Adjustable Speed Drive for efficient control of Induction Motor

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Declaration

We hereby certify that No portion of our project" Adjustable speed drive for efficient control of induction motor" referred to in this report has been submitted in fulfillment of another degree or qualification for any other institute or university. The main purpose of the thesis is to provide the reader with brief information about the project if they want to implement the project or decide to continue with further advancements in the future.

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In the name of Allah, the kindest and the most merciful.

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Abbreviations

VFD	**V**ariable **F**requency **D**rive
THD	**T**otal **H**armonic **D**istortion
PWM	**P**ulse **W**idth **M**odulation
AC	**A**lternating **C**urrent
DC	**D**irect **C**urrent
DTC	**D**irect **T**orque **C**ontrol
FOC	**F**orce **O**riented **C**ontrol
RPM	**R**evolution **P**er **M**inute
PID	**P**roportional **I**ntegral **D**erivative
FET	**F**ield **E**ffect **T**ransistor
VSD	**V**arible **S**peed **D**rive
PCB	**P**rinted **C**ircuit **B**oard
PMAC	**P**ermanent **M**agnet **A**lternating **C**urrent
SPWM	**S**inusoidal **P**ulse **W**idth **M**odulation
IGBT	**I**nsolated **G**ate **B**ipolar **T**ransistor
MOSFET	**M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
DMOSFET	**D**epletion **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
EMOSFET	**E**enhancement **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor

Abstract

A device known as an Adjustable Speed Drive, also referred to as a Variable Frequency Drive (VFD), is responsible for modifying the frequency of the input power to the motor. As the frequency changes, the speed of the motor adjusts accordingly. The AC voltages supplied to the motor are initially passed through a Bridge-type Rectifier consisting of diodes that form a bridge. The rectifier then converts the AC voltages into DC voltages. An LC filter is utilized to reduce the ripples on the DC output, which is then transmitted to the inverter segment. The DC buses are composed of an LC filter consisting of an inductor and capacitor. The DC output from the bus is filtered and then converted into AC voltages using IGBTs or FETs within the inverter segment. This process of inverting DC voltages into AC voltages is performed by inverters, which consist of IGBTs or FETs. The inverter uses Pulse Width Modulation (PWM) to generate a three-phase AC output. The Variable Frequency Drive is primarily responsible for enhancing the efficiency and performance of induction motors, and it regulates the motor by maintaining a constant voltage-to-frequency ratio.

Developed countries are consistently striving to optimize the power output of induction motors and seeking to maximize the efficiency and cost-effectiveness of electric sources. As the load varies at the motor output, it functions as a potentiometer for the microcontroller, which then signals the controller to adjust the PWM signal widths accordingly. The inverter is responsible for transmitting the desired sinewave input to the motor, which operates at a specific speed by turning switches, such as FETs or IGBTs, at specified intervals. However, if the output from the inverter is directly fed to the motor without being filtered, it will generate noise and incur heat losses. As such, the LC filter is used to smoothen the sine wave coming from the inverter and eliminate any harmonics or ripples. Consequently, the motor can operate more seamlessly with the sinewave provided to it.

Chapter 1

Introduction and Problem Statement

1.1 The problem to be addressed

The induction motor is most commonly used in various industrial applications, and the load on an induction motor always varies depending on the application. However, an induction motor's speed cannot match the load. [1]
Due to the inability to adjust the speed of the motor with changes in the load, the motor consumes the same amount of energy regardless of the load.[2] Since the motor consumes the same amount of energy regardless of the load on the motor, it must take rated power from the supply. As a result, the energy consumption remains the same when the load varies. [3]
A major concern in developing countries like Pakistan is energy conservation. One solution in order to deal with energy issues and energy crises is to save energy with the least amount of cost. AC motors are responsible for 45 percent of the world's total electricity consumption. There are some issues associated with these motors because they draw a lot of current when they are starting up, which can affect their health. For example, they produce heat and their power consumption increases as a result of these large currents.

1.2 Proposed answer

The objective of this project is to develop Variable Frequency Drives (VFDs) capable of operating at various speeds. By providing adjustable speeds, the system becomes more efficient as the motor only receives the required input power to achieve the desired output. Moreover, VFDs can gradually increase the motor speed and prevent any large inrush current spikes during start-up. These drives are ubiquitous and are employed in a variety of machines such as mine mills, compressors, pumps, and conveyors.
Our project aims to regulate the speed of the induction motor by utilizing the frequency control method, which involves altering the frequency of the motor in tandem with its

speed.
According to the equation:

$$N_s = 120f/P$$

Here,

N_s = Synchronous speed
f= Frequency
P = No. of Poles of the Motor

The synchronous speed of the motor depends on the number of poles and frequency, Hence. Ş̧ynchronous Speed is proportional to the Frequency So, we will vary the speed of the motor through varying the frequency of the input signal applied to the motor. [3]
A device which varies the frequency of the motor is known as Variable Frequency Drive and often known as VFD.
The Variable Frequency Drive (VFD) provides linear control over the speed of the motor. This control can help achieve more precise and accurate motor speed regulation. