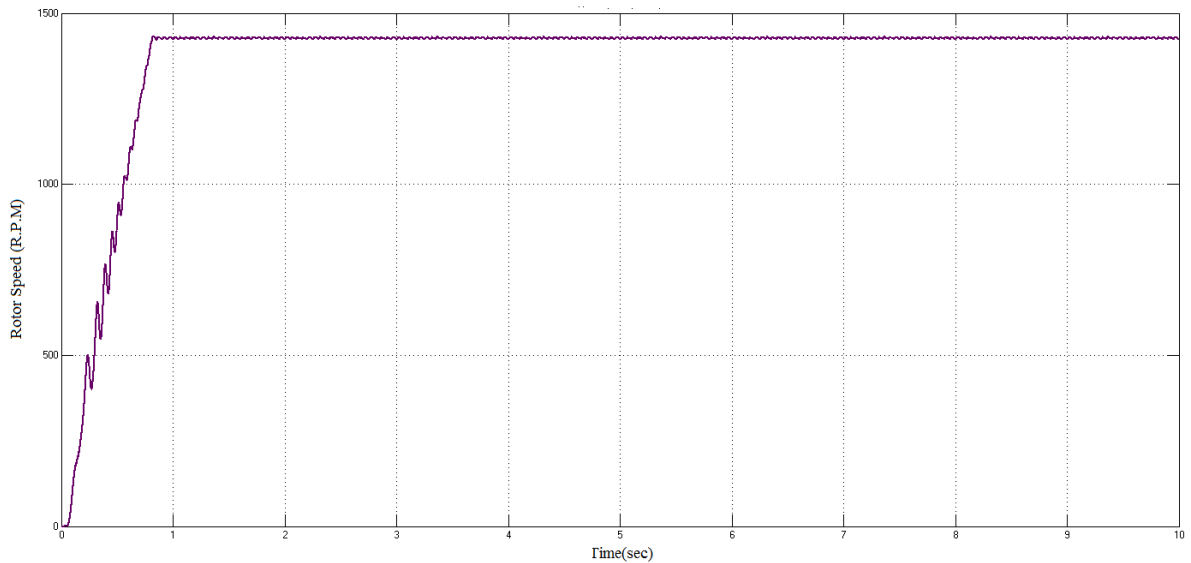
figure 4.8: The response without controller

4.4.1 First method:

After all components are connected in the plant and the parameters is selected, it is time to find the k_i and k_p constant to make the plant response without errors and without ripple in the speed. The constant of k_p and k_i changed by seeing the response: if it not satisfactory the previous step will repeated until the response been satisfactory, and the value we select is (k_p=9, k_i=10).

Three reference speeds (full speed, 900,700) selected to see rotor speed response, and the next figures depended on this speed reference.

First figure (4.9) shows speed in full speed reference (1467) and torque in that speed is shown in figure (4.10).
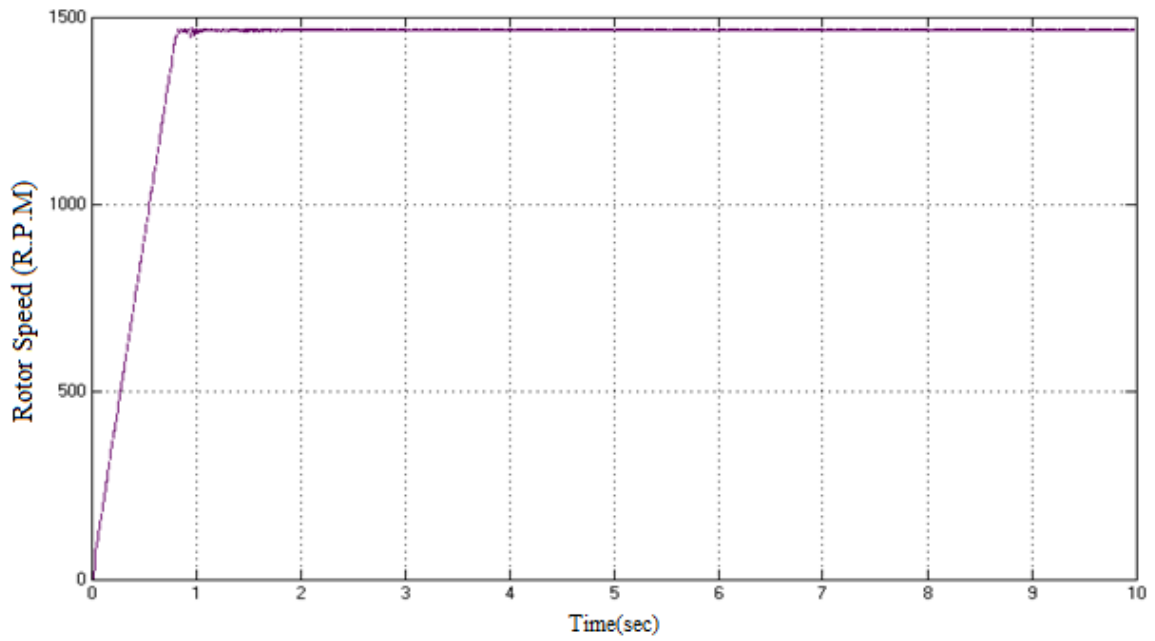
Figure 4.9: Rotor speed in full speed R.P.M (1467)
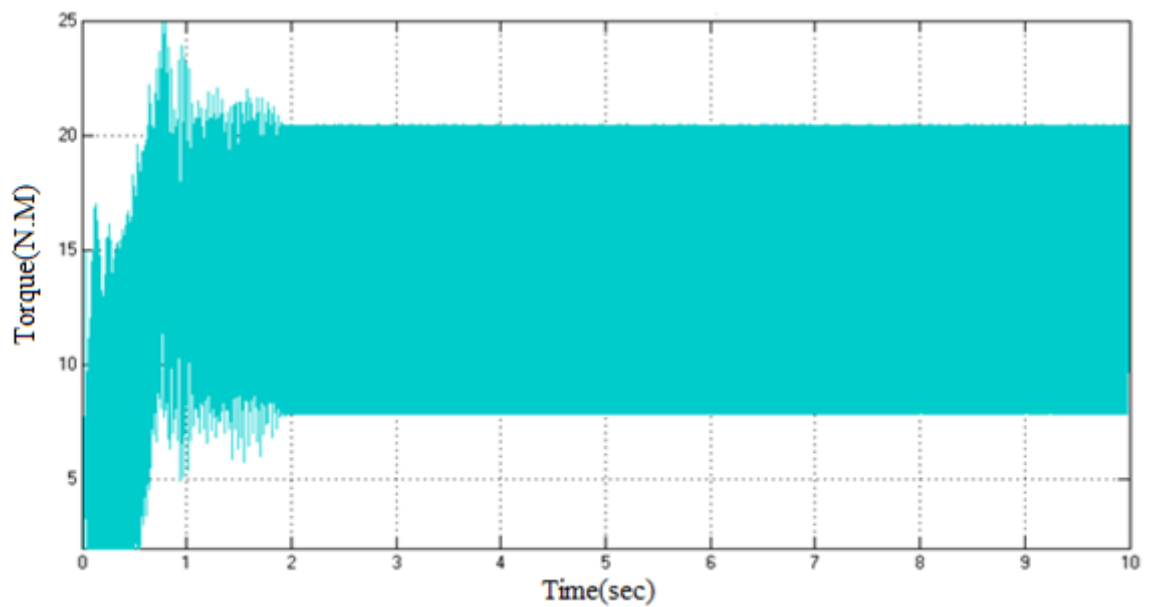
Figure 4.10: torque in full speed (1467) (N*m)

Our motor has rated speed (1500) in (420V, 50Hz), to make the Vrms and frequency be less than (420V, 50Hz) Saturation should be placed, but the actual full speed "figure (4.9)"is (1467) that is because we have slip in induction motor. We calculate the slip in next eq(4.9)

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$$slip = \frac{rated\ speed - actual\ speed}{rated\ speed} = \frac{1500 - 1467}{1500} = 0.022 \qquad (4.9)$$

The slip in rated voltage and frequency is 0.022, the slip depends on the load on rotor so then a decrease on load happen followed by decrease on slip , that meant then the load on rotor be close to zero the speed will be close to actual speed.

Second figure (4.11) shows speed in speed reference (900) and torque in that speed is shown in figure (4.12).
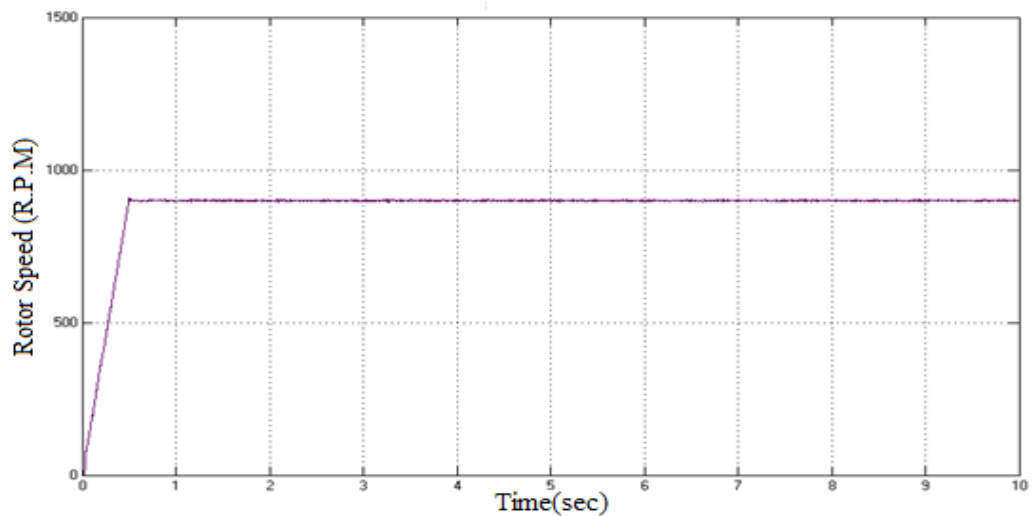
Figure 4.11: Rotor speed in speed R.P.M (900)
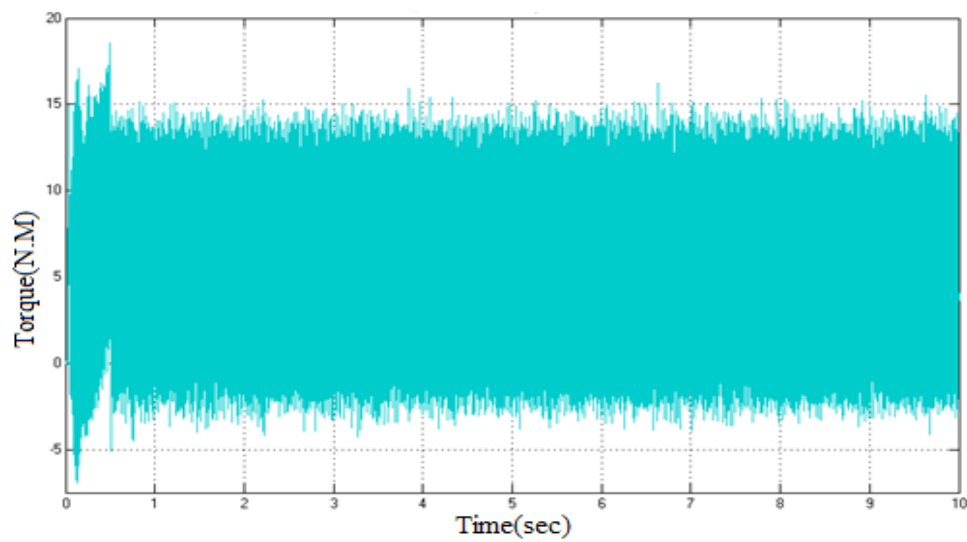
Figure 4.12: torque in speed (900) (N*m)

In that speed (900) the error is large to be seen in large scale "figure (4.11)" and the torque decreases compared to that in full speed case.

Third speed (700) is shown in figure (4.13) while torque in that speed is shown in figure (4.14).
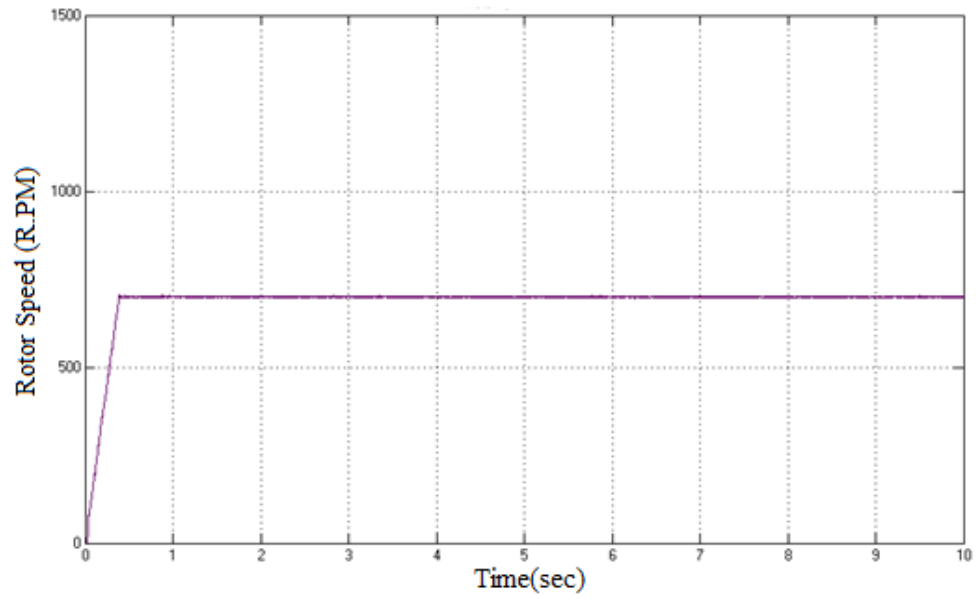
Figure 4.13: Rotor speed in speed R.P.M (700)
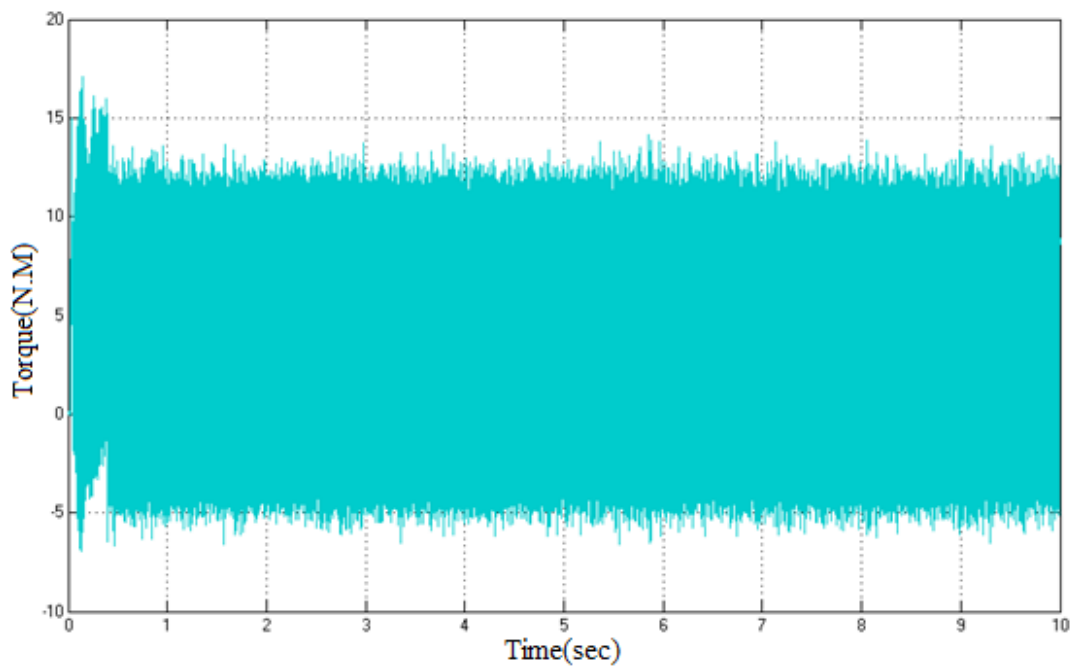
Figure 4.14 torque in speed (700) (N*m)

the errors in figure (4.13) speed (700) but they look like the errors in speed (900) this means the feedback control side is very good to try make actual speed equal to the reference speed but that means the value of k_i and k_p should be changed to another value to decrease the errors.

In order to show the performance and the robustness of this technique, next figure(4.15) shows the compression between the response of the system with PI controller and without PI controller in rated speed of the motor:
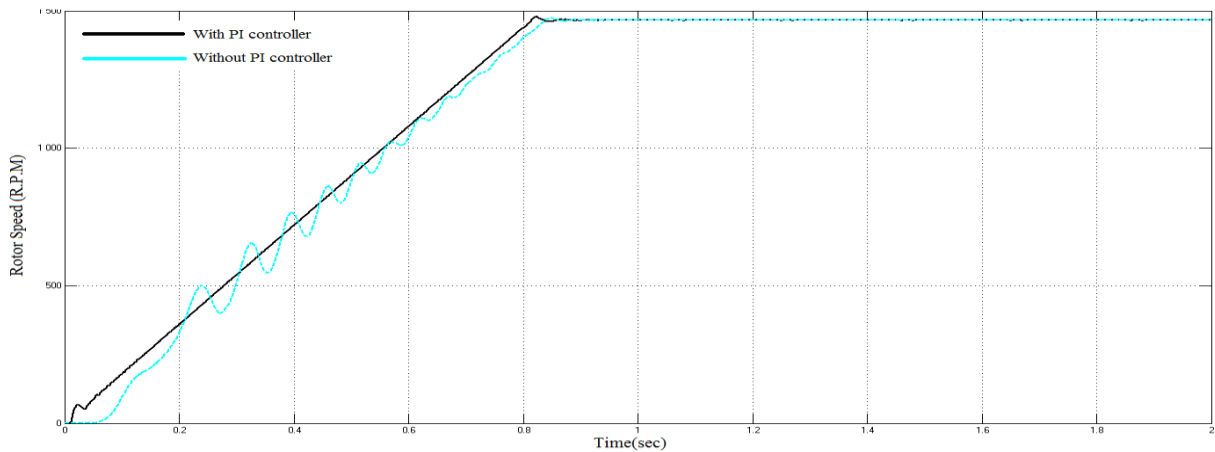
figure 4.15: The response with PI controller (first method) and without PI controller

4.4.2 Second method:

 The value selected in operation through calculation of PI controller gave the parameter (k_p=56.54 , k_i=4441.3) and this method also perform reference speed that used in the first method (full speed, 900,700) to see rotor speed response. and also perform changing on the load and take two loads (no load, half load) to test with it the speed reference.

 Next figure (4.16) shows speed in full speed reference (1467) and torque in that speed is shown in figure (4.17).
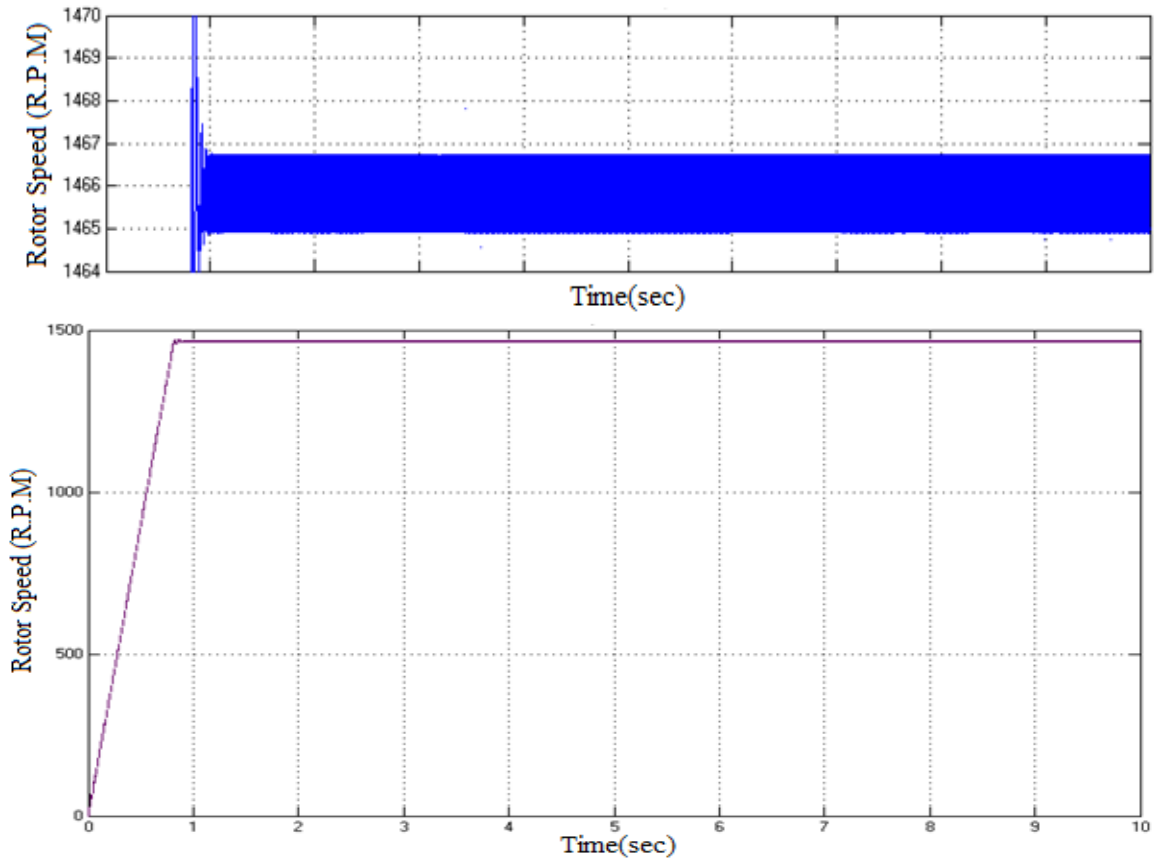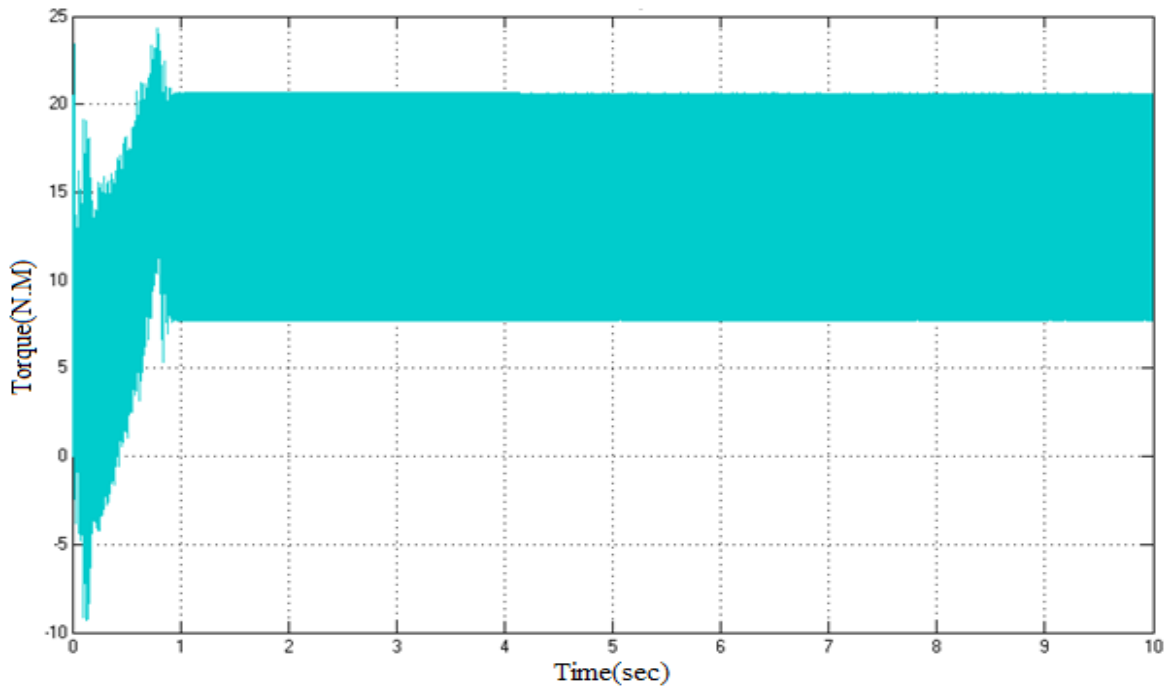
Figure 4.16: Rotor speed (1466) R.P.M

Figure 4.17: torque in full speed (1466) (N*m)

By the second method of tuning, clear the oscillation in the speed and adjust system to actual value and make the error nearer to zero. The error in full speed equals ±0.00068 and the rise time is same as that in the first method because the reference speed in to control side intervention as ramp function to reduce starting current thus leading to decrease starting torque .

Next figure (4.18) shows speed (900 R.P.M) and torque in that speed is shown in figure (4.19).
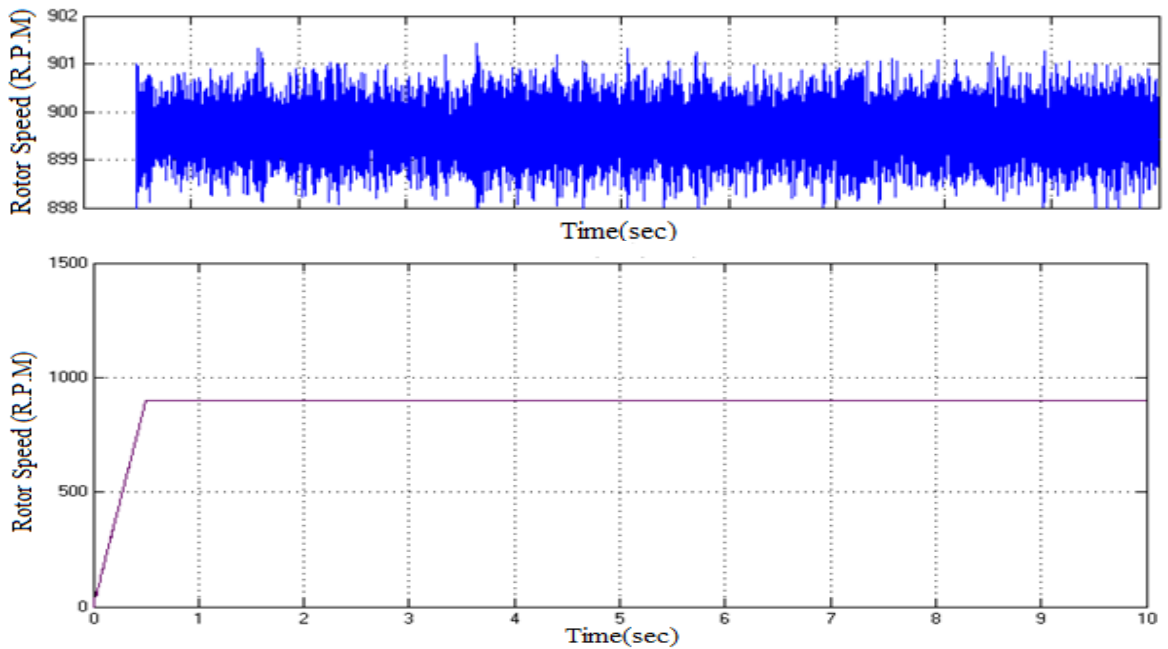
Figure 4.18: Rotor speed in speed R.P.M (900)
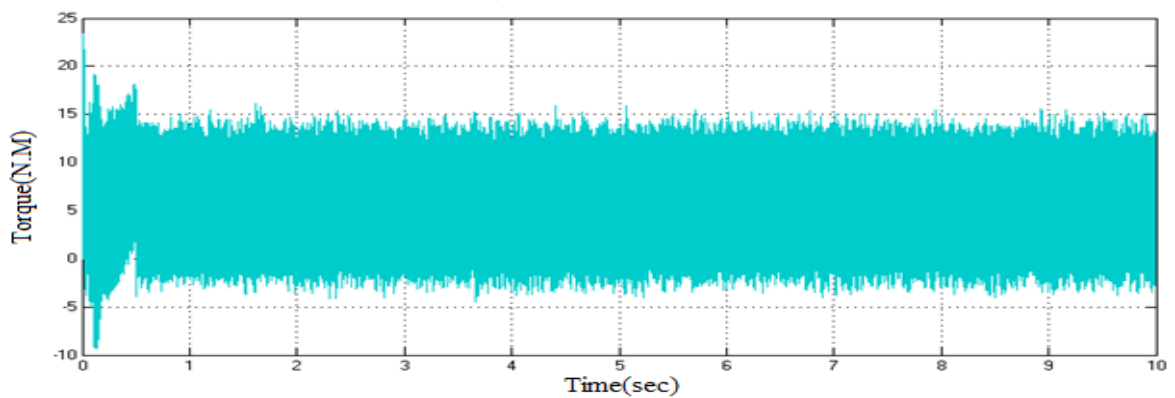
Figure 4.19: torque in speed (900) (N*m)

