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Presented by: ALI ZAIDI

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Study and Simulation of a Variable Speed Drive of a Three-Phase Asynchronous Motor

In front of the jury composed of:

Pr. BENYATTOU Loutfi	Université Mohamed Boudiaf M'sila	Président
Dr. ZOUGGAR El Oualid	Université Mohamed Boudiaf M'sila	Rapporteur
Pr. ROUABHI Riyadh	Université Mohamed Boudiaf M'sila	Examinateur
Pr. KHODJA Djalel Eddine	Université Mohamed Boudiaf M'sila	Examinateur

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I dedicate this thesis

To my parents, may Allah the almighty god protect them.

To my sister, the Engineer Chaima Zaidi

To my dear brothers Mr Zakaria and Mr Abdulraouf

To My colleagues "Mohammed", "Bilal","

To all those who knew me and contributed to my support

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GENERAL INTRODUCTION 1
1. CHAPTER ONE : ASYNCHRONOUS MACHINE 3
1.1. Introduction 4
1.2. Definition: 4
1.3. Construction of the asynchronous machine: 4
1.3.1. Stator: 4
1.3.2. Rotor: 5
1.3.3. Bearings 5
1.3.4. Shaft: 5
1.3.5. End Covers: 5
1.3.6. Cooling system: 6
1.4. Star, delta, and star-delta connection: 6
1.5. General Operating Principle of an Asynchronous Machine: 7
1.5.1. Basic Components of an Induction Motor: 7
1.5.2. Operation of an Asynchronous Machine: 7
The functioning of a three-phase asynchronous motor or induction motor is based on the principle of induction. Here is what it consists: 7
I.5.2.1. Generation of the Rotating Magnetic Field: 7
1.5.2.2. Electromagnetic induction in the rotor: 8
1.5.3. The energy balance and formulas for an asynchronous motor: 9
1.5.3.1. Power consumption Pin: 10
1.5.3.2. Stator copper losses PCUS: 10
1.5.3.3. Rotor copper losses PCUR : 10

1.5.3.4. Core losses Pcore: 10

1.5.3.5. Air-Gap Power Pag: 11

1.5.3.6. Mechanical Power Pmech: 11

1.5.3.7. Friction and Windage Losses Pp: 11

1.5.3.8. Additional losses Pstray: 12

1.5.3.9. Delivered power Pout : 12

1.5.3.10. Efficiency η : 12

1.6. Modeling of the induction machine: 13

1.6.1. Simplifying assumptions: 13

1.6.2. Modeling the induction motor in the three-phase: 13

1.7. Advantages and disadvantages of induction motors: 16

1.8. Conclusion : 17

2. CHAPTER TWO : VARIABLE SPEED-DRIVE 18

2.1. Introduction: 19

2.2. The benefits of variable speed control: 19

2.3. The main functions of electronic speed drives: 19

2.4. Construction of a variable speed drive: 20

2.5. Power circuit: 20

2.5.1. Rectifier: 20

2.5.1.1. Diode rectifiers (uncontrolled rectifiers): 21

2.5.2. Filter : 23

2.5.3. The three-phase PWM voltage inverter: 24

2.6. Transistor IGBT: 26

2.7. Control topologies for an induction machine: 26

2.7.1. Scalar control (The v/f= constant algorithm): 26
2.7.2. Vector control: 27
2.8. Analogies and relationships between vector control and scalar control: 27
2.9. Inverter types for asynchronous machines: 28
2.9.1. Action on the number of pole pairs: 29
2.9.2. Action on slip: 29
2.9.3. Action on frequency: 30
2.10. Studying the torque: 30
2.11. Frequency converter for induction motors: 31
2.12. Conclusion: 32
3. CHAPTER THREE : STUDY & SIMULATING 34
3.1. Introduction 35
3.2. How it works: 35
3.3. Asynchronous machine parameters : 35
3.4. Block diagram : 37
3.5. Electric Circuit Diagram: 38
3.6. Control Part: 39
3.6.1. Arduino : 39
3.6.2. Driver IR2112: 40
3.7. Power part : 42
3.7.1. IGBT (IRG4PC50UD) : 42
3.7.2. THE INVERTER : 43
3.8. Software Part: 44
3.8.1. Simulation diagram: 44

3.8.2. PWM program flow chart : 45

3.9. PCB Diagram (EasyEDA): 47

3.10. Simulation signals on Proteus: 49

3.11. Conclusion : 50

GENERAL CONCLUSION 52

BIBLIOGRAPHIE 53

TABLE OF FIGURES

CHAPTER ONE : ASYNCHRONOUS MACHINE

Figure 1- 1: exploded view of an asynchronous motor 6
Figure 1- 2: shows the difference between the star and delta connection 7
Figure 1- 3: Simplified two-pole three-phase stator winding 8
Figure 1- 4: The right-hand rule for the electric field's direction 9
Figure 1- 5: Power-flow diagram of asynchronous motor 9
Figure 1- 6: Representation of the asynchronous motor 14

CHAPTER TWO : VARIABLE SPEED DRIVE

Figure 2- 1: Variable speed drive (VFD) 19
Figure 2- 2: Variable speed drive power circuit 20
Figure 2- 3: Three-phase rectifier 21
Figure 2- 4: Three-phase input voltage 22
Figure 2- 5: Three-phase output voltage 22
Figure 2- 6: Filter structure 23
Figure 2- 7: The three-phase inverter 25
Figure 2- 8: Three-phase inverter in MATLAB/SIMULINK 25
Figure 2- 9: Three-phase PWM inverter Signals in MATLAB/SIMULINK 25
Figure 2- 10:Voltage and frequency variation 27
Figure 2- 11: Diagram of the decoupling principle for MAS by analogy with MCC 27
Figure 2- 12: Torque versus speed diagram 28
Figure 2- 13: Induction motor Torque-speed characteristics 30
Figure 2- 14: Linear variation of motor voltage with frequency variation 31

TABLE OF FIGURES

CHAPTER THREE: STUDY & SIMULATION

Figure 3- 1: Block diagram for the simulation 10
*Figure 2- 2: Electrical diagram of variable speed drive for three-phase asynchronous motor from EasyEDA ……………..**Error! Bookmark not defined.***
Figure 3- 3: Arduino Mega 2560 .... ***Error! Bookmark not defined.***
Figure 3- 4: Typical connection of IR2112 .... ***Error! Bookmark not defined.***
Figure 3- 5: 3 IR2112 Drivers with bootstraps "From Proteus" 40
Figure 3- 6: IRG4PC50UD Part 41
Figure 3- 7: Diagram of The Inverter from PROTEUS 42
Figure 3- 8: Diagram of simulation from Proteus 43
Figure 3- 9: PWM Program flow chart 41
Figure 3- 10: 2D PCB Diagram 42
Figure 3- 11: 3D PCB Diagram 42
Figure 3- 12: PWM Out the Arduino 43
Figure 3- 13: PWM Out the Arduino 43
Figure 3- 14: Three-Phase signals on the rectifier 44

NOTATIONS AND SYMBOLES

AC: Alternating current.

DC: Direct current.

VFD: Variable frequency drive, or Variable speed drive(VSD).

PWM: Pulse width modulation.

IGBT: insulated gate bipolar transistors.

FOC: Field-oriented control.

IRFOC: Indirect Rotor field-oriented control.

SC: Speed control.

n_s: Synchronous speed (in revolutions per minute, rpm).

$f =$ Frequency of the AC supply (in Hz).

$p =$ Number of pole pairs in the stator winding.

$n_r =$ is the Rotor Speed.

S = Represent the slip of the asynchronous(induction)*machine*.

P_{in} = input power to the motor (in watts, W).

V = Line to line voltage (in Volts, V).

I = Line current (in Amperes, A).

ω = angulair velocity (used in motor controlling speed).

$cos\phi$ = Power factor of the Motor.

$P_{js} =$ *for Stator copper losses* (*in watts*, W).

$R_s =$ *for Resistance of the stator windings per phase* (*in ohms*, Ω).

$I_s =$ *for Stator current* (*in Amperes*, A).

$P_{jr} =$ *for Rotor copper losses* (*in watts*, W).

$R_r =$ *for Resistance of the rotor* (*in ohms*, Ω).

$I_r =$ *for rotor current* (*in Amperes*, A).

$P_{\text{hysteresis}}$” described in the formula by : $f \,.\, B^n$.

"P_{eddy}" described in the formula by ; $f^2.B^2$.

$B = Magnetic\ flux.$

$P_{ag} = power\ in\ the\ air\ gap\ ,and\ includes\ mechanical\ power\ and\ rotor\ copper\ losses.$

$P_{stator\ losses} = Total\ stator\ losses\ (P_{js} + P_{core}).$

$P_{mech} = power\ available\ at\ the\ rotor\ shaft.$

P_{friction}: in moving parts like endure.

P_{windage}: to windage losses.

κ = stray loss factor.

P_{in} = input electrical power (in watts, W).

$P_{losses} = its\ the\ total\ of\ all\ losses\ in\ the\ motor.$

$T = the\ Torque$

P_{out} = is the delivered power or the mechanical output power .

P_{in} = electical input power.

V_{sa}, V_{sb}, V_{sc}: Stresses applied to the three stator phases

i_{sa}, i_{sb}, i_{sc}: Currents that pass through the three stator phases.

$\Phi_{sa}, \Phi_{sb}, \Phi_{sc}$: Total flow through these windings.

V_{ra}, V_{rb}, V_{rc}: Rotor voltages.

i_{ra}, i_{rb}, i_{rc}: Rotor currents.

$\Phi_{ra}, \Phi_{rb}, \Phi_{rc}$: Rotor flux.

R_s: Resistance of a stator phase.

R_r: Resistance of a rotor phase.

$Te = Electromagnetic\ torque.$

$T_l = Load\ torque.$

SCR: Silicon-controlled Rectifier.

$L_f = inductance.$

NOTATIONS AND SYMBOLES

V_a, V_b, V_c: $simple\ voltages\ delivered\ by\ the\ inverter.$

U_{ab}, U_{bc}, U_{ca}: $the\ inverter's\ composite\ voltages.$

GENERAL INTRODUTION

GENERAL INTRODUCTION

Electric motors are the backbone of contemporary industry. Among electric motors, three-phase asynchronous motors (also known as induction motors) are the most popular type of motors used in industry, their popularity is due to their simplicity of construction and operation, their long life and low cost, as well as ease of maintenance in comparison with DC motors which were historically dominant in variable speed applications.

An asynchronous motor operates by electromagnetic induction: an alternating current in the stator winding creates a rotating magnetic field that induces a current in the rotor, causing a torque that starts it turning. The speed of rotation is slightly less than the speed of the magnetic field (the slip principle).

Although asynchronous motors have many advantages, their most prominent constraint is their inherent nearly constant speed characteristic. This makes them unsuitable for high-performance applications where precise, continuous speed variation is required. Traditionally, this domain was the exclusive realm of DC motors due to their simpler speed and torque control. However, with the rapid development of power electronics and advanced control techniques, effective solutions have been found to overcome this limitation in AC motors, the most prominent of which is the Variable Speed Drive (VSD).

VSDs, often implemented as Variable Frequency Drives (VFDs), enable the precise control of the speed of asynchronous motors by varying the frequency and voltage of the electrical source from which they are supplied. This technology provides vast opportunities for improving the efficiency of industrial processes, achieving significant energy savings, and implementing advanced functions such as soft starting, regenerative braking, and precise rotation reversal.

The purpose and objective of this project is to study and simulate a Variable Speed Drive (VFD) system for controlling the speed of a three-phase asynchronous motor. This work will cover the theoretical background of the operation of asynchronous motors, then study the variable speed drive system, and finally design and simulate an applicable control circuit. [2]

To achieve the above goal, the following three chapters have been considered for this topic:

- Chapter I: Theoretical Basis of the Asynchronous Motor. This chapter introduces asynchronous motors and reviews their working principle, structure, equivalent circuit, and basic characteristics.
- Chapter II: Study of Variable Speed Drives (VFDs). This chapter deals with the VFD system, where its different parts will be studied, from the rectifier circuit to the inverter, as well as various control strategies. Special focus will be given to the Voltage/Frequency (V/f) control strategy using Pulse Width Modulation (PWM).
- Chapter III: System Design and Simulation. This chapter deals with the practical side, where the complete circuit of the system will be designed and simulated using the appropriate software "Proteus", and the controller will be implemented and programmed using Arduino IDE platform.

At the end of this work, I hope to present a satisfactory design, and that this study will be the basis for further exploration in the field of high-performance control of induction motors.

1. CHAPTER ONE : ASYNCHRONOUS MACHINE

1.1. Introduction

Asynchronous motor, also known as induction motor is a type of alternating current electric motor which runs at a speed that is less than the magnetic field stator's synchronous speed. The rotor in an asynchronous engine does not follow directly from the rotating current in the stator; instead, it turns because of electromagnetic induction that takes place in relation with a magnetic field which is produced also by the stator.

In this type of motor, the principle behind its operation is the electromagnetic induction; this is with reference to the alternating current field that is supplied to the stator windings thereby producing a revolving magnetic field. As a result of this field, an induced current is produced in the rotor which interacts with the initial field to produce torque. It has also been noted that the rotor turns slightly slower than the synchronous rotor with a difference between their speeds referred to as slip which enables the motor to produce torque.[1]

1.2. Definition:

An asynchronous motor is one that runs at speeds a little below the synchronous ones. The difference between the speed of operation and synchronous speed is referred to as slip.

The slip for an asynchronous motor increase with increasing load. While the three-phase induction motors are arguably the most widespread type of three-phase motors globally, there are many categories of asynchronous motors.[3]

1.3. Construction of the asynchronous machine:

An asynchronous motor or induction motor is made up of various important parts that aid in its operation. Below is a short description:

1.3.1. Stator:

This is the stationary part of the motor. It is made up of laminated steel sheets to lower eddy current losses. It comprises of:

Winding: Copper or aluminum coils places at the stator slots. On supplying Alternating Current (AC) the stator winding produces rotating magnetic field.

Core: The stator core is mostly composed of silicon steel and it serves the purpose of holding the windings as well as providing a path for the flow of the magnetic flux arising from the same.

1.3.2. Rotor:

The rotor is the rotating part of the engine and there are two types:

Squirrel Cage: This is the most common type of rotor in induction motors. It contains conducting bars shorted at both ends by conducting rings. It forms a closed circuit, and when the rotating magnetic field of the stator induces a current in the rotor, it creates a magnetic field that starts to rotate the rotor.

Wound Rotor: This rotor replaces the bars of the squirrel cage rotor with wound coils. These are then connected to an external resistor or slip ring arrangement. This type is used in applications where better starting torque or speed control is required.

1.3.3. Bearings

Bearings are used to support the rotor and provide free rotation. They are fitted at the ends of the rotor shaft.

1.3.4. Shaft:

The shaft is linked to the rotor and transmits mechanical power from the motor to the load to which the blower is fitted. It must be of sufficient strength to sustain the mechanical stress induced by the functioning of the engine.

1.3.5. End Covers:

These are the covers on both ends of the stator. They enclose the engine components, shielding them from any external influences. At the same time, they create the possibility of mounting the engine to some supporting structure.

1.3.6. Cooling system:

Induction motors are generally cooled by air or water. Good cooling keeps the engine from getting too hot and running inefficiently.

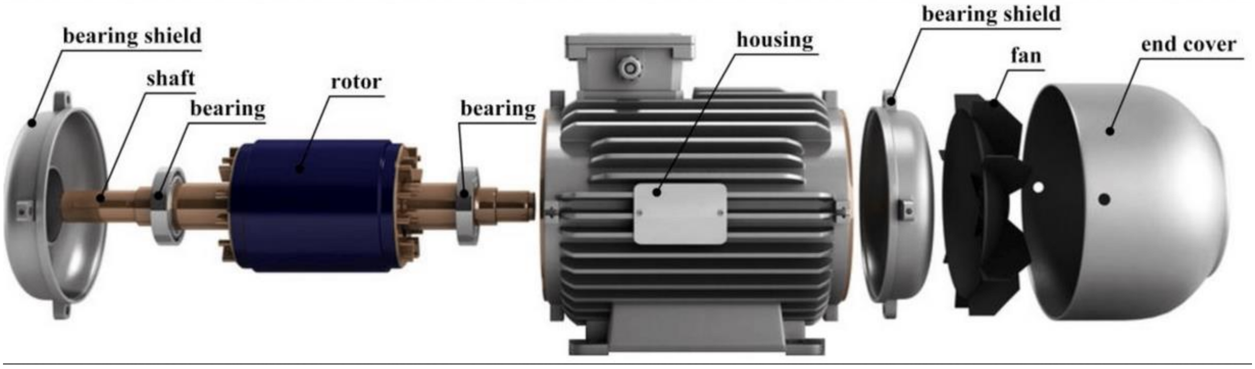

Figure 1- 1: exploded view of an asynchronous motor

1.4. Star, delta, and star-delta connection:

There are two ways to connect the motor to the three-phase electrical grid.

Star connection and delta connection. With a star connection, the voltage at the terminals of each coil is the individual voltage.

The voltage at the terminals of each coil is the individual voltage (e.g. 230V for a 400V).

In a delta connection, each of the coils is supplied with a nominal mains voltage (e.g. 400V). A star connection is used if a 230V motor must be connected to connected to 400 V mains supply or to start the motor at low power in case of a load with high mechanical inertia.

This method first switches the star motors on to minimize starting current and torque then changes to delta for full power when the motor approaches its rated speed. This is very effective in applications requiring high powers with high inertia, like large compressors and conveyors, where a soft start becomes essential to avoid mechanical and electrical stress.

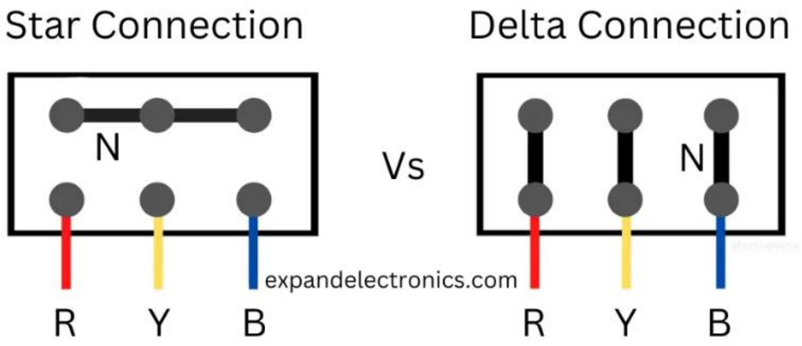

Figure 1- 2: shows the difference between the star and delta connection

1.5. General Operating Principle of an Asynchronous Machine:

Induction motors (asynchronous motors are otherwise called), constitute the basis of industrial motor applications. Induction motors are mainly used due to their rugged and robust construction, simplicity, and high reliability. This Operation is based on electromagnetic induction and that is how it works:

1.5.1. Basic Components of an Induction Motor:

An induction motor consists of two primary parts:

- Stator (Stationary part)
- Rotor (Rotating part)

1.5.2. Operation of an Asynchronous Machine:

The functioning of a three-phase asynchronous motor or induction motor is based on the principle of induction. Here is what it consists:

I.5.2.1. Generation of the Rotating Magnetic Field:

- The stator winding of the motor is three-phase AC.
- Because of the phase difference between the currents in each stator winding, this three-phase current creates a spinning magnetic field inside the stator.
- The synchronous speed of this revolving magnetic field is denoted by n_s, which can be found using:

$$n_s = \frac{120\,.\,f}{p}$$

$f =$ Frequency of the AC supply (in Hz).

$p =$ Number of pole pairs in the stator winding.

$n_s =$ Synchronous speed (in revolutions per minute, rpm).

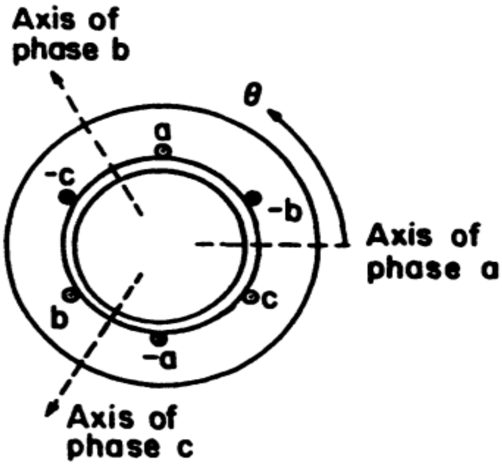

Figure 1- 3: Simplified two-pole three-phase stator winding

1.5.2.2. Electromagnetic induction in the rotor:

Faraday's law of electromagnetic induction states that the rotor windings suffer relative motion as the stator's spinning magnetic field passes through the rotor conductors. These currents create magnetic fields, and those fields interact with the stator's magnetic field.

1.5.2.3. The production of torque:

According to the Lorentz force law, as seen in "Figure 1.4," the rotor experiences a torque as a result of the magnetic field collaboration. This torque causes the rotor to revolve in unison with the stator's rotating magnetic field.

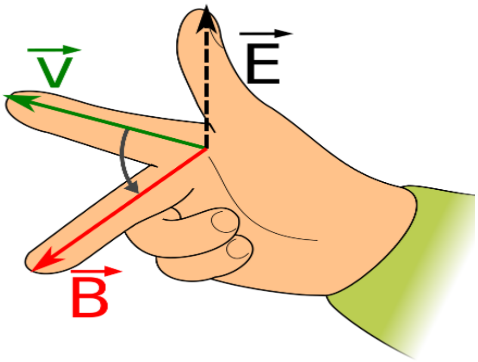

Figure 1- 4: The right-hand rule for the electric field's direction

1.5.2.4. Slip and Rotor Speed:

The rotor cannot rotate at synchronous speed because the induced current would be eliminated since there would be no relative motion between the rotor and the stator's magnetic field.

Slip (S) measures the constant tiny lag between the synchronous speed and the rotor:

$$\mathrm{S} = \frac{n_s - n_r}{n_s}$$

n_r = is the Rotor Speed.

S = Represent the slip of the asynchronous (induction)machine.

1.5.3. The energy balance and formulas for an asynchronous motor:

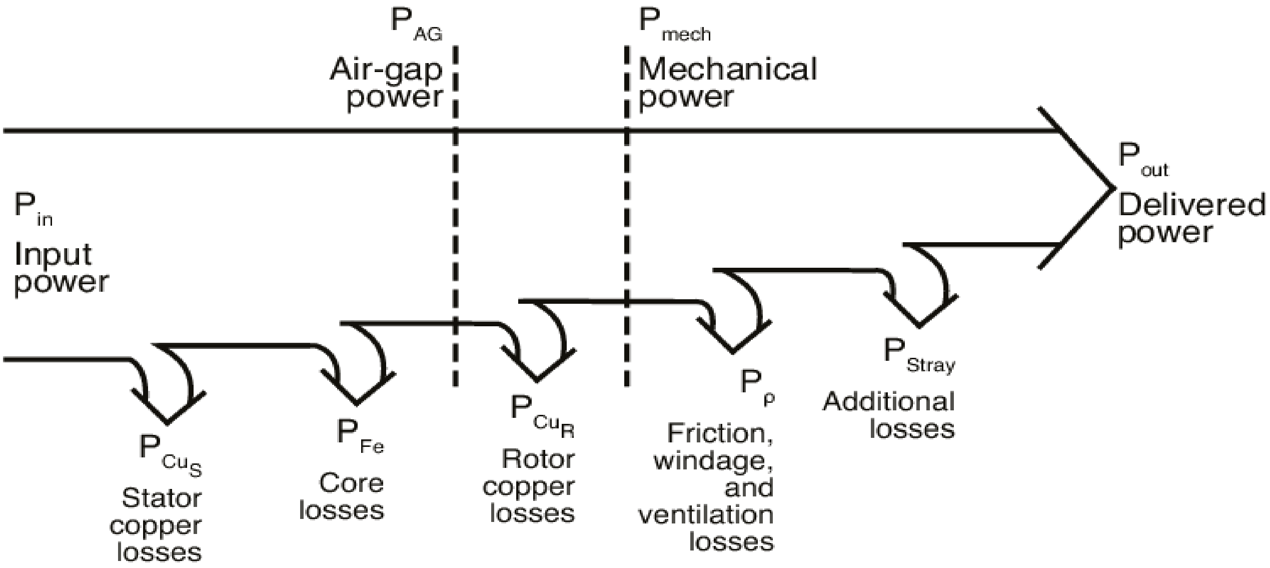

Figure 1- 5: Power-flow diagram of asynchronous motor

1.5.3.1. Power consumption P_{in}:

$$P_{in} = \sqrt{3} \cdot V \cdot I \cdot cos\phi$$

P_{in} = input power to the motor (in watts, W).

V = Line to line voltage (in Volts, V).

I = Line current (in Amperes, A).

$cos\phi$ = Power factor of the Motor.

1.5.3.2. Stator copper losses P_{CU_S}:

$$P_{CU_S} = 3 \,.\, R_s \,.\, I^2{}_s$$

$P_{js} = for\ Stator\ copper\ losses\ (in\ watts, W).$

$R_s = for\ Resistance\ of\ the\ stator\ windings\ per\ phase\ (in\ ohms, \Omega).$

$I_s = for\ Stator\ current\ (in\ Amperes, A).$

1.5.3.3. Rotor copper losses P_{CU_R} :

$$P_{CU_R} = 3 \,.\, R_r \,.\, I^2{}_r$$

$P_{jr} = for\ Rotor\ copper\ losses\ (in\ watts, W).$

$R_r = for\ Resistance\ of\ the\ rotor\ (in\ ohms, \Omega).$

$I_r = for\ rotor\ current\ (in\ Amperes, A).$

1.5.3.4. Core losses P_{core}:

We use for it :

$$P_{core} = P_{hysteresis} + P_{eddy}$$

"$P_{\text{hysteresis}}$" described in the formula by : $f \,.\, B^n$, n nearly ≈ 1.6.

"P_{eddy}" described in the formula by ; $f^2 . B^2$.

Where :

- $f = Frequency$
- $B = Magnetic\ flux$

1.5.3.5. Air-Gap Power P_{ag}:

$$\boldsymbol{P_{ag} = P_{in} - P_{stator\ losses}}$$

In terms of rotor slip:

$$\boldsymbol{P_{ag} = P_{CU_R}/s}$$

$P_{ag} = power\ in\ the\ air\ gap\ , and\ includes\ mechanical\ power\ and\ rotor\ copper\ losses.$

$P_{stator\ losses} = Total\ stator\ losses\ (P_{js} + P_{core}).$

$S = slip.$

1.5.3.6. Mechanical Power P_{mech}:

Mechanical power is the actual power extracted from the rotor, which receives air gap power minus rotor copper losses. This is the power that creates the load on the motor shaft.

$$\boldsymbol{P_{mech} = P_{ag} \cdot (1 - s)}$$

Or :

$$\boldsymbol{P_{mech} = \ P_{ag} - P_{CU_R}}$$

$P_{mech} = power\ available\ at\ the\ rotor\ shaft.$

1.5.3.7. Friction and Windage Losses P_p:

$$\boldsymbol{P_p = P_{friction} + P_{windage}}$$

- $P_{friction}$: in moving parts like endure.
- $P_{windage}$: to windage losses.

1.5.3.8. Additional losses P_{stray}:

Stray losses are difficult to measure directly. In fact They are usually measured using standardized testing procedures, such as IEEE 112 or IEC 60034. A simplified empirical approach is as follows:

$$\boldsymbol{P_{stray} = \kappa \,.\, P_{in}}$$

$\kappa =$ stray loss factor (it goes between 0.005 to 0.02).

$P_{in} =$ input electrical power (in watts, W).

1.5.3.9. Delivered power P_{out} :

It represents the mechanical delivered power at the motor shaft, and it's move from the Air-gap power; the formula of P_{out}:

$$\boldsymbol{P_{out} = T \,.\, \omega} \qquad \textbf{or } \boldsymbol{P_{out} = P_{in} - P_{losses}}$$

$P_{losses} = its\ the\ total\ of\ all\ losses\ in\ the\ motor\ , and\ the\ formula\ is\ :$

$$\boldsymbol{P_{losses} = P_{CU_S} + P_{CU_R} + P_{core} + P_{mech} + P_{stray}}$$

$T = the\ Torque\ and\ it\ is\ :\ {}^{P_{ag}}/_{\omega}$

$\omega = {}^{2\pi n_s}/_{60}$

1.5.3.10. Efficiency η :

Related to :

$$\boldsymbol{\eta = \frac{P_{out}}{P_{in}} \,.\, 100\%}$$

$P_{out} =$ is the delivered power or the mechanical output power .

$P_{in} =$ electical input power.

1.6. Modeling of the induction machine:

1.6.1. Simplifying assumptions:

Asynchronous machine modeling is based on several simplifying assumptions[11]:

- Magnetic circuits are symmetrical.
- The induction distribution.
- The air gap is constant.
- Saturation phenomena are neglected, allowing magnetic flux to be considered as a linear function of currents.
- The effect of notching is negligible.
- The influence of skin effect and heating on the characteristics is not considered.

The important consequences of these assumptions include:

a) Flux additivity.
b) Constancy of self-inductances.
c) Sinusoidal law of variation of mutual inductances between stator and rotor windings as a function of the electrical angle between their magnetic axes.

1.6.2. Modeling the induction motor in the three-phase:

The three-phase electric machine consists of a stator and a moving rotor. The stator has three star- or delta-coupled windings fed by a three-phase system of voltages, creating a magnetic field in the machine's air gap.[13]

The three-phase generalized electric machine is an ideal three-phase bipolar machine, with six windings (three on the stator and three on the rotor) [12], that’s what we describe in Figure 1.6:

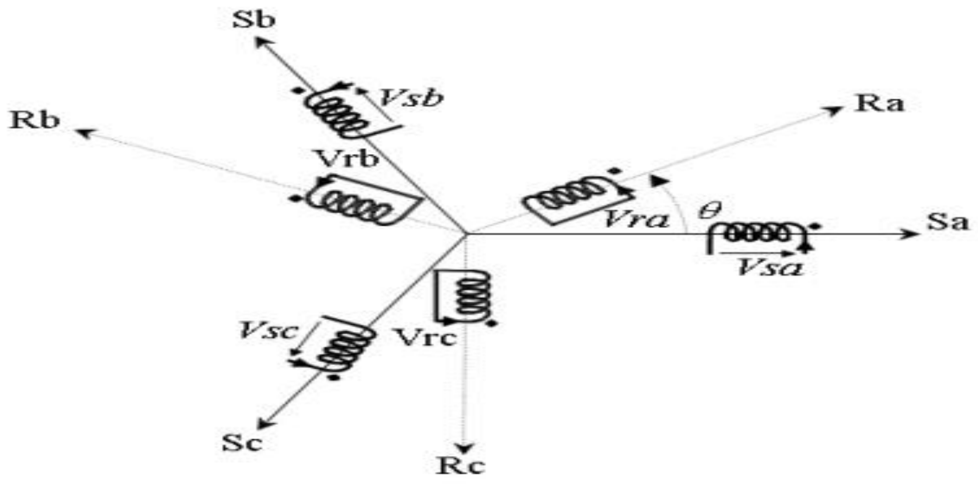

Figure 1- 6: Representation of the asynchronous motor

Considering "Figure 1.6", the electrical equations of the Three-phase induction machine can be written as follows

➢ Electric Equations :

$$\begin{cases} V_{sa} = R_s i_{sa} + \frac{d}{dt}\Phi_{sa} \\ V_{sb} = R_s i_{sb} + \frac{d}{dt}\Phi_{sb} \\ V_{sc} = R_s i_{sc} + \frac{d}{dt}\Phi_{sc} \end{cases}$$

$$\begin{cases} V_{ra} = R_r i_{ra} + \frac{d}{dt}\Phi_{ra} \\ V_{rb} = R_r i_{rb} + \frac{d}{dt}\Phi_{rb} \\ V_{rc} = R_r i_{rc} + \frac{d}{dt}\Phi_{rc} \end{cases}$$

V_{sa}, V_{sb}, V_{sc}: Stresses applied to the three stator phases

i_{sa}, i_{sb}, i_{sc}: Currents that pass through the three stator phases.

$\Phi_{sa}, \Phi_{sb}, \Phi_{sc}$: Total flow through these windings.

V_{ra}, V_{rb}, V_{rc}: Rotor voltages.

i_{ra}, i_{rb}, i_{rc}: Rotor currents.

$\Phi_{ra}, \Phi_{rb}, \Phi_{rc}$: Rotor flux.

R_s: Resistance of a stator phase.

R_r: Resistance of a rotor phase.

- In Stator :

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{sa} \\ \Phi_{sb} \\ \Phi_{sc} \end{bmatrix}$$

- **In Rotor :**

$$\begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix}$$

With “V, I and Φ” are voltage, current, and flux respectively.

Rs and Rr are respectively the resistance of a stator phase and the resistance of a rotor phase.

Maximum mutual inductance between a stator phase and a rotor phase.

Magnetic Equations :

For the stator :

$$\begin{bmatrix} \Phi_{sa} \\ \Phi_{sb} \\ \Phi_{sc} \end{bmatrix} = [L_s] \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + [M_{sr}] \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix}$$

For the rotor :

$$\begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix} = [L_r] \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} + [M_{sr}] \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}$$

The real flux matrix shows two inductance sub-matrices:

$$[\Phi_s] = [L_{ss}][i_s] + [M_{sr}][i_r]$$

$$[\Phi_r] = [M_{rs}][i_s] + [L_{rr}][i_r]$$

With:

$$[L_{ss}] = \begin{bmatrix} l_s & M_s & M_s \\ M_s & l_s & M_s \\ M_s & M_s & l_s \end{bmatrix}$$

$$[L_{rr}] = \begin{bmatrix} l_r & M_r & M_r \\ M_r & l_r & M_r \\ M_r & M_r & l_r \end{bmatrix}$$

- **Mechanical Equation :**

$$Te - T_l = J\frac{d\omega_m}{dt} + f\omega$$

$Te = Electromagnetic\ torque.$

$T_l = Load\ torque.$

1.7. Advantages and disadvantages of induction motors:

- **The Advantages:**

- **IMs (Induction motors) is easy to build.**
- **Robust construction and require low maintenance.**
- **Good standardization and interchangeability between manufacturers.**
- **Can be started directly from the grid (with moderate starting torque depending on design).**
- **Higher efficiency (typically up to 95%, and higher for large ratings).**

- **The disadvantages :**

  - **If the load torque exceeds the motors maximum torque (pull-out torque), the motor will stall.**
  - **They are not self-excited: induction motors require reactive power (magnetizing current) from the supply.**

1.8. Conclusion :

Before the discovery of asynchronous motors, DC motors were in wide usage, though the problems of their maintenance and expenses involved made them less popular as compared to AC motors. The asynchronous motors find vast application in industries nowadays.

Speed Variation of Asynchronous Motors In several situations, obtaining a variation in the speed of asynchronous motors or limiting their starting current becomes essential. For this purpose, we have brought in the aspect of speed variation that we shall see below in detail.

2. CHAPTER TWO : VARIABLE SPEED-DRIVE

2.1. Introduction:

The most used motors in industry are three-phase asynchronous motors These motors have an almost constant speed and are not very suitable for speed adjustment.

Direct current (DC) motors thus are typically preferred when a large speed variation is needed. However, today there are electronic drive systems (variable speed drives) that allow the speed of induction motors to be varied.

In this chapter, we will study the different components of a variable speed drive.