Next figure (4.20) shows speed (700 R.P.M) and torque in that speed is shown in figure (4.21).
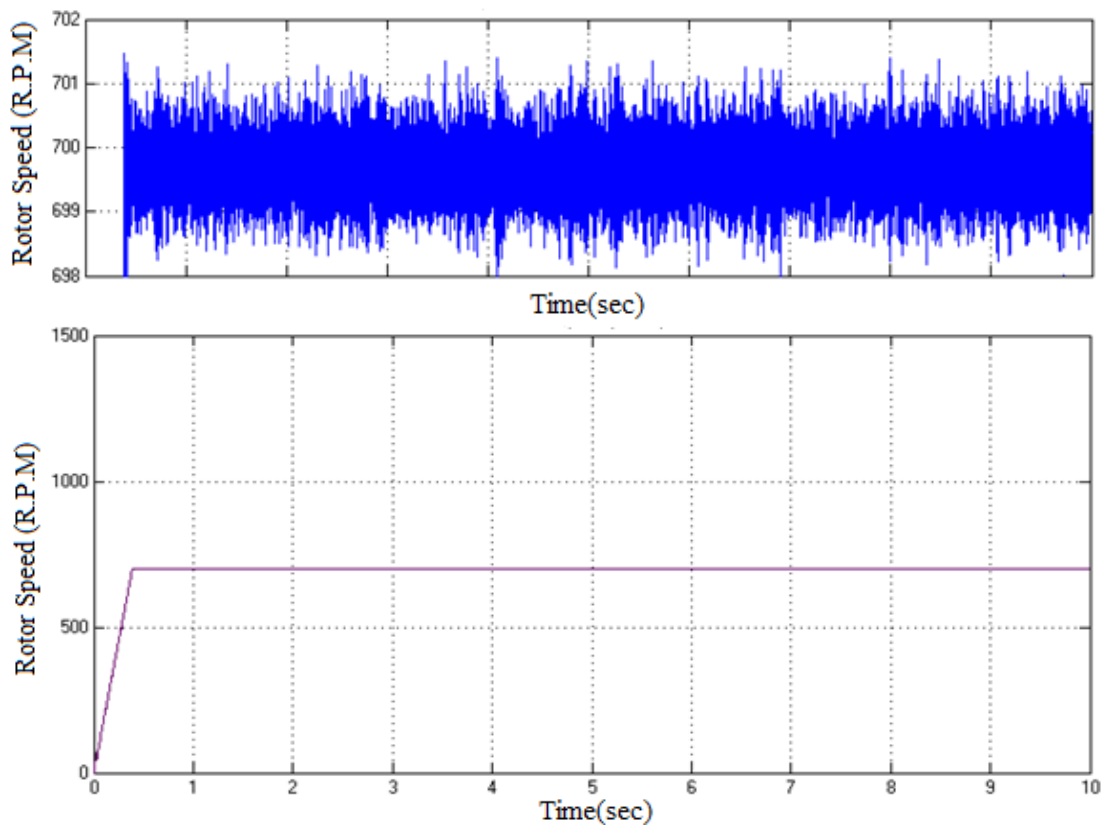

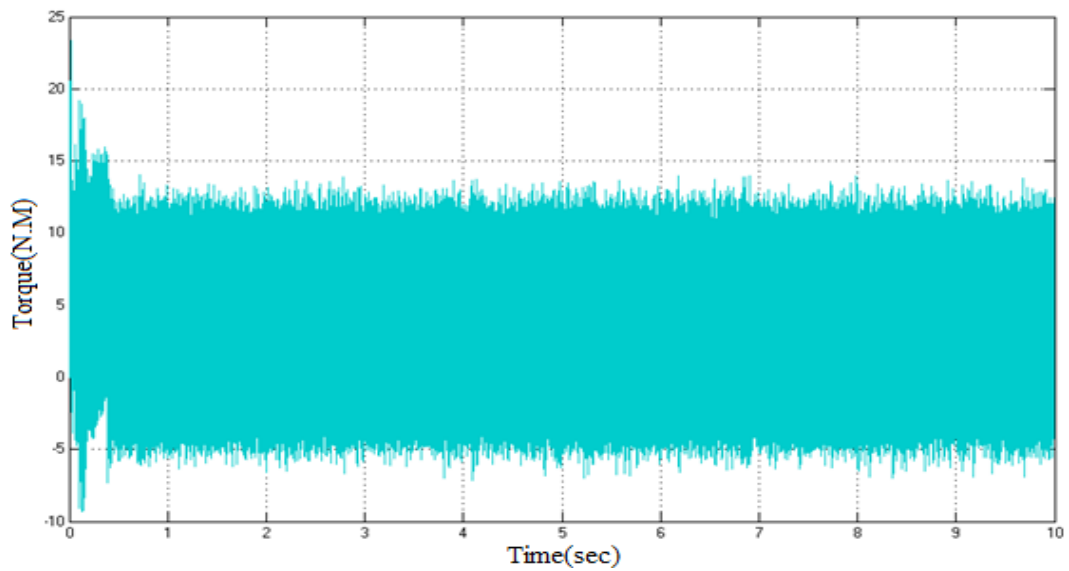Figure 4.20: Rotor speed in speed R.P.M (700)

Figure 4.21: torque in speed (700) (N*m)

In the (900,700) speed figures the actual speed just increases or decreases in range 1.5 Rpm maximum.

Change the value in load and take (no load, half load) to see the effect of the variable load on speed and torque:

Run the motor at (no load) and see the effect on the three speeds and torque.