2.2. The benefits of variable speed control:

Many industrial systems driven by electric motors use speed variation to optimize their operation.[1]

Figure 2- 1: Variable speed drive (VFD)

Examples of Use :

- Adjusting the flow rate of a pump or a fan.
- Controlling the speed of a production line conveyor.
- Regulating the speed of a paper or steel mill processing line.
- Adjusting the cutting or feed speed of machine tools.
- Controlling the speed of transportation systems for people (train, cable car, etc.).

2.3. The main functions of electronic speed drives:

- Speed variation.
- Controlled acceleration.
- Speed regulation.
- Controlled deceleration.
- Reversal of direction.

2.4. Construction of a variable speed drive:

The frequency converter, supplied by the mains at a fixed voltage and frequency, provides the motor with supply the motor with alternating current at variable voltage and frequency.

To supply an asynchronous motor with constant torque at any speed, it is necessary to maintain a constant flux. Speed, the flux must be kept constant. This requires that voltage and frequency evolve simultaneously and in the same proportions.

2.5. Power circuit:

The power circuit consists of a rectifier and an inverter which, from the rectified voltage, produces voltage of variable amplitude and frequency.[14]

Rectified voltage, produces a voltage of variable amplitude and frequency.

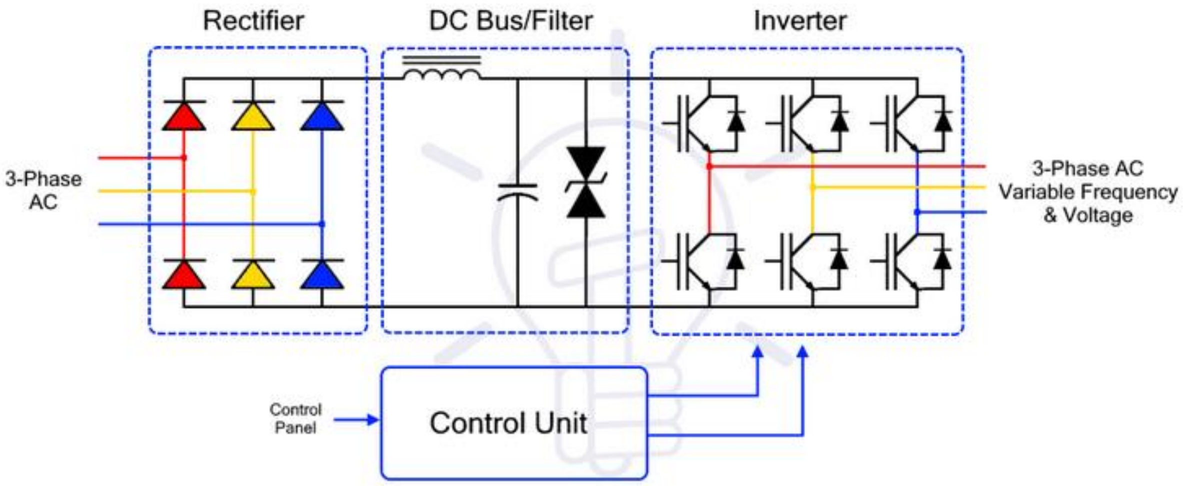

Figure 2- 2: Variable speed drive power circuit

The main function of a VFD is to change the operating frequencies of the AC supply. The operation uses four blocks or sections of the VFD to convert the AC into DC and then into AC with different frequencies. The sections are Rectifier Section, DC Bus / Filter Section, Inverter Section, and Control Unit Section. Below are the circuits that are explained.

2.5.1. Rectifier:

The rectifier is a crucial component that converts power source alternating current (AC) into direct current (DC). To control the motor's speed and torque, this DC is exposed to further processing.[4]

Its role is converts the Three-phase AC into DC voltage, by that it made the DC output stable, which modulates the frequency and amplitude of the voltage to the motor.

[in Annexes] and [20]

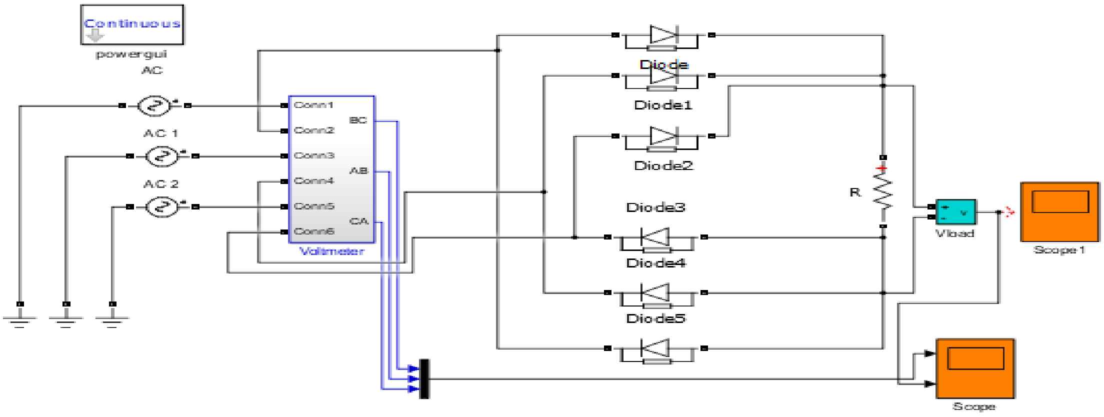

Figure 2- 3: Three-phase rectifier

As every part in machines, rectifier it has its types:

2.5.1.1. Diode rectifiers (uncontrolled rectifiers):

They are the most basic and widely-used type of VFD rectifiers. These are diodes in a three-phase bridge configuration, making them capable of AC-to-DC conversion on its own and without any outside control.

- **Features:**

Self-controlled: This type of rectifiers converts AC into DC without any external control circuits and in a noiseless manner.

Unidirectional Power Flow: This type of power flow just flows from the supply to the load, so it may not be helpful in regenerative braking.

Harmonic Distortion Harmonic Distortion: The diode rectifiers cause harmonic distortion leading the grids to deploy harmonic filter.

Simple Design: These simple designs feature low cost of production and high strength, while also being very reliable and cheap to maintain.

- Applications :

Non regenerative applications such as fans, pumps and compressors, simplicity, and reliability Diode rectifiers in most of the VFDs.

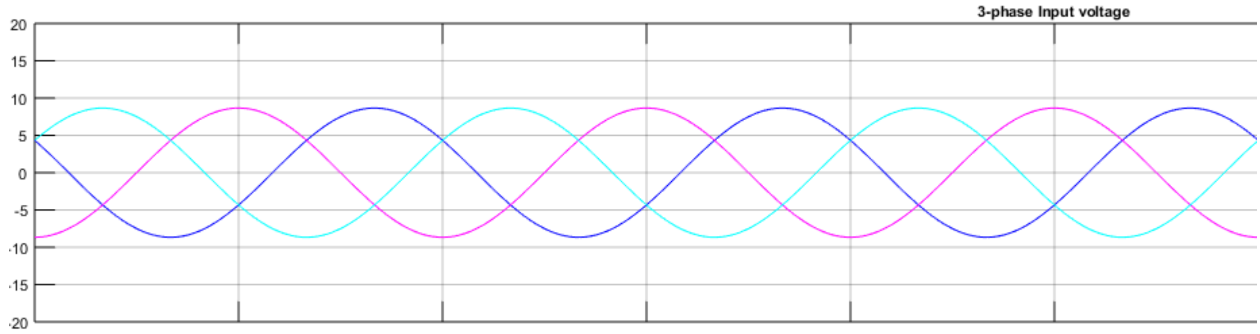

Figure 2- 4: Three-phase input voltage

2.5.1.2. Thyristor rectifiers (controlled rectifiers):

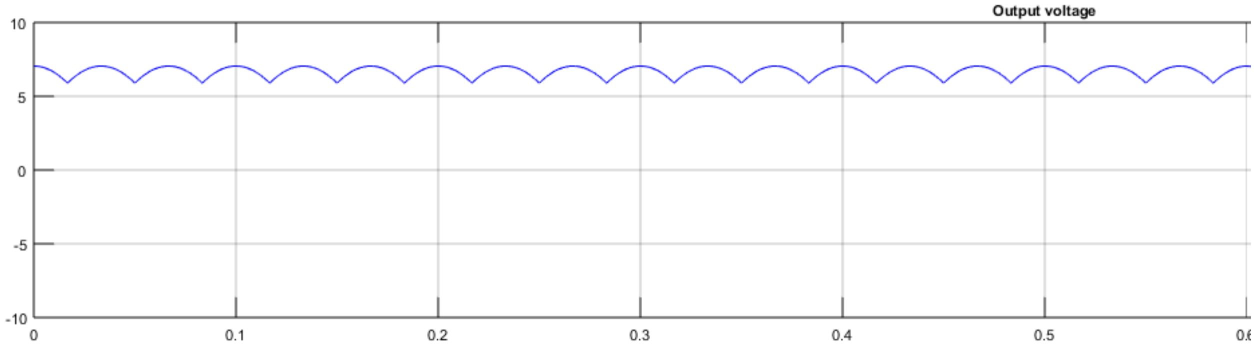

Figure 2- 5: Three-phase output voltage

Thyristor rectifiers, also called controlled rectifiers, use thyristors (SCRs) instead of diodes to provide controllable DC output. Such systems normally find applications for which one wants to have strict control on DC voltage. For a thyristor rectifier, the firing angle regulates the DC output voltage.

- Features:

1-Predisposition Voltage: Varying the firing angle-that is, the point in the AC cycle where the thyristors are fired-allows for variations of the output DC voltage. This flexibility allows for controlling speed and torque in motors for VSD applications.

2-Regenerative Capability: Thyristor rectifiers can support regenerative braking. In the case of the motor acting like a generator, the thyristors allow flowback into the supply, which is not possible in diode rectifiers since they allow only a unidirectional power flow.

3-Complex Control: A triggering circuit is required for the control of the firing angle of the thyristors. This adds complexity to the drive system but gives better control.

4-Higher Efficiency: Thyristor rectifiers have the possibility to be more efficient with better control compared to diode rectifiers, especially in cases when the drive needs to operate in a variation of loads or speeds.

5- Power Factor Improvement: The controlled rectifier is also able to improve power factor compared to uncontrolled diode rectifiers.

- Applications :

Thyristor-based rectifiers are normally used on very high-performance VSDs where precision control of the DC voltage is needed, such as in conveyors, cranes, elevators, and welding machines, with added features of being able to handle regeneration or returning energy back to the grid or power supply.[5]

So in such cases, since the DC is controllable in these applications, many more innovative motor control strategies can be implemented along with overall system performance enhancements.

2.5.2. **Filter :**

The filter consists of an inductor connected in series with a capacitor.
The capacitor ensures a substantially constant voltage at the inverter input, and absorbs the negative current returned by the load.[6]

The inductor makes the current more or less constant.

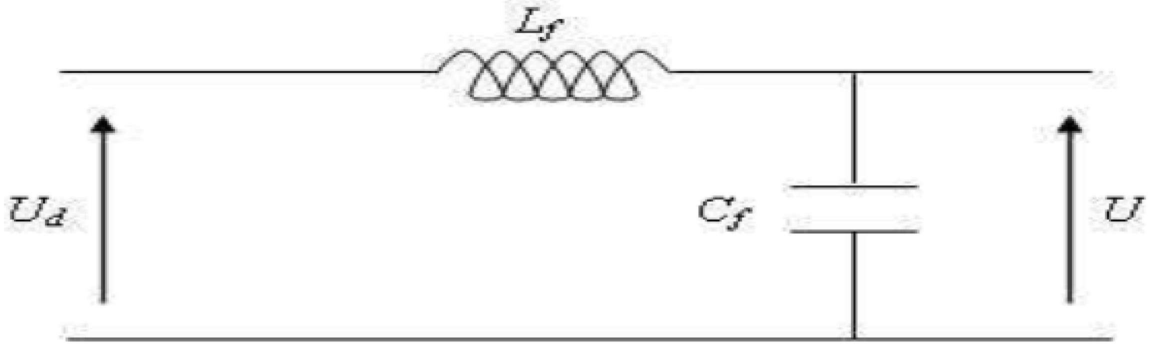

Figure 2- 6: Filter structure

$$\frac{dI_d}{dt} = \frac{1}{If}(U - U_d)$$

$$\frac{dU}{dt} = \frac{1}{Cf}(I_d - I)$$

The filter transfer function is given by the following relationship:

$$F = \frac{U(s)}{U_d(s)} = \frac{1}{1 + (\sqrt{L_f C_f S})^2}$$

The role of the capacitor C_f is to act as a voltage source at the inverter input, to supply reactive energy to the machine, and to absorb the negative current restored by the load.

The role of the inductance L_f is to smooth the current id. The filter is second-order, with

cut-off frequency .

$$F_c = \frac{1}{\sqrt{L_f C_f}}$$

2.5.3. The three-phase PWM voltage inverter:

The inverter is the last stage of the frequency converter and is located just in front of the motor. It is responsible for providing the engine with a variable amount of electricity suitable for its operation. In fact the inverter is made of semiconductors, mainly IGBTs (insulated gate bipolar transistors) and freewheeling diodes, arranged in pairs in three arms.

These components are controlled by signals from the control circuit. Voltage inverters consist of switching units, usually based on transistors for standard applications or thyristors for high-performance applications. Inverters are static converters that convert DC voltage into AC voltage, thus creating an AC voltage source from a DC power supply.

Pulse Width Modulation (PWM) is a technique used to control the switches of an inverter. It produces a series of pulses of fixed amplitude, either positive or negative, whose width is modulated to produce an AC voltage suitable for the motor's requirements. [9] [15]

"Figure 2-8" [19]

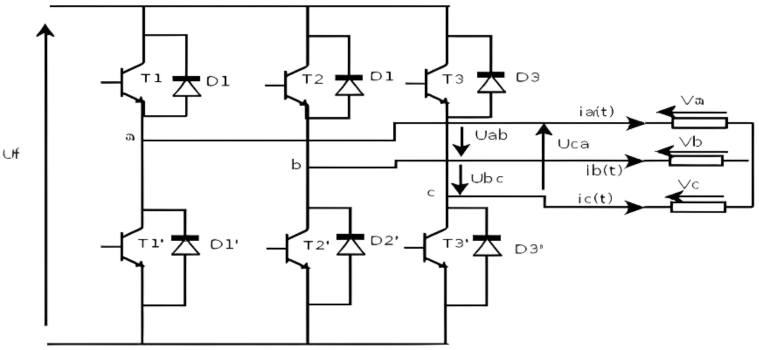

Figure 2- 7: The three-phase inverter

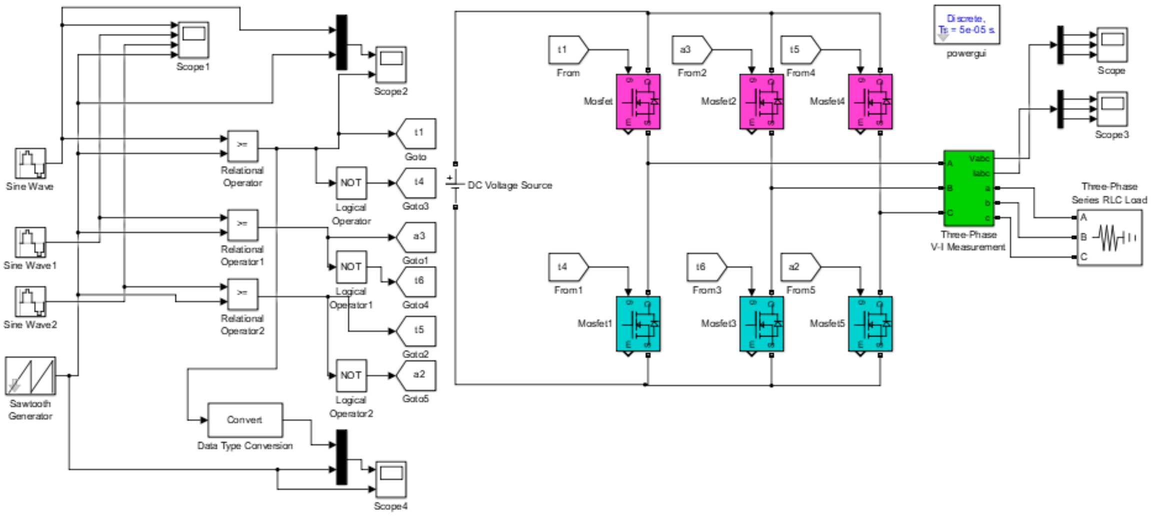

Figure 2- 8: Three-phase inverter in MATLAB/SIMULINK

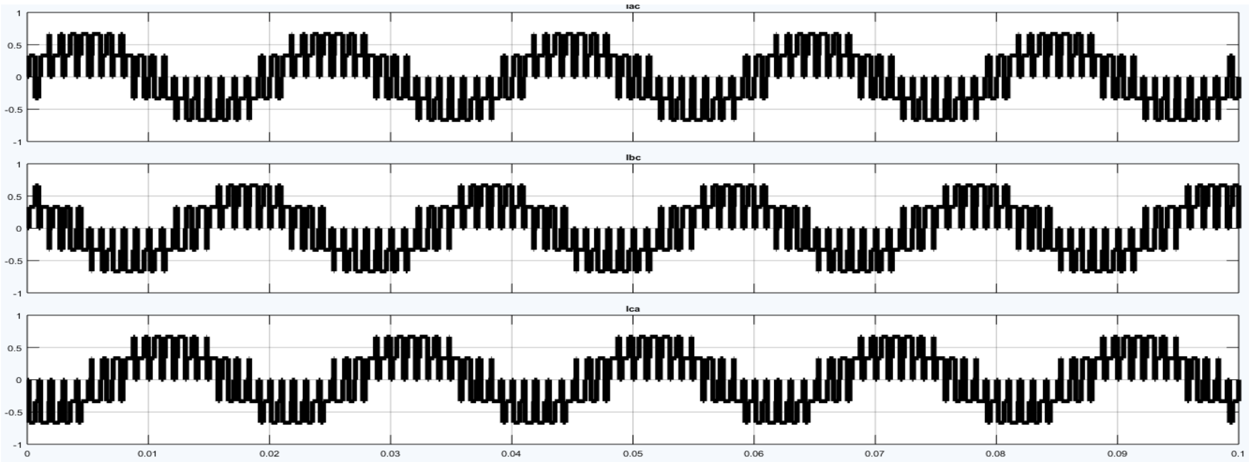

Figure 2- 9: Three-phase PWM inverter Signals in MATLAB/SIMULINK

V_a, V_b, V_c: *simple voltages delivered by the inverter.*

U_{ab}, U_{bc}, U_{ca}: $the\ inverter's\ composite\ voltages.$

$$\begin{cases} U_{ab} = V_a - V_b \\ U_{bc} = V_b - V_c \\ U_{ca} = V_c - V_a \end{cases}$$

Or simple voltages are given by:

$$\begin{cases} V_a = \frac{1}{3}(U_{ab} - U_{ca}) \\ V_b = \frac{1}{3}(U_{bc} - U_{ab}) \\ V_c = \frac{1}{3}(U_{ca} - U_{bc}) \end{cases}$$

2.6. Transistor IGBT:

IGBT is a power semiconductor device belonging to the transistor family, mainly used as an electronic switch in power electronics applications. This device realizes the merits of previous ones, combining the easy control characteristics of FETs with the conduction losses by flow that characterize bipolar transistors. This has made possible substantial steps forward in applications of power electronics, improving operation reliability and energy efficiency.

They have enabled developments that seemed impossible. They are, however, particularly suited for variable-speed applications and electrical machines. In modern life, most products with electronic power devices and converters will involve IGBTs but operate unobtrusively.[11]

Their applications range widely in everyday technologies, from automotive systems, trains, subways, buses, aircraft, and maritime vessels (ships) to elevators, household appliances, televisions, and home automation systems.[15]

2.7. Control topologies for an induction machine:

2.7.1. Scalar control (The v/f= constant algorithm):

This algorithm belongs to the family of scalar control methods. The principle of these methods is to act on the frequency and amplitude of the input currents or voltages in order to vary the speed of rotation of the space vectors (flux, voltage, etc.), and thus vary the torque and speed of the motor.

With the algorithm, the amplitude and frequency of the motor voltage are varied so that their ratio remains constant. Speed for a constant resistive torque.[7]

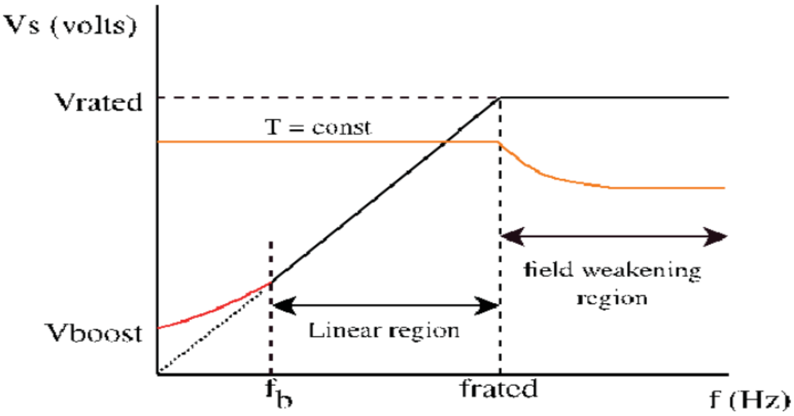

Figure 2- 10:Voltage and frequency variation

2.7.2. Vector control :

Vector control, also known as field-oriented control (FOC), is a method of controlling variable-speed drives, in which the three-phase stator currents of an AC electric motor are transformed into two orthogonal components.

The first vector adjusts the motor's magnetic flux, while the second adjusts the torque. They are then decoupled, and operation becomes similar to that of a DC motor.[8]

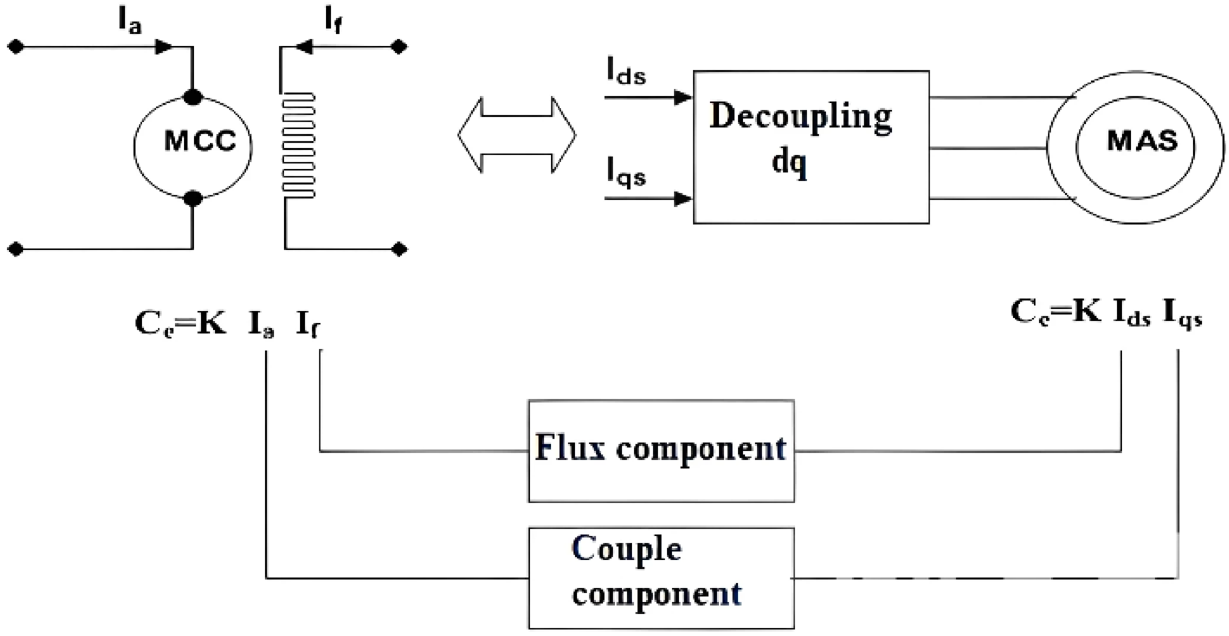

Figure 2- 11: Diagram of the decoupling principle for MAS by analogy with MCC

2.8. Analogies and relationships between vector control and scalar control:

As mentioned, while SC is based on the induction machine model in the steady state, VC is based on the dynamic induction machine model, so VC provides dynamic (instantaneous) torque control. SC presents torque control only in the steady state, and has no information during the transient state at all.

For these reasons, a comparison of the two strategies will be presented. It is possible to find some similarity between the block of each control. [8]

This similarity is shown in the following table:

SCALAR CONTROL	VECTOR CONTROL
❖ Based on the Induction machine model in permanent regime. ❖ Easy to install. ❖ Dynamic. ❖ Amplitude control.	❖ Based on the Induction machine model in transitional regime. ❖ Precise and fast. ❖ Adaptive ❖ Control of amplitude and phase

main control advantage (IRFOC) is enabled to control flow and torque, however, control (SC) enables speed and torque to be controlled.

2.9. Inverter types for asynchronous machines:

The operating point (T, ω) in quadrant 1 of the steady-state operation of the machine plus load is located at the intersection of characteristics $Te = f(\omega)$ of the motor and $T = f(\omega)$ of the load. The speed of the asynchronous machine is therefore obtained by acting on the torque it produces, so, if we refer to its expression above, the number of pole pairs, the machine's supply voltage, slip or frequency.[18]

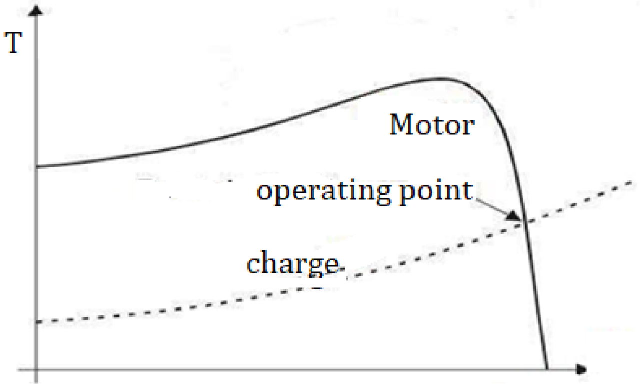

Figure 2- 12: Torque versus speed diagram

2.9.1. Action on the number of pole pairs:

Changing the number of poles is one way to control speed, as it depends on changing the number of pole pairs (P) in the stator. However, this method results in discontinuous variation (stepped increments) in speed, making it unsuitable for adjusting the desired operating point with high precision or for tasks requiring fine-tuning [1].

The relationship between the number of poles and the synchronous frequency of the motor can be summarized as follows:

- An increase in the number of pole pairs (or total poles) leads to a decrease in the magnetic field rotation frequency (and thus the motor speed).
- A decrease in the number of pole pairs (or total poles) leads to an increase in the magnetic field rotation frequency (and thus the motor speed).

The following table shows the main field rotation frequencies (synchronous speed) for a three-phase induction motor when powered by a 50 Hz network $n_s = {}^{f}/_{p}$

Numbers of pole pairs	**1**	**2**	**3**	**4**
Rotating field frequency for a 50 Hz network	3000 tr/min	1500 tr/min	1000 tr/min	750 tr/min

2.9.2. Action on slip :

The use of rotor resistors allows the speed to be set below the rated speed, but with deplorable efficiency. We therefore try to recover this energy transmitted to the rotor:

this is the hypo-synchronous cascade reserved for very high-power machines with wound rotors.[1]

$$S = \frac{n_s - n}{n_s}$$

$$n = f/p$$

$n = n_s(1 - s)$

2.9.3. Action on frequency :

Since the rotation frequency of the machine is proportional to the stator winding supply frequency of the stator windings, we'll try to create a variable-frequency network for these windings

These are voltage inverters. We can also inject currents into the windings to impose the machine's torque. These are current inverters or current switches. We can also convert directly from the mains frequency to a lower variable frequency; the frequency of the supply directly influences rotational frequency of the motor:

- If the frequency increases, the rotational frequency of a motor increase.
- If the frequency decreases, the rotational frequency of a motor decrease.

2.10. Studying the torque :

Under these conditions, the motor torque characteristics for different supply frequencies

Shift on the “figure II.10”.[9]

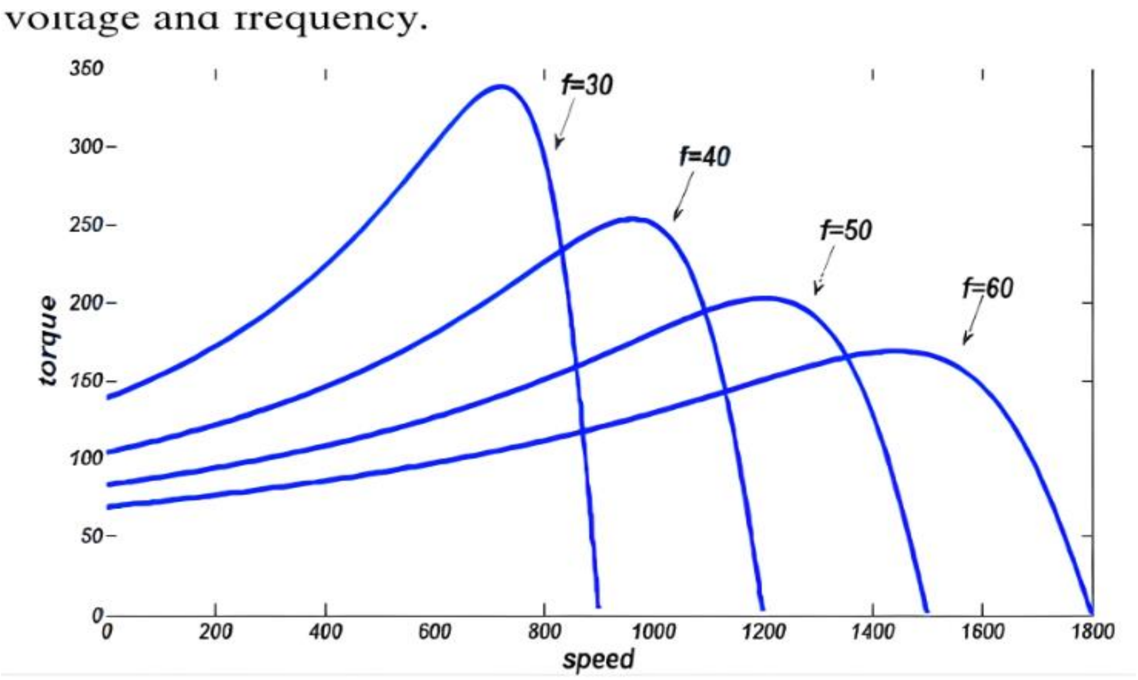

Figure 2- 13: Induction motor Torque-speed characteristics

The inverter supplies the motor with a proportional voltage and frequency up to value of 50 Hertz. At frequencies above 50 Hertz, the motor voltage can no longer increase (the winding is supplied at its rated voltage), the U/f ratio decreases, the flux decreases, resulting in a reduction in maximum torque.

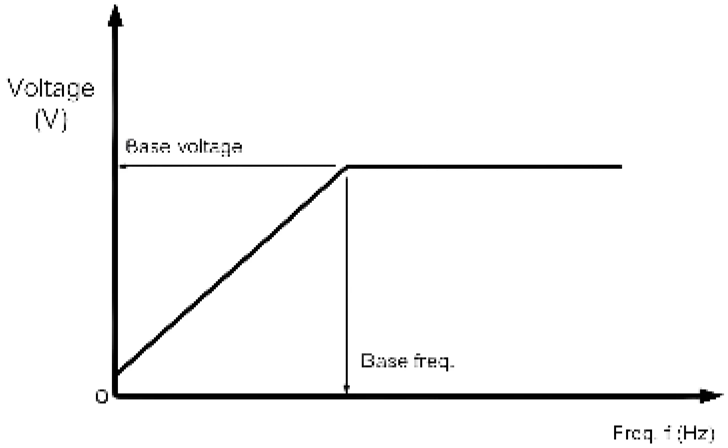

Figure 2- 14: Linear variation of motor voltage with frequency variation

2.11. Frequency converter for induction motors:

The most obvious and effective way to achieve variable speed control of an asynchronous motor is to change the frequency of the electrical supply. The inverter within the VFD system supplies the motor with a voltage waveform whose amplitude and frequency can be controlled, while keeping the voltage-to-frequency ratio (V/f) approximately constant [5]. By controlling the frequency applied to the motor, the inverter can change the speed of the rotating magnetic field in the stator, thereby precisely controlling the operating speed of the motor [1].

The following table shows a comparison between the characteristics of an asynchronous motor when powered directly from the mains and when powered via a variable frequency drive (VFD), highlighting the changes in various parameters:

Induction motor	**Under normal conditions**	**With a variable speed drive**

Starting current	Very high, on the order of 6 to 8 times rated current	Limited in the motor (usually 1.5 times the rated current).
Starting torque	High and uncontrolled, approximately 2 to 3 times the rated torque	1.5 times the rated torque, controlled during the entire acceleration period.
starting	Abrupt; duration depends only on the motor characteristics and the connected load	Smooth and controlled, no vibrations.
Speed	Slightly varies with load (close to the rated speed Nn)	Can be adjusted from 0 to a value higher than the synchronous speed (Ns).
Maximum torque	High, approximately 2 to 3 times the rated torque	High and available across the entire speed range (1.5 times the rated torque).
Electric braking	Relatively complex	Easy.
Reverse direction of march	Only possible after the motor has stopped	Easy.
Risk of stalling	Yes, in case of overload or voltage drop	No.

it shows the differences and benefits of using a variable frequency drive (VFD) with an asynchronous motor.

2.12. Conclusion :

In this chapter we have explained what a variable frequency drive is, what its characteristics are, how they have been studied, and control methods and commands.

which will enable us to use them effectively in the design.

3. CHAPTER THREE : STUDY & SIMULATING

3.1. Introduction

Multiple techniques are available for controlling induction motors, just as with DC motors. One of the most important of these is Power Converters, which are an essential part of power electronics. but the most famous is undoubtedly the modification of the speed of AC machines.

Today, Arduinos are widely used in many fields. Programming of the Arduino is done in several ways, the most famous of which is the ARDUINO IDE, which is widely supported and when the code is applied correctly and without errors, a .hex file is created that is added to the Arduino part in the PROTEUS ISIS software.

3.2. How it works:

By powering the Arduino, a square-wave signal (PWM) is emitted, passed through a optocoupler which provides galvanic isolation, and then through a driver which ensures the correct operation of the IGBTs whose basic function is to switch as quickly as possible electrical currents with the lowest losses, giving an alternating current with which the motor runs.