Operating speed 1498 R.P.M at no load is illustrated in the next figure(4.22):
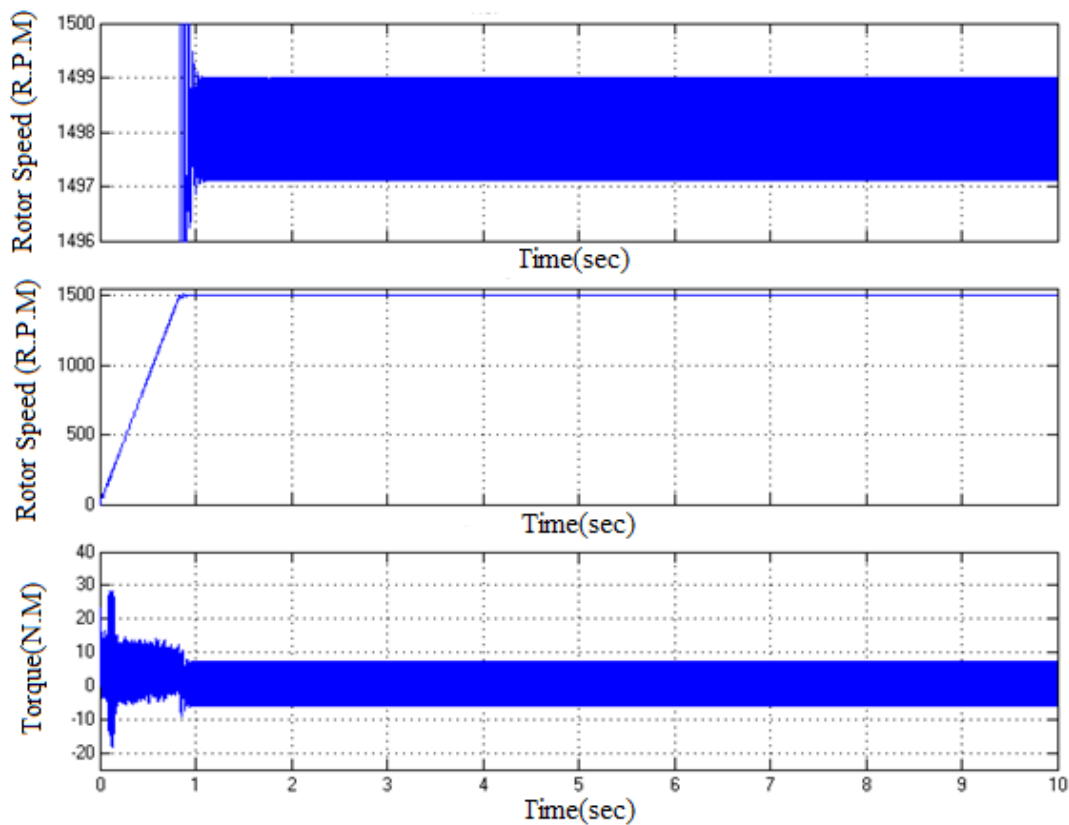

Figure 4.22: full speed and torque in no-load

We can see the full speed change from 1466 to 1498 with decreasing in load from full-load to no-load that because the slip changes to 0.0013.

$$slip = \frac{rated\ speed - actual\ speed}{rated\ speed} = \frac{1500 - 1498}{1500} = 0.0013 \qquad (4.10)$$

Operating the speed in (900,700) Rpm at no load is shown in figure (4.23) and figure (4.24) respectively.
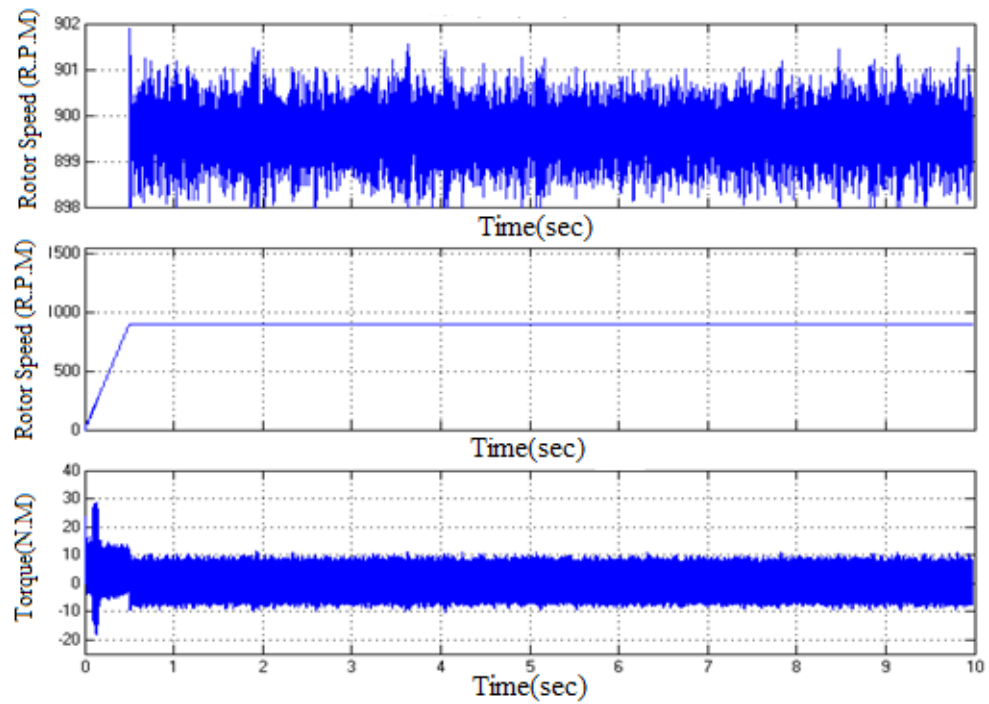

Figure 4.23: Speed in 900 Rpm speed and torque in no-load
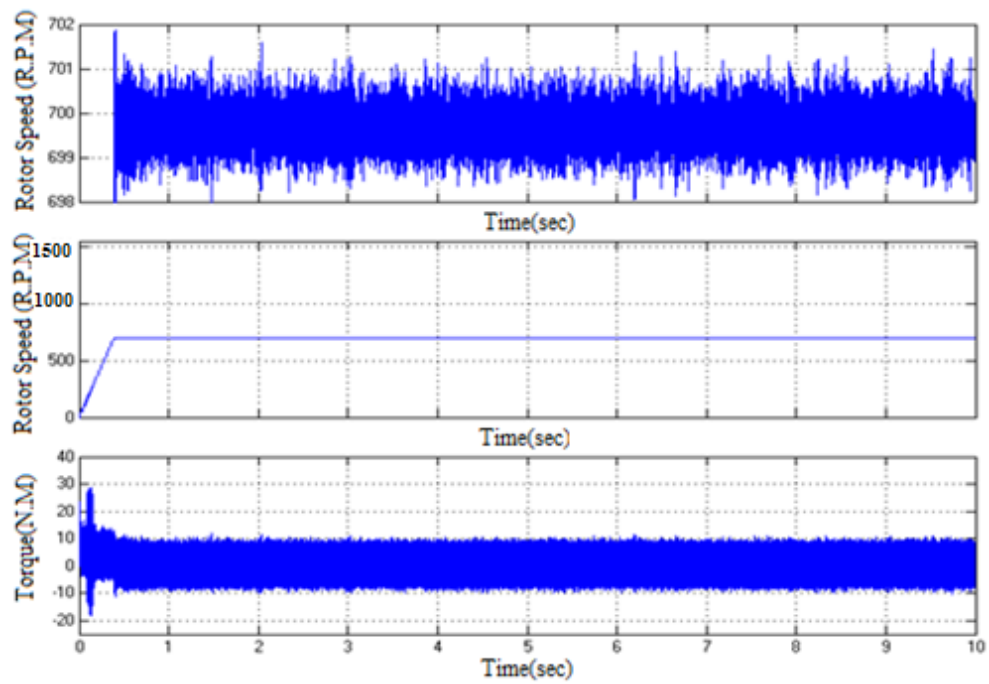

Figure 4.24 : Speed in 700 Rpm speed and torque in no-load

From figure (4.23) and figure (4.24) note that the speed is similar to speed in full load before stability and the only difference is in the torque.