3.3. Asynchronous machine parameters :

Before moving to the simulation part including diagram parts, we need to set the parameters for our motor:

a) Main features of the machine	
Nominal power	5.5 KW
Nominal current	11 A
Nominal voltage	380V
Nominal stator frequency	50Hz
Nominal rotor speed	1450 Rpm
Nominal power factor	0.85
Number of pole pairs	2
b) Electrical parameters	
Stator phase resistance	Rs = 1.0 Ω
Rotor phase resistance	Rr = 1.0 Ω
Stator phase self-inductance	Ls=0.17 H
Rotor phase self-inductance	Lr=0.17 H
Mutual inductance	Lm=0.16 H
c) Mechanical parameters	
Moment of inertia of rotating masses	0.0282 kg.m²
Coefficient of friction	f=0 Nm/rad*sec

3.4. Block diagram :

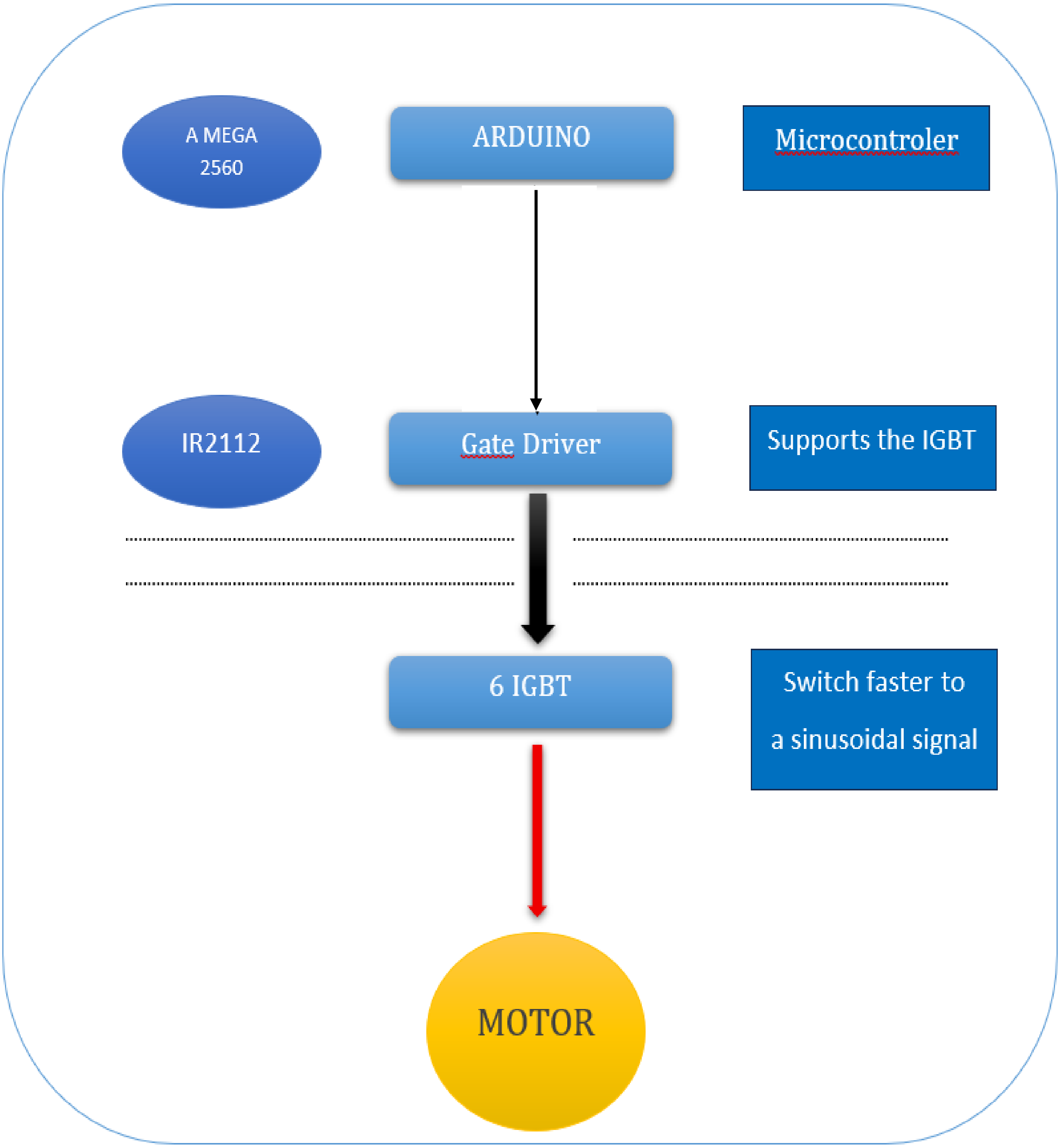

Figure 3- 1: Block diagram for the simulation

3.5. Electric Circuit Diagram:

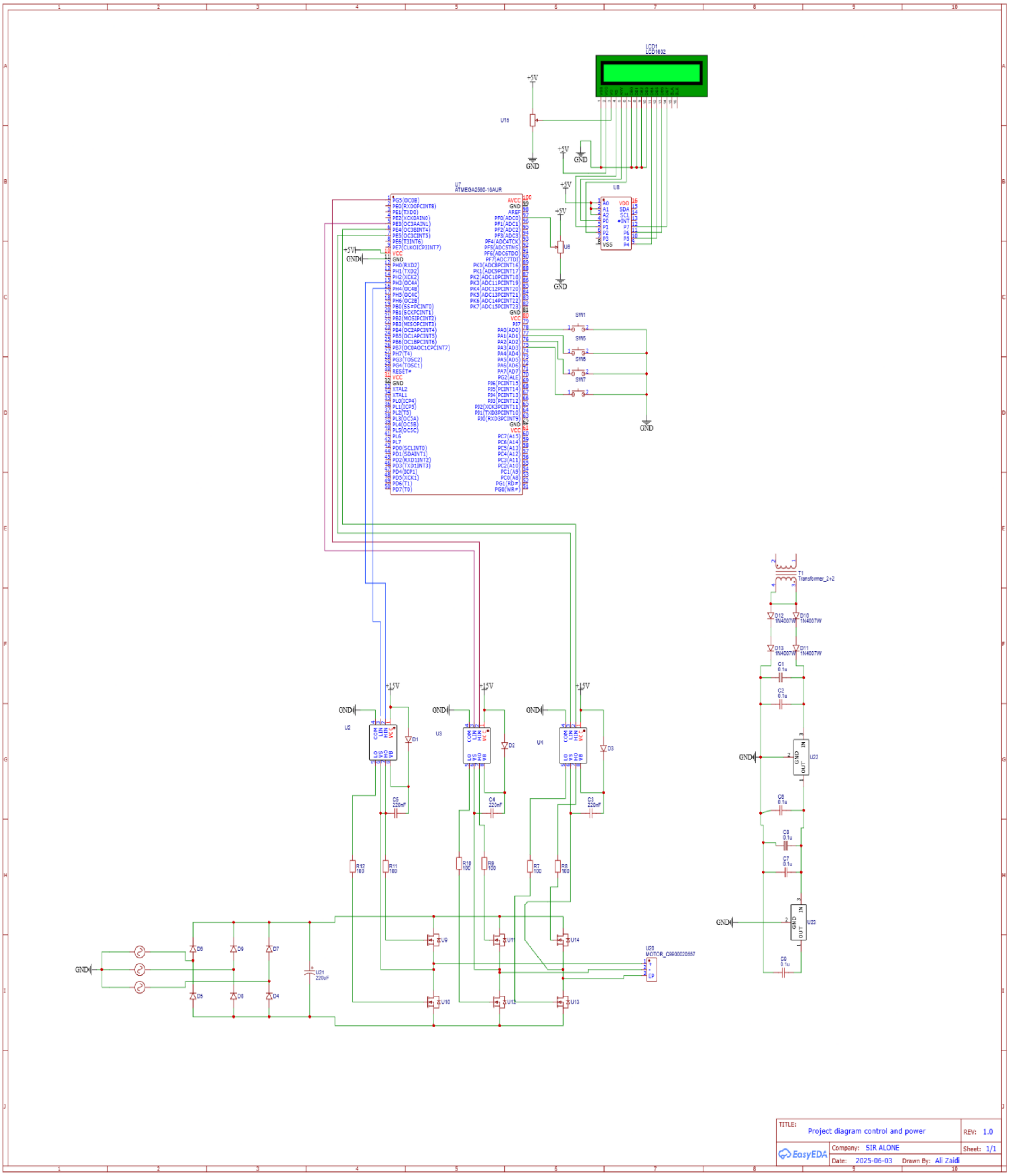

Figure 3- 2: Electrical diagram of variable speed drive for three-phase asynchronous motor from EasyEDA

3.6. Control Part:

3.6.1. Arduino :

Arduino is a circuit board in which all the elements for the function of a microcontroller are present. A microcontroller is a small computer processor with digital (0 or 1) or analog (variable voltage) inputs and outputs. Programs for the interpretation of inputs and control of outputs can be stored and run on a microcontroller. Programming is usually done on a computer and then uploaded to the microcontroller, The commands are sent through transistors, because these consume more energy, and even through relays, which consume less.

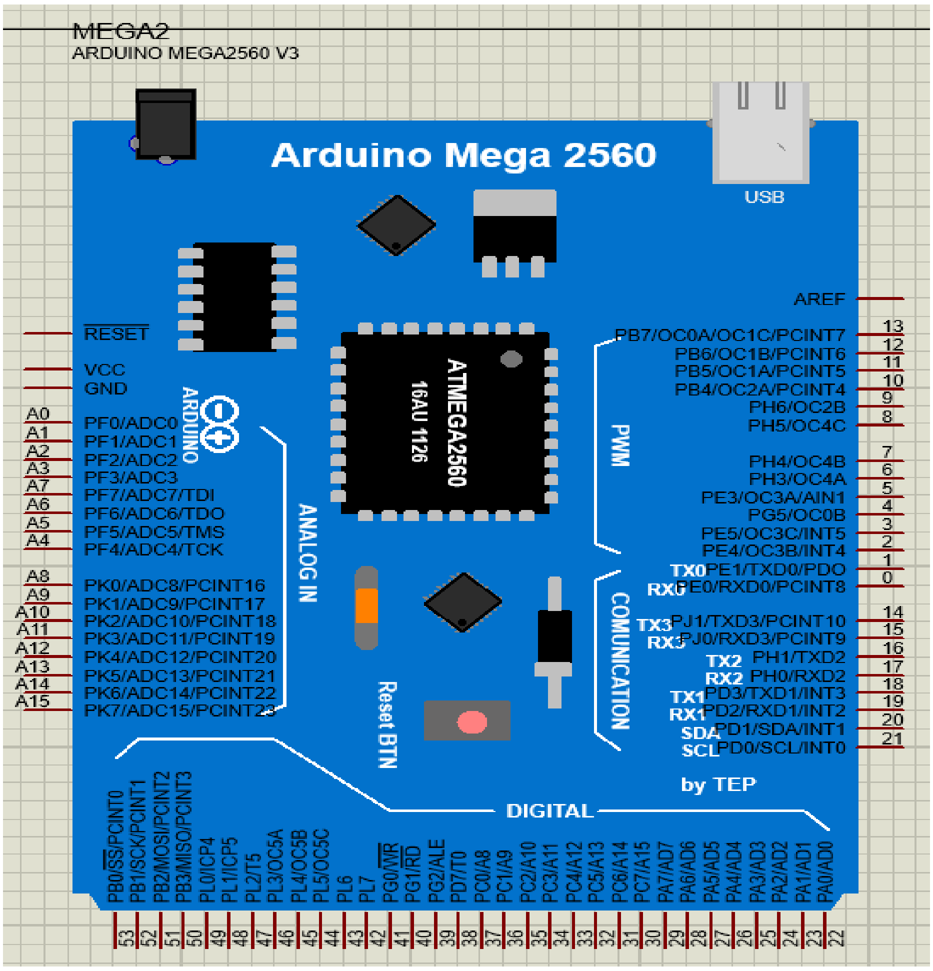

Figure 3- 3: Arduino Mega 2560

We chose the ARDUINO Mega 2560 for our project because it has 15 PWM outputs that can be used to generate pulse-width modulated signals. More specifically, these outputs are Digital outputs 2 to 13. It has more RAM and ROM than the Arduino Uno and Arduino Nano. A timer is used to generate a PWM signal. The greatest precision is obtained with a 16-bit timer. For integrated schematics.

3.6.2. Driver IR2112:

The IR2112 are high voltage, high speed power MOSFET and IGBT drivers with independent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. The logic input is compatible with standard CMOS or LSTTL output, down to 3.3V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 600 volts.[18]

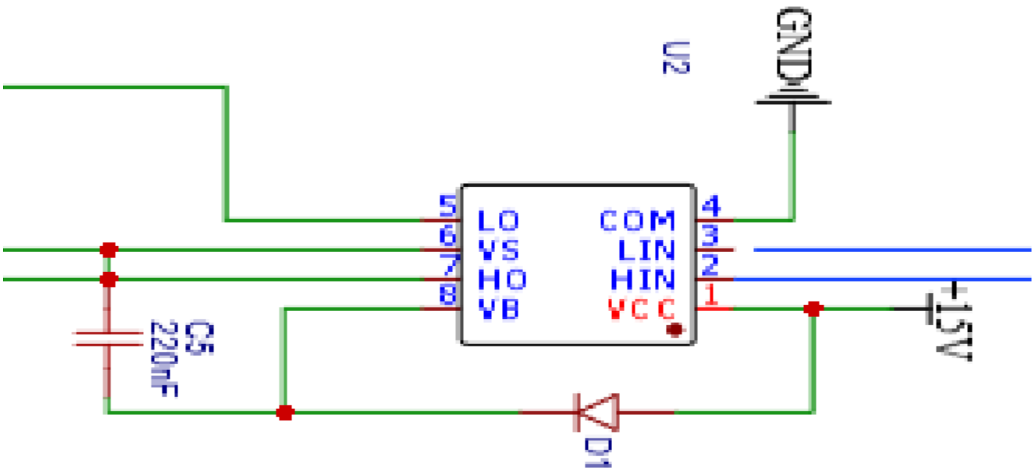

Figure 3- 4: Typical connection of IR2112

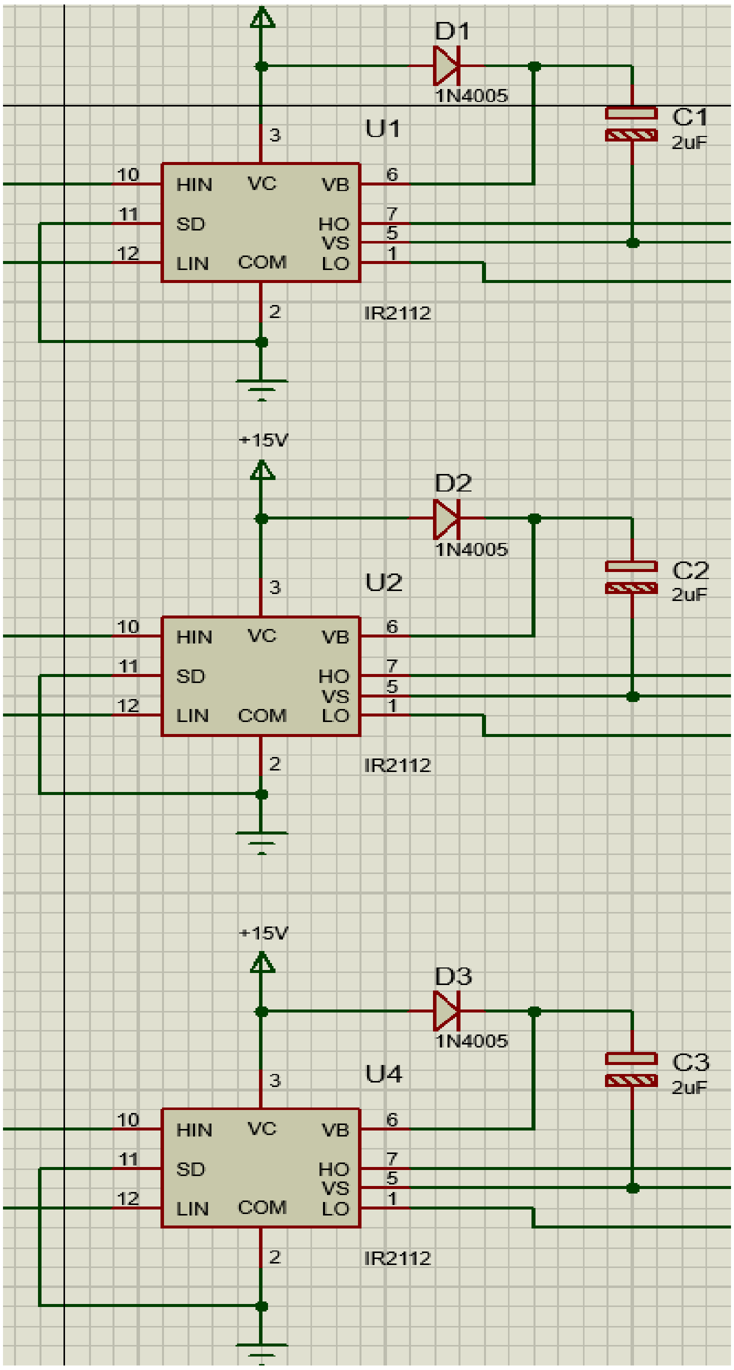

Figure 3- 5: 3 IR2112 Drivers with bootstraps "From Proteus"

3.7. *Power part :*

3.7.1. IGBT (IRG4PC50UD) :

The IGBT has a collector and emitter like a bipolar transistor, but replaces the base with a high-resistance electrode, which is the MOS gate. It consists of a low-gain PNP bipolar transistor and an N-channel MOS that supplies the base current. The internal structure is illustrated in the following figure. In this case I chose IRG4PC50UD.