After tested the rotor speed in full load and no-load the motor started at half to test his effect on previous three speeds and their torque and also the new value of full speed appeared.

Figure (4.25) shows new full speed when we run our motor in half load .
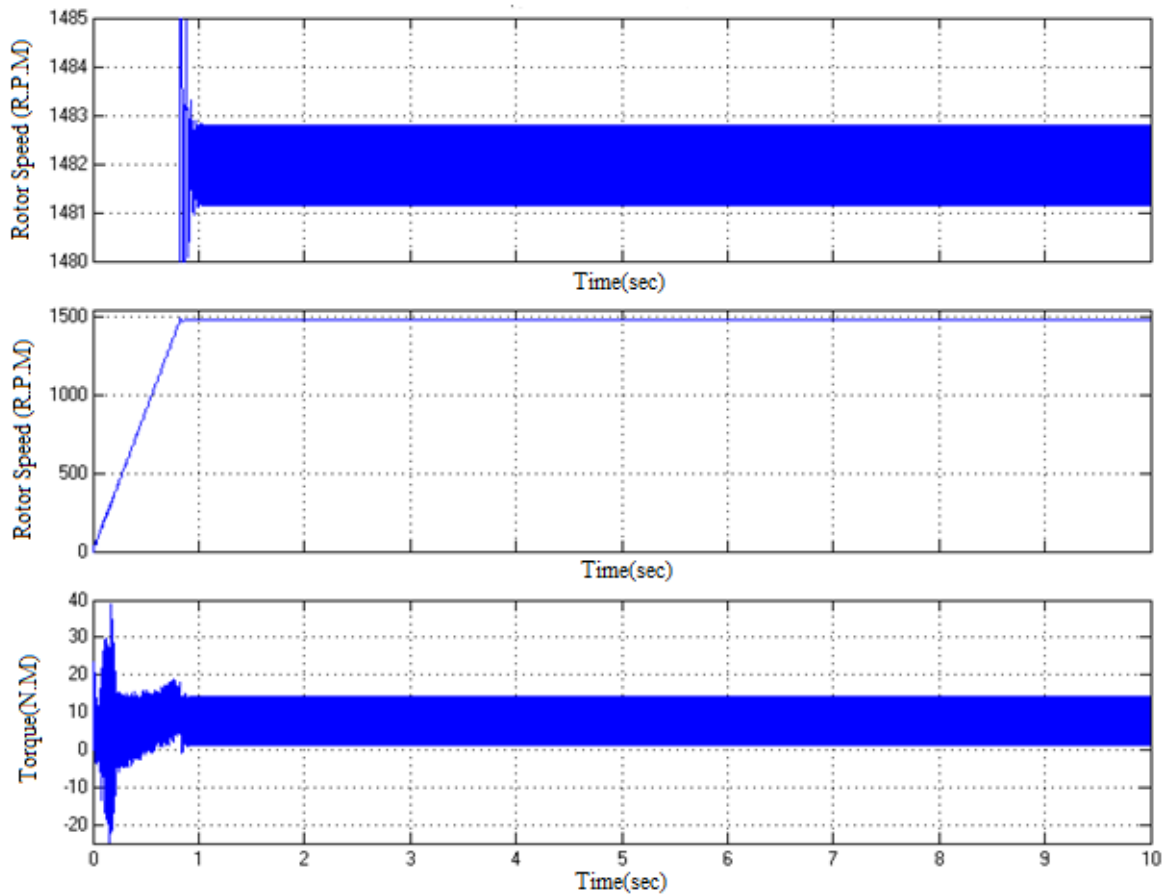

Figure 4.25: full speed in 1482 Rpm and torque in half load

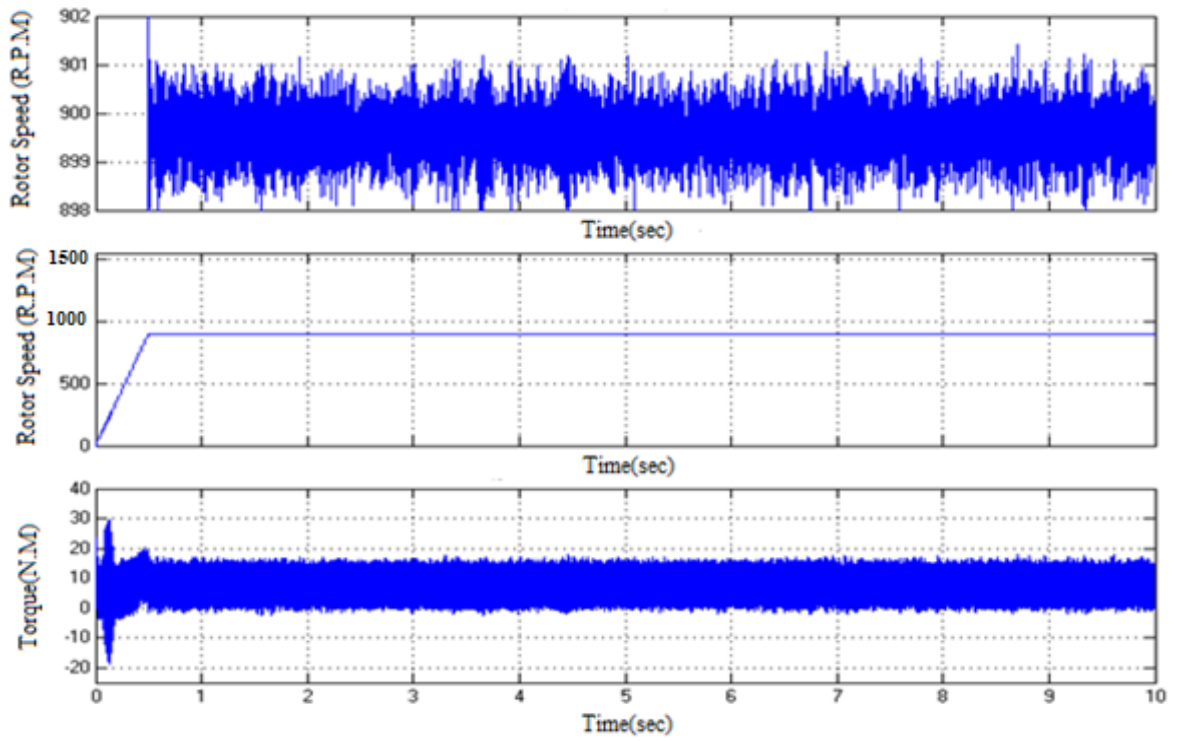Operating the speed in (900,700) Rpm at no load is shown in figure (4.26) and figure (4.27) respectively.