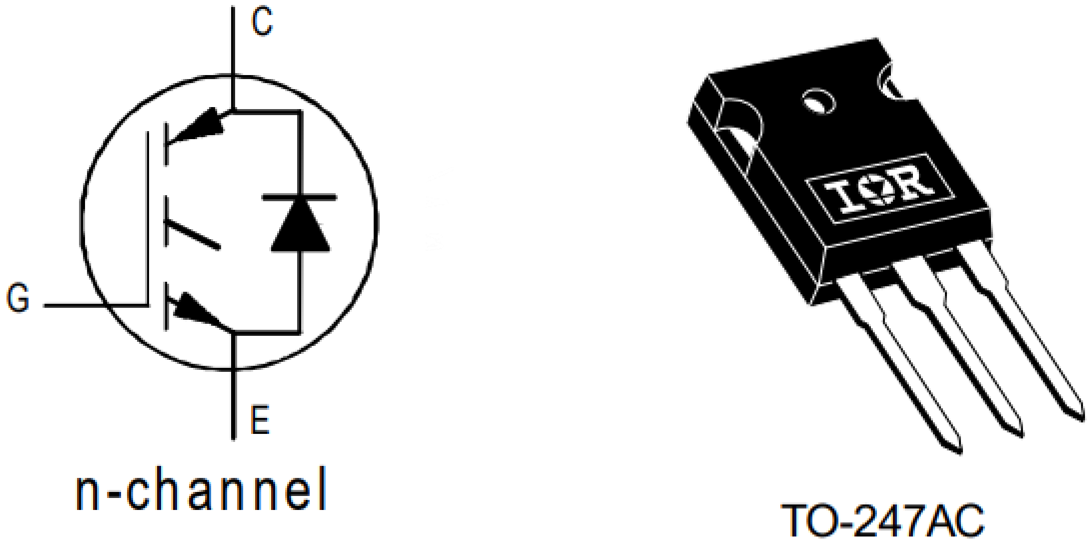

Figure 3- 6: IRG4PC50UD Part

3.7.2. THE INVERTER :

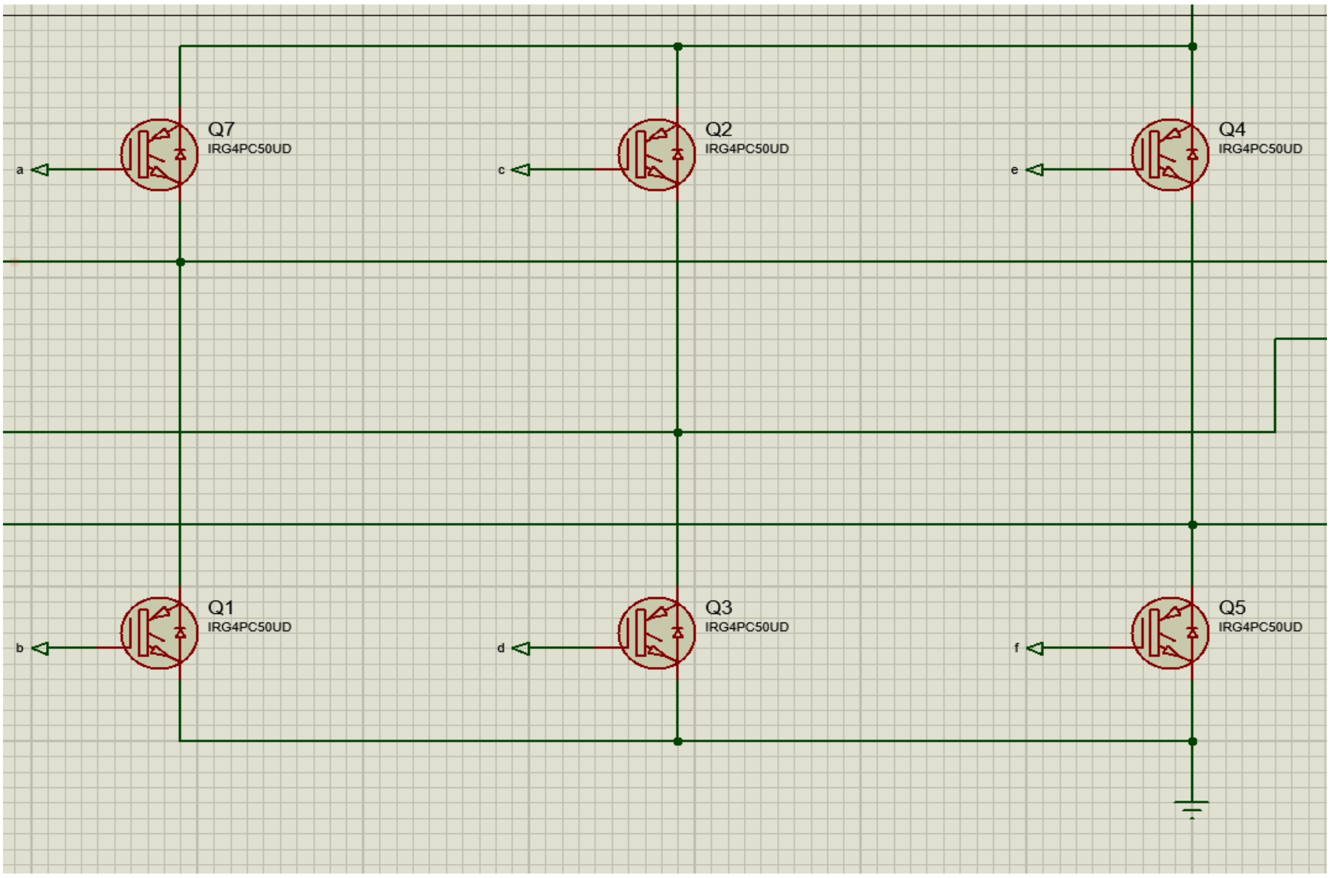

Figure 3- 7: Diagram of The Inverter from PROTEUS

3.8. Software Part:

3.8.1. Simulation diagram:

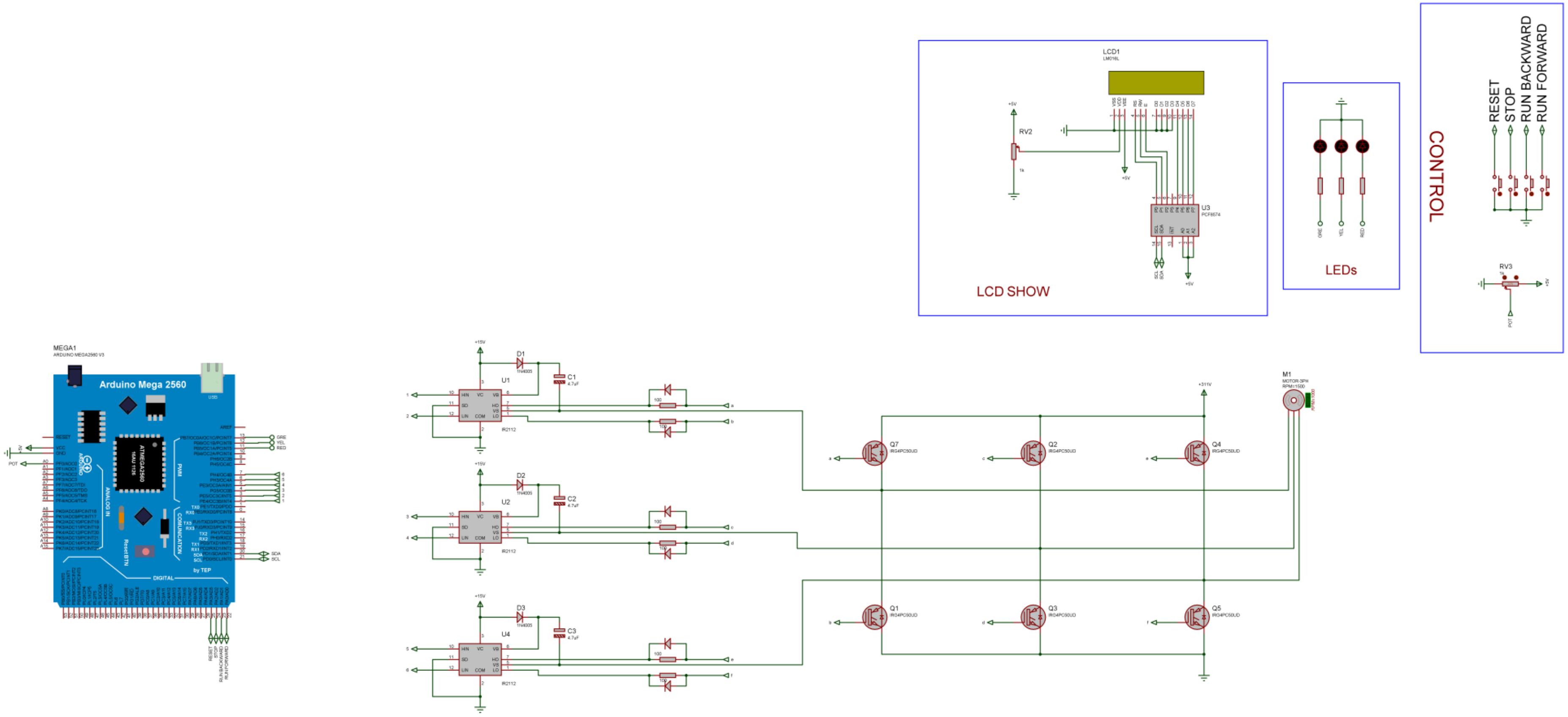

Figure 3- 8:Diagram of simulation from Proteus

The simulation diagram consists of the Arduino Mega 2560 board, a potentiometer to vary the frequency of the 6 PWMs, it consists A (HIGH AND LOW), B (HIGH AND LOW) and C (HIGH and LOW) , 5 Buttons:

- RUN FORWARD (Run The circuit and by that the motor forward)
- RUN BACKWARD (Run the circuit and by that the motor in the reversed direction)
- STOP (Stoping the circuit)
- RESET (If some fault happened we press this button the reset the system)
- LCD CHANGER (because the LCD is small "16x2" so i made it in two

3 LEDs :

- YELLOW LED : for DEBUGING.
- GREEN LED : for RUNNING.
- RED LED : for FAULT.

3.8.2. PWM program flow chart :

The next figure shows the PWM program flowchart for an arduino Mega2560:

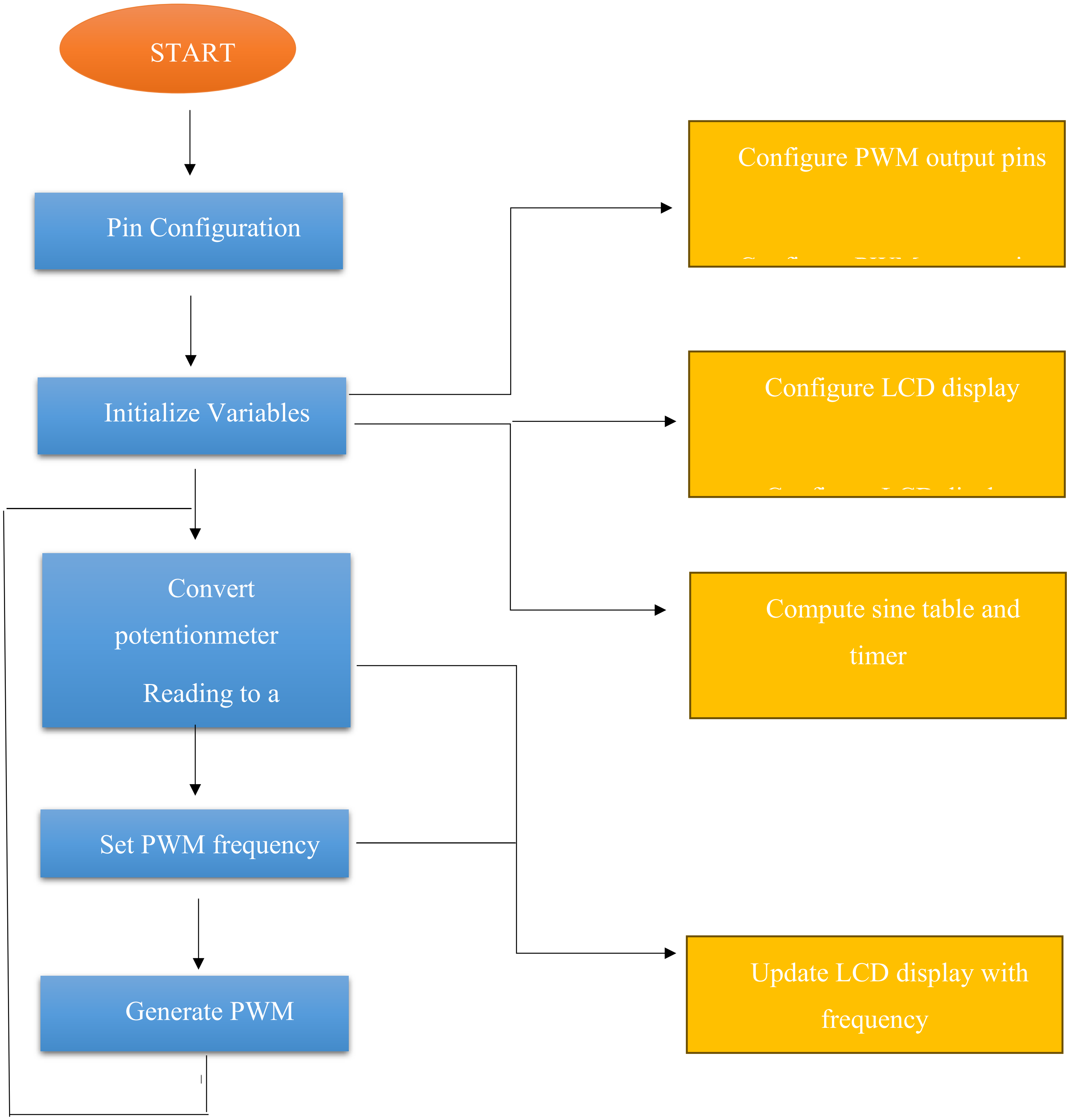

Figure 3- 9: PWM Program flow chart

3.9. PCB Diagram (EasyEDA):

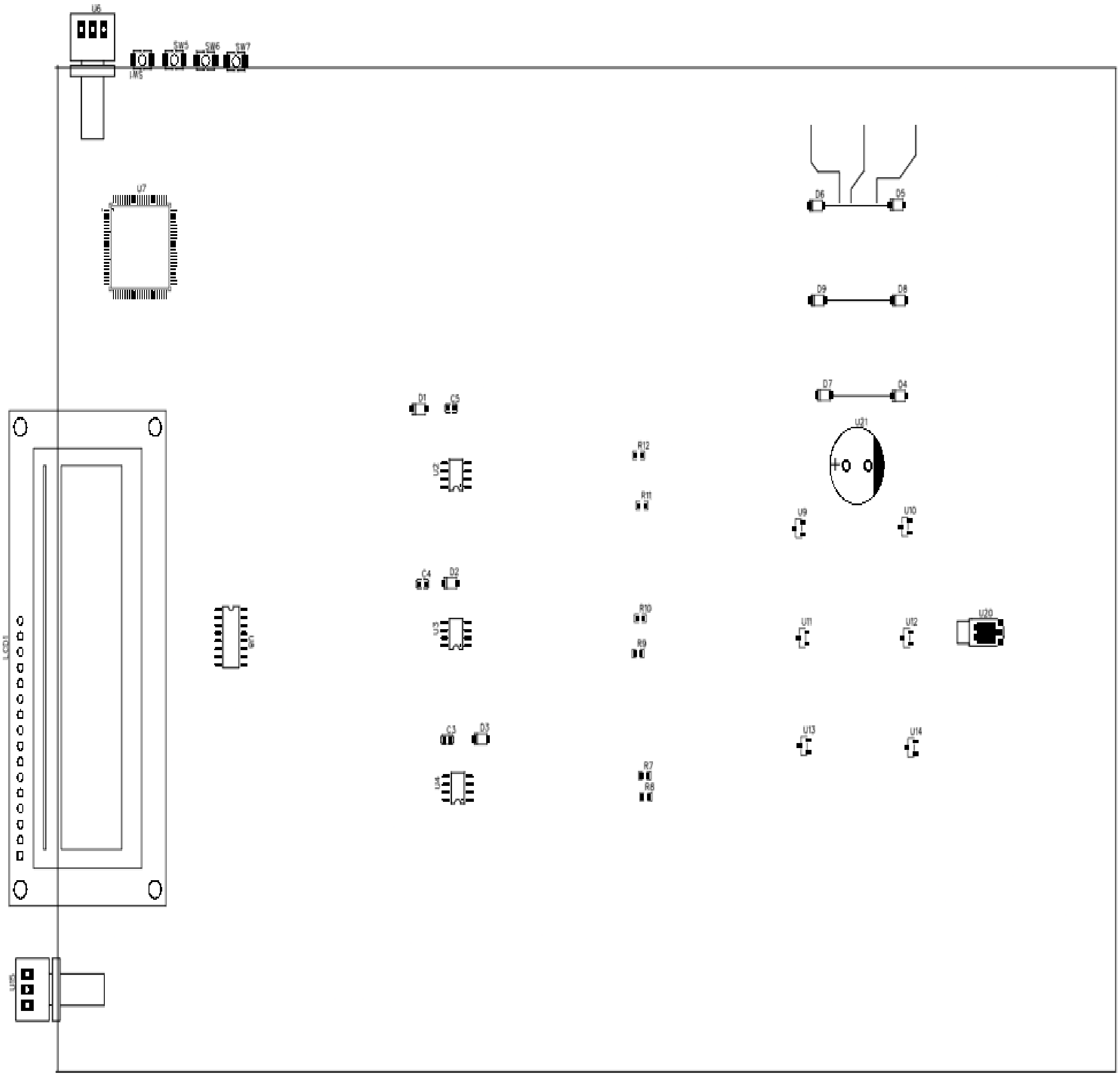

Figure 3- 10 : 2D PCB Diagram

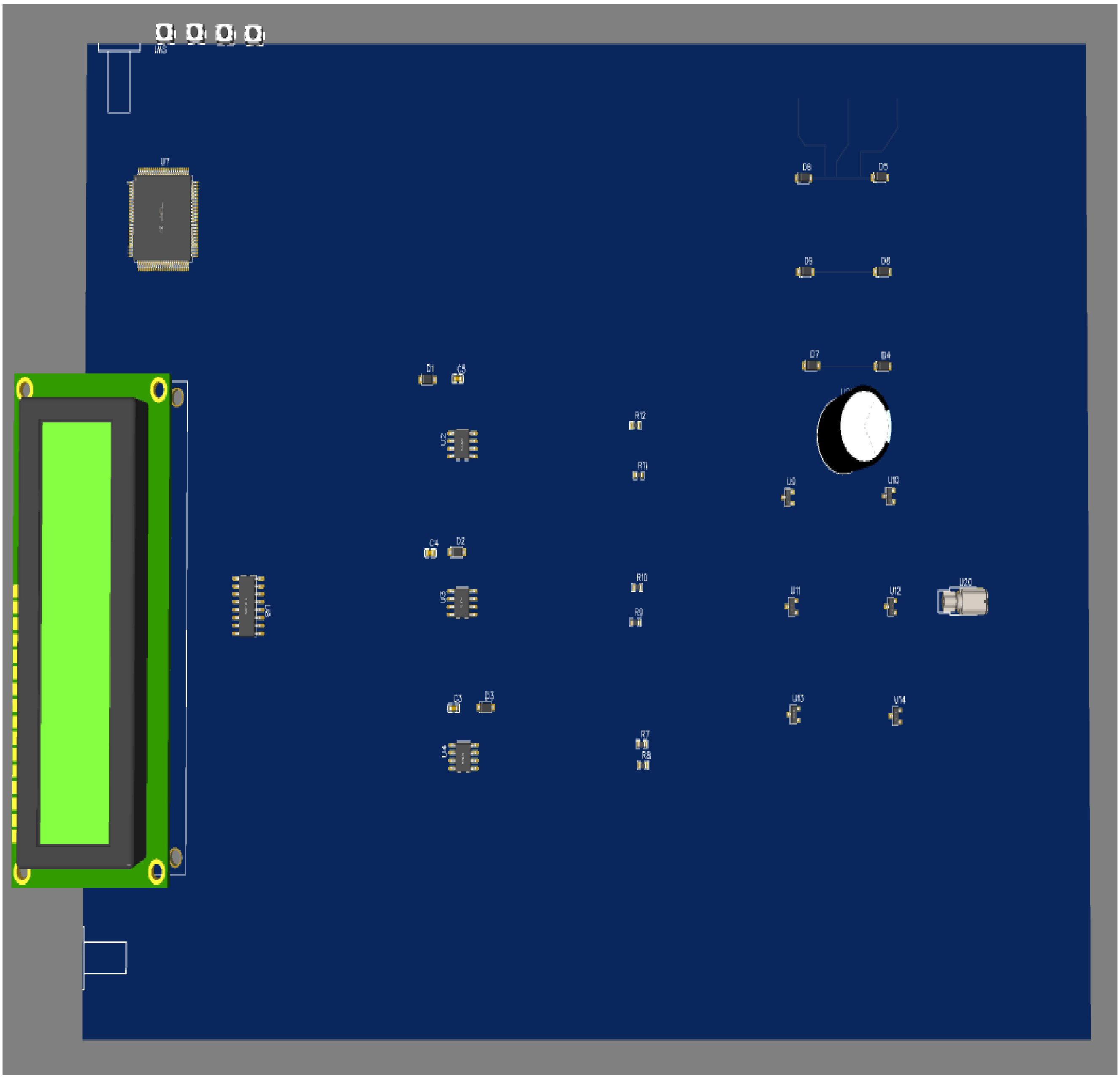

Figure 3- 11: 3D PCB Diagram

3.10. Simulation signals on Proteus:

After entering our program in the ARDUINO MEGA 2560 on Proteus and simulating, by varying the potentiometer, we will obtain the following results:

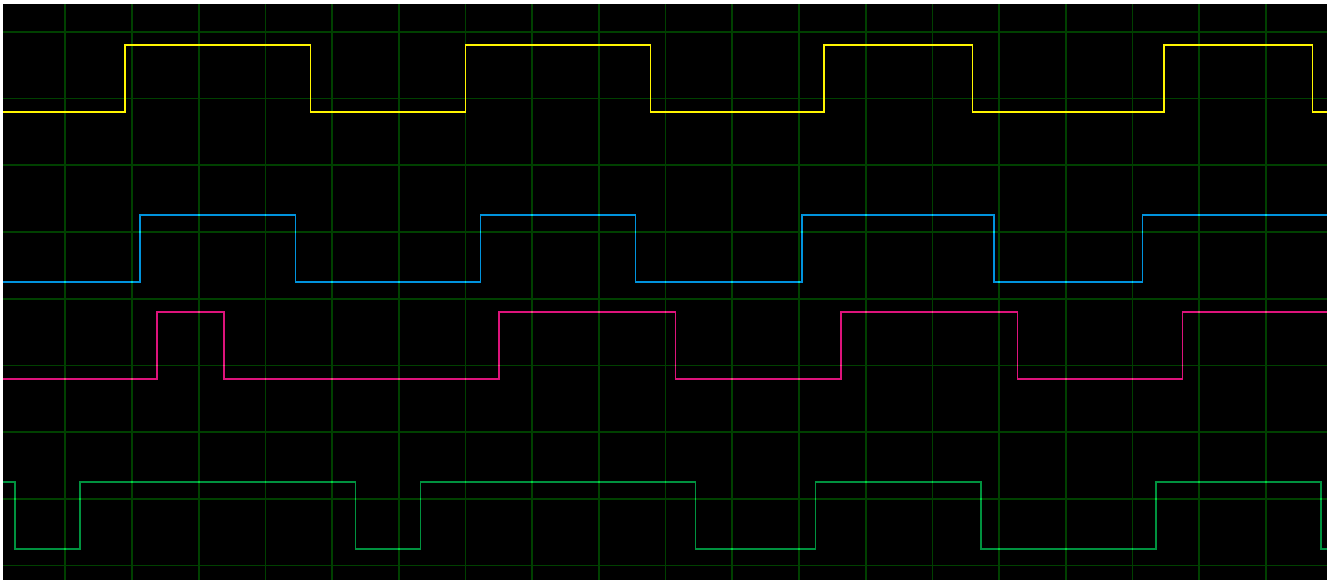

Figure 3- 12: PWM Out the Arduino

Channel A : A_High (PH1+)

Channel B : A_Low (PH1-)

Channel C : B_High (PH2+)

Channel D : B_LOW (PH2-)

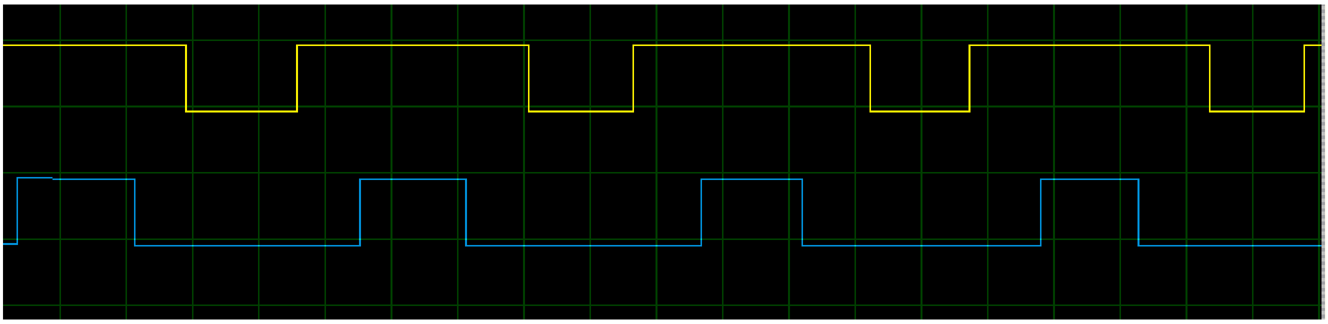

Figure 3- 13: PWM out the ARDUINO

Channel A : C_High (PH3+)

Channel B : C_Low (PH3-)

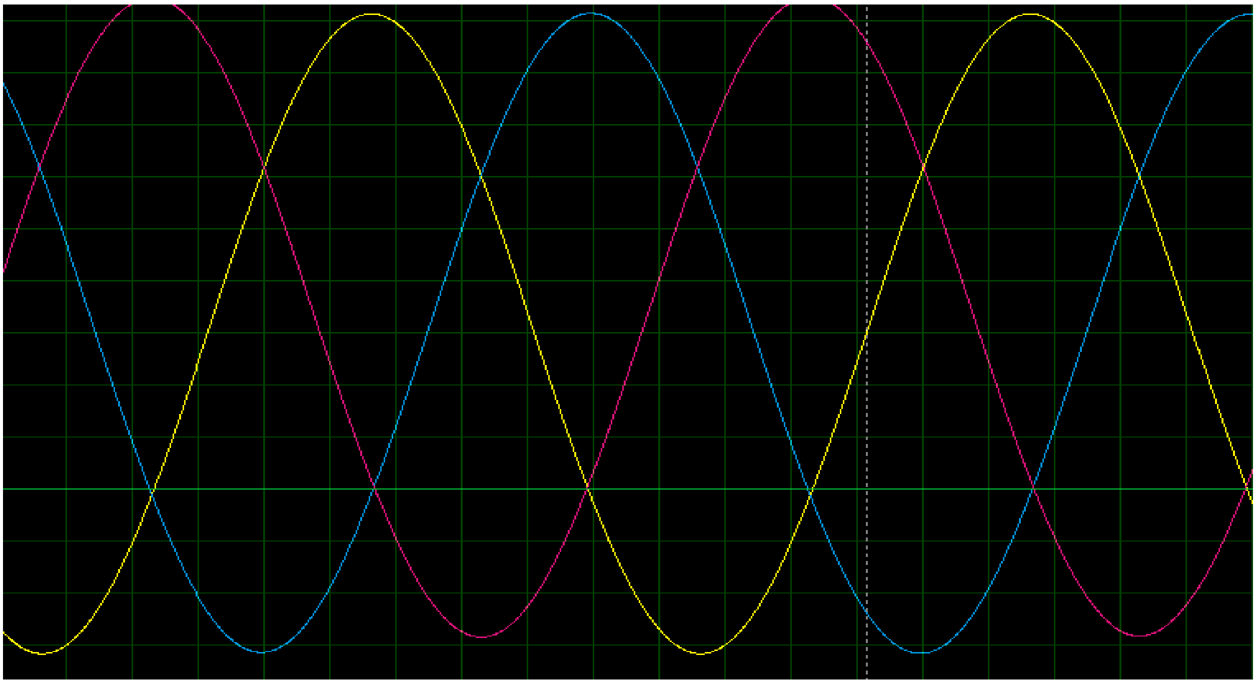

Figure 3- 14: Three-Phase signals on the rectifier

As shown in the simulation results, the current harmonics are greatly reduced and ripple is almost eliminated when the motor is supplied by a PWM inverter compared to simple full wave control. The advantage of PWM control is that not only can it vary the output frequency, but also the amplitude (or voltage) of the stator voltage. This control characteristic (Voltage (V) and Frequency (f) can be varied) is exactly what enables modern PWM inverters to efficiently and effectively supply a motor supply to control the required V/f ratio at different speeds for a given application. This in turn helps to maintain the required flux and torque with minimal low pass filters externally bypassed around the control loop as used with older control techniques.

3.11. Conclusion :

These days, asynchronous motors are frequently linked to variable speed drives or electronic starters to carry out functions like braking, starting, and rotational direction changes in addition to speed changes. The analysis and simulation of power electronics converters have been the focus of this chapter. utilized in rectifier-inverter systems, which are asynchronous machines, to adjust their speed. A PWM inverter-voltage rectifier set was selected as one of the frequency converters used to change

GENERAL CONCLUSION

GENERAL CONCLUSION

Throughout our study, we have presented and designed a variable speed drive for asynchronous motors, drawing inspiration from famous variable speed drives for its reliability, for this study, we were primarily interested in squirrel-cage asynchronous motors where we studied the motor's constitution and operation principle in the first Chapter. In the second chapter, we looked at variable speed drive technology by studying its circuitry to inverter and control by generating PWM signals.

In Chapter 3, by examining the above about the motor and variable speed drive Considering the theoretical aspect as well as the DATASHEET of each component, the circuit was designed using PROTEUS 8.17 and to create the card and then the PCB, EasyEDA Web was used. Finally, this work reaches the purpose and hope it will provide a basis for future studies on variable speed drives for induction motors