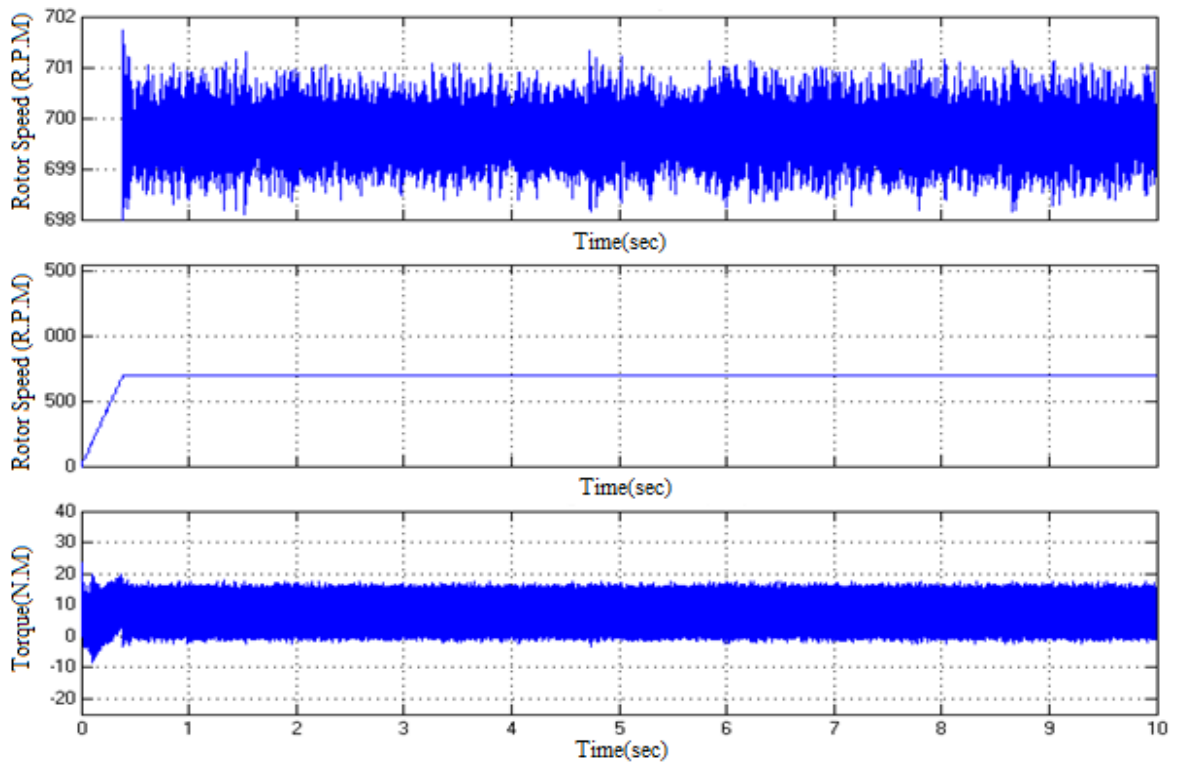Figure 4.26: Rotor speed in 900 Rpm and torque in half load

Figure 4.27: Rotor speed in 700 Rpm and torque in half load

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From figure (4.26) and figure (4.27) note that speed is similar to speed in full load before stability and the only difference is in the torque.

In order to show the performance and the robustness of this technique, next figure(4.28) shows the compression between the response of the system with PI controller and without PI controller in rated speed of the motor:
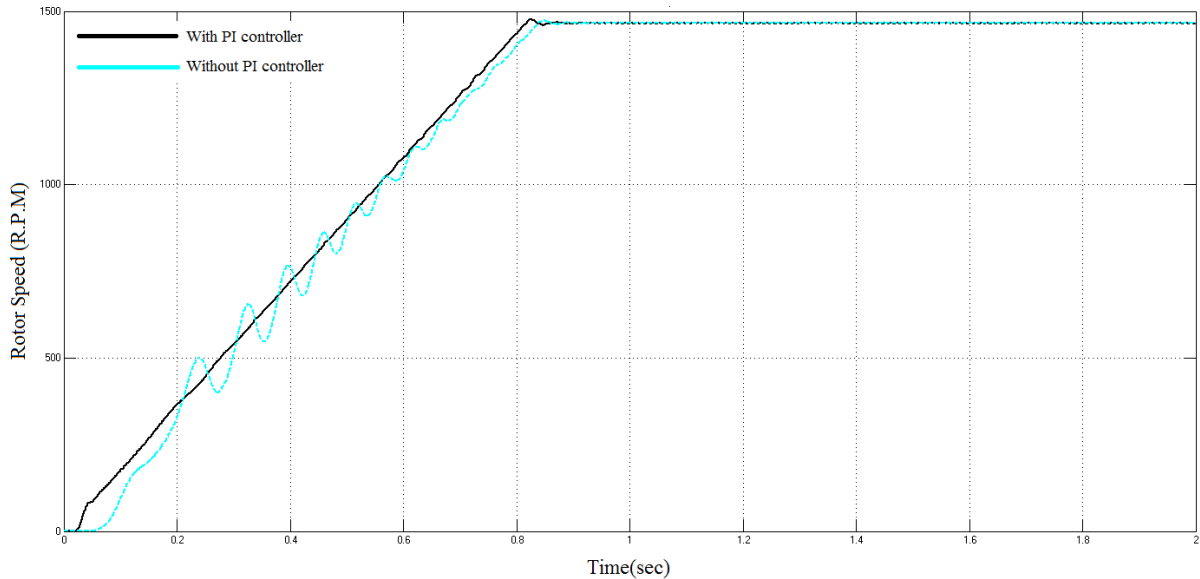

figure 4.28: The response with PI controller (second method) and without PI controller

From the previous figures for three speeds and their torques in the second method found that the rotor speed increases and decreases in range 1.5Rpm unless the motor had enough voltage to start it and that range increase in bad starting condition , and from that conclude that the errors are so small and not exceeding 0,1%. Also found that the electrical torque have harmonic produced by harmonic in the output voltage from inverter, but impact does not represent a problem because practically the oscillation in torque is cleared by the moment of inertia. The rise time for any speed can be calculated in equation (4.10) because in the design takes $557.97*10^{-6}$sec for any 1Rpm.

$$rise\ time\ (speed) = speed * 557.97 * 10^{-6} \qquad (4.10)$$

Also note that the overshoot for any speed does not exceed 0.01.

CHAPTER FIVE

CONCLUION AND RECOMMENDATIONS

5.1 Conclusion:

In this project a technique was used for control of induction motor by controlling in voltage and frequency in the same time by the PWM technique. In order to get torque proportional to speed V/f ratio was used constant in all speed and use feedback control and insert PI controller to improve the response of the system and clear the error and oscillation. The effectiveness of the proposed technique was confirmed through MATLAB/SIMULINK simulation results in different induction motor operating conditions. Simulation results show good performance of the control of the induction motor drive at high and low speeds and can start at any speed. In addition to, the simulation results show the robustness of the proposed algorithm of control of the induction motor by use the V/f ratio and PI controller .

5.2 Recommendations :

Lastly we recommended by :

- Make the technique used in this project through simulation a practical method and try to provide the required tools for doing this.
- Implement a low pass filter for the output from the pulse width modulation (PWM).
- Make the parameter of controller variable by using Artificial Intelligent control and find the optimal control in any speed.

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