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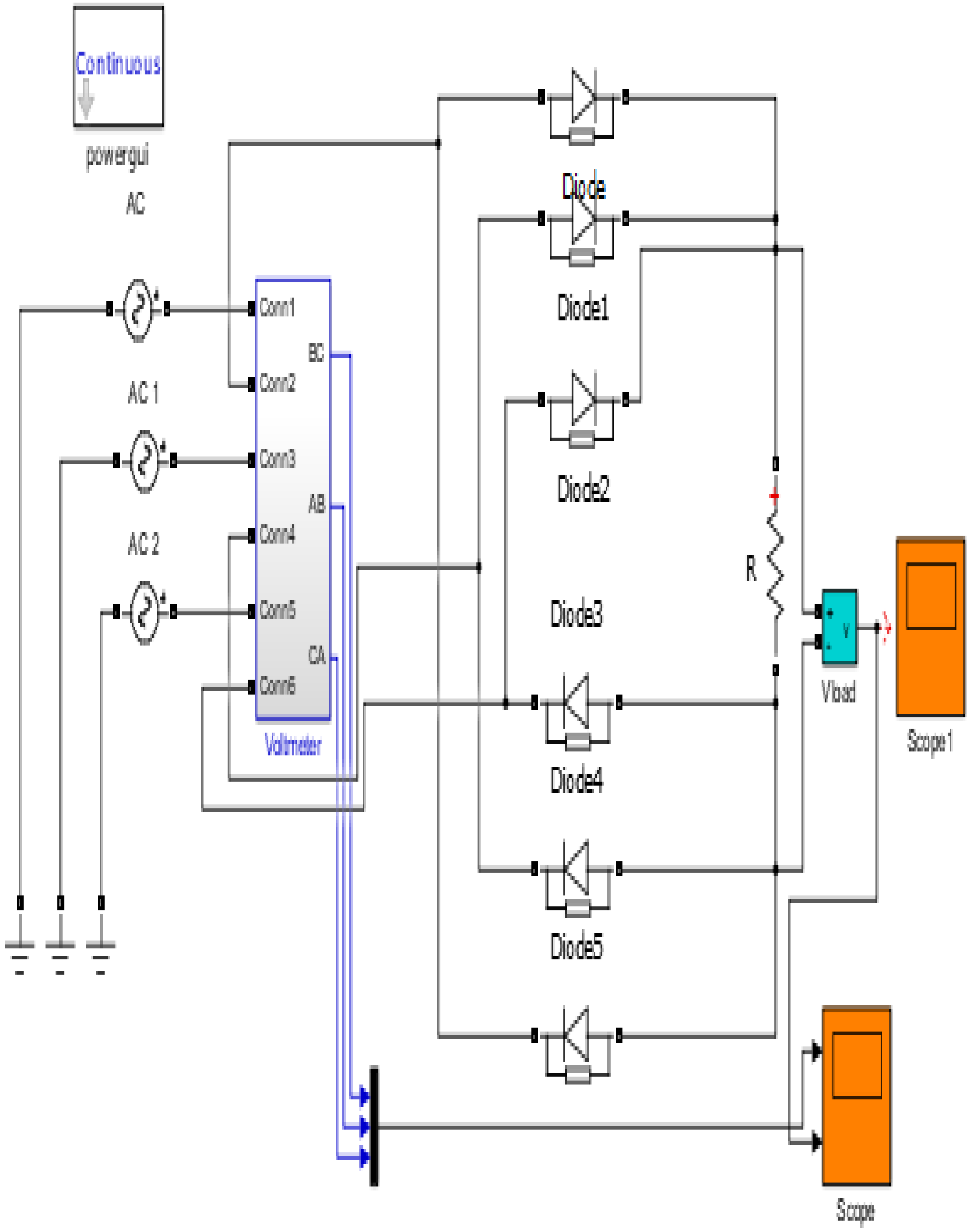
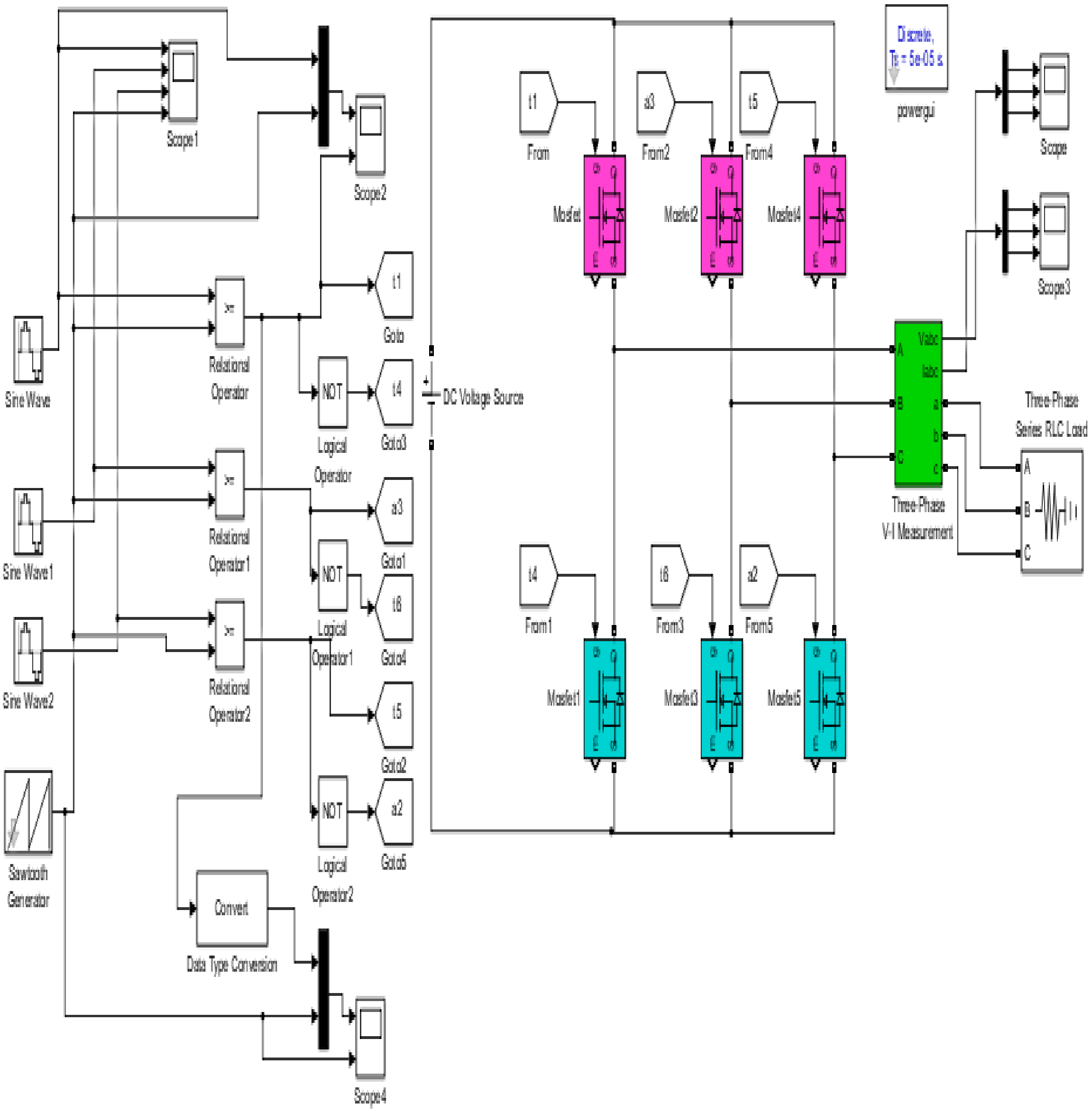
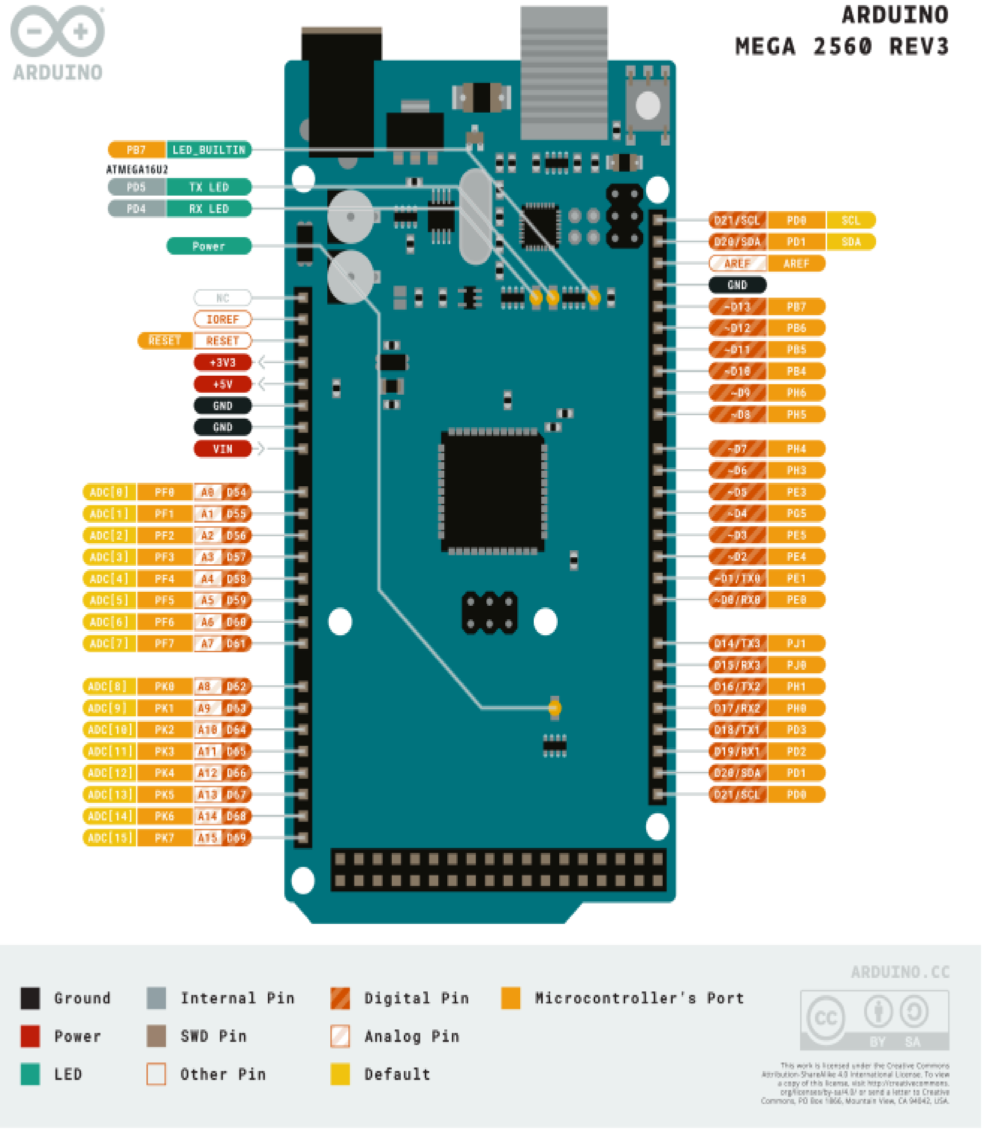
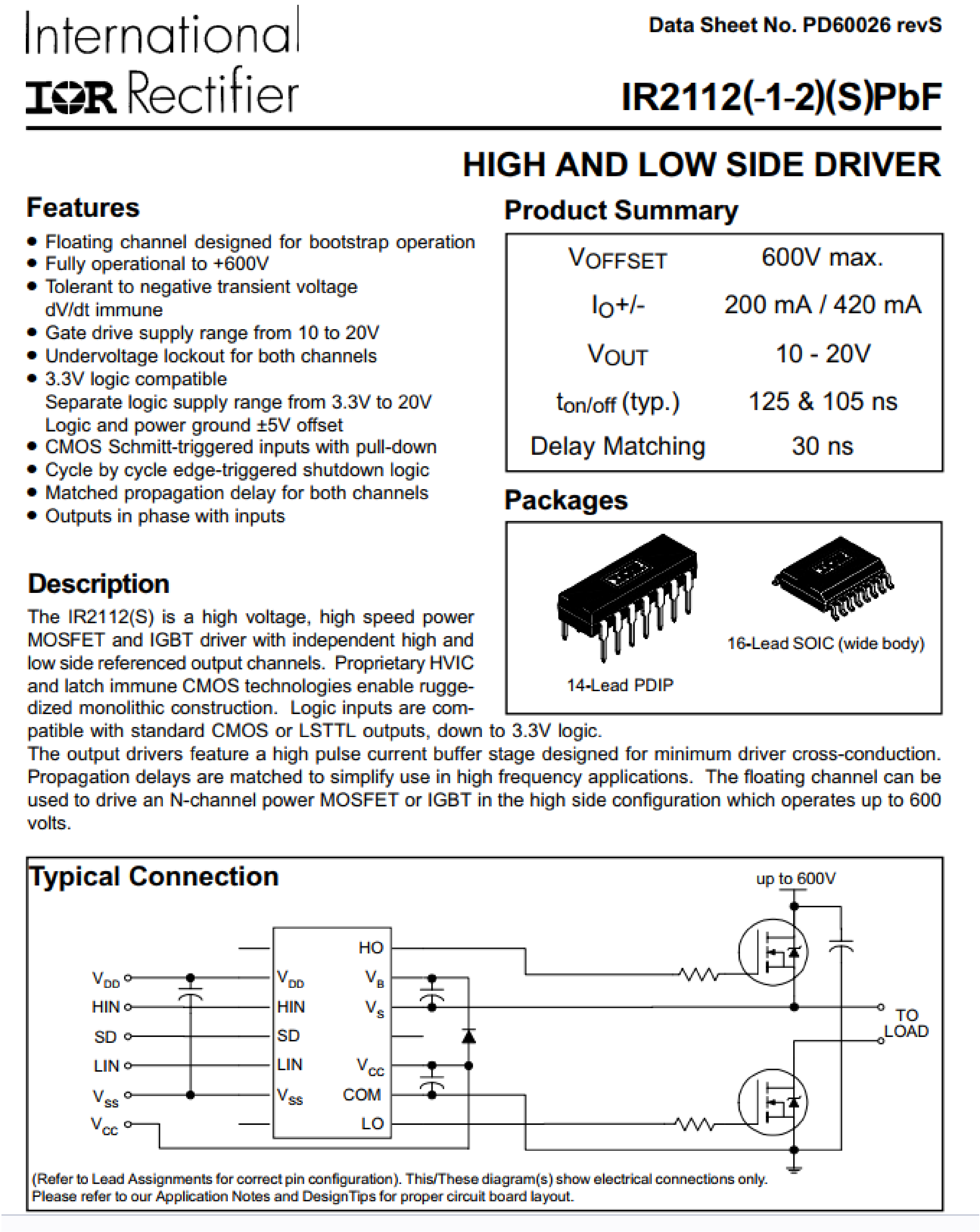

Continuous
powergui
AC
AC 1
AC 2
Conn1
Conn2
Conn3
Conn4
Conn5
Conn6
BC
AB
CA
Voltmeter
Diode
Diode1
Diode2
Diode3
Diode4
Diode5
R
v
Vload
Scope1
Scope


Scope1
Scope2
Sine Wave
Sine Wave1
Sine Wave2
Sawtooth Generator
>=
Relational Operator
Relational Operator1
Relational Operator2
NOT
Logical Operator
Logical Operator1
Logical Operator2
t1
Goto
t4
Goto3
a3
Goto1
t6
Goto4
t5
Goto2
a2
Goto5
Convert
Data Type Conversion
Scope4
DC Voltage Source
t1
From
a3
From2
t5
From4
Mosfet
Mosfet2
Mosfet4
t4
From1
t6
From3
a2
From5
Mosfet1
Mosfet3
Mosfet5
Discrete,
Ts = 5e-05 s.
powergui
Scope
Scope3
Vabc
Iabc
A
B
C
a
b
c
Three-Phase
V-I Measurement
Three-Phase
Series RLC Load
A
B
C

5 Connector Pinouts



Arduino Mega 2560 Rev3 Pinout



International
IOR Rectifier

Data Sheet No. PD60026 revS

IR2112(-1-2)(S)PbF

HIGH AND LOW SIDE DRIVER

Features

- Floating channel designed for bootstrap operation
- Fully operational to +600V
- Tolerant to negative transient voltage
  dV/dt immune
- Gate drive supply range from 10 to 20V
- Undervoltage lockout for both channels
- 3.3V logic compatible
  Separate logic supply range from 3.3V to 20V
  Logic and power ground ±5V offset
- CMOS Schmitt-triggered inputs with pull-down
- Cycle by cycle edge-triggered shutdown logic
- Matched propagation delay for both channels
- Outputs in phase with inputs

Product Summary

V_{OFFSET}	600V max.
I_O+/-	200 mA / 420 mA
V_{OUT}	10 - 20V
$t_{on/off}$ (typ.)	125 & 105 ns
Delay Matching	30 ns

Packages

14-Lead PDIP

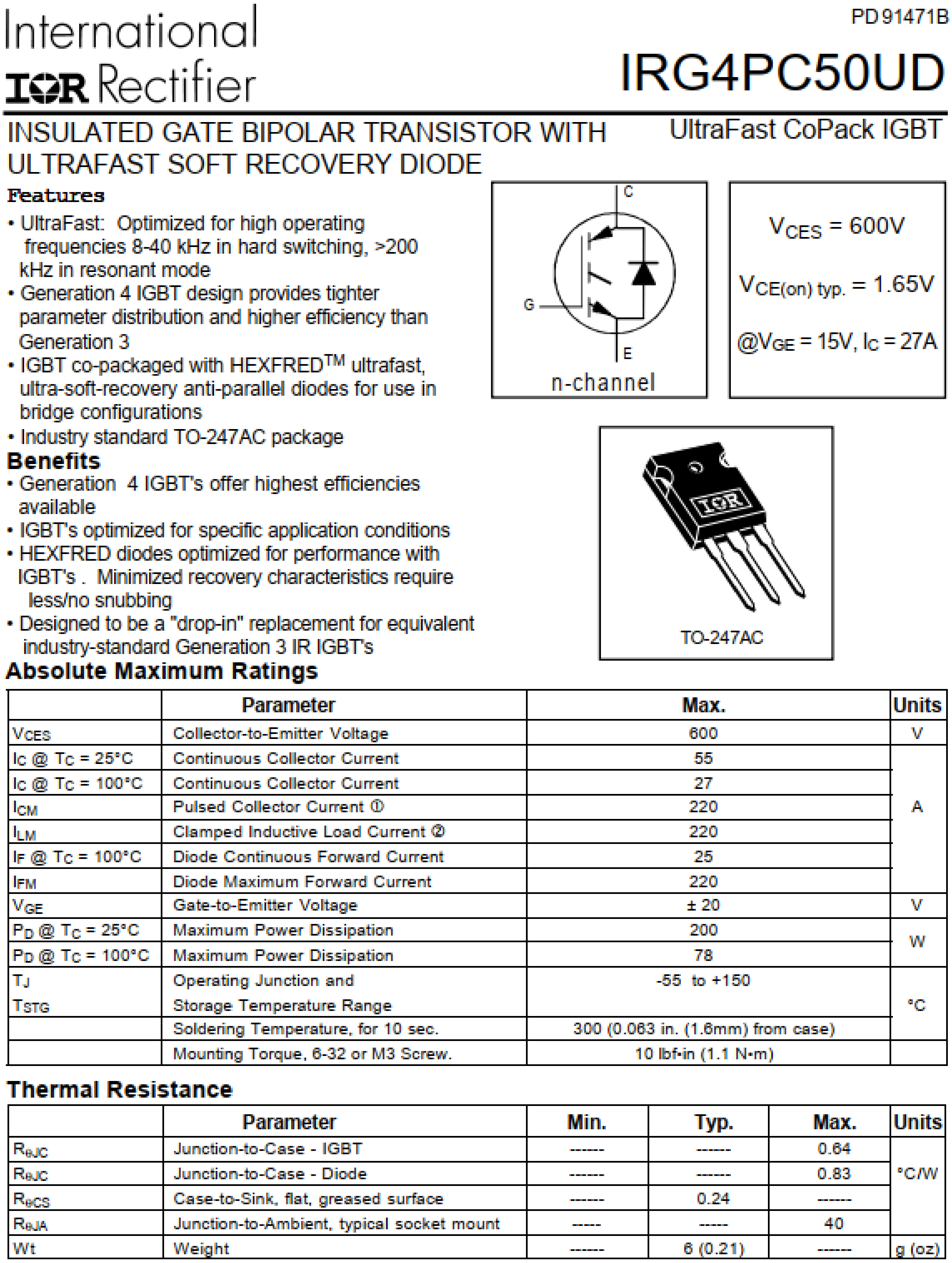
16-Lead SOIC (wide body)

Description

The IR2112(S) is a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. Logic inputs are compatible with standard CMOS or LSTTL outputs, down to 3.3V logic. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 600 volts.

Typical Connection

(Refer to Lead Assignments for correct pin configuration). This/These diagram(s) show electrical connections only. Please refer to our Application Notes and DesignTips for proper circuit board layout.



International
IOR Rectifier

PD 91471B

IRG4PC50UD

INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE

UltraFast CoPack IGBT

Features

- UltraFast: Optimized for high operating frequencies 8-40 kHz in hard switching, >200 kHz in resonant mode
- Generation 4 IGBT design provides tighter parameter distribution and higher efficiency than Generation 3
- IGBT co-packaged with HEXFRED™ ultrafast, ultra-soft-recovery anti-parallel diodes for use in bridge configurations
- Industry standard TO-247AC package

V_{CES} = 600V

$V_{CE(on)\ typ.}$ = 1.65V

@V_{GE} = 15V, I_C = 27A

Benefits

- Generation 4 IGBT's offer highest efficiencies available
- IGBT's optimized for specific application conditions
- HEXFRED diodes optimized for performance with IGBT's . Minimized recovery characteristics require less/no snubbing
- Designed to be a "drop-in" replacement for equivalent industry-standard Generation 3 IR IGBT's

Absolute Maximum Ratings

	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Voltage	600	V
I_C @ T_C = 25°C	Continuous Collector Current	55	A
I_C @ T_C = 100°C	Continuous Collector Current	27	
I_{CM}	Pulsed Collector Current ①	220	
I_{LM}	Clamped Inductive Load Current ②	220	
I_F @ T_C = 100°C	Diode Continuous Forward Current	25	
I_{FM}	Diode Maximum Forward Current	220	
V_{GE}	Gate-to-Emitter Voltage	± 20	V
P_D @ T_C = 25°C	Maximum Power Dissipation	200	W
P_D @ T_C = 100°C	Maximum Power Dissipation	78	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 sec.	300 (0.063 in. (1.6mm) from case)	
	Mounting Torque, 6-32 or M3 Screw.	10 lbf•in (1.1 N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case - IGBT	------	------	0.64	°C/W
$R_{\theta JC}$	Junction-to-Case - Diode	------	------	0.83	
$R_{\theta CS}$	Case-to-Sink, flat, greased surface	------	0.24	------	
$R_{\theta JA}$	Junction-to-Ambient, typical socket mount	-----	-----	40	
Wt	Weight	------	6 (0.21)	------	g (oz)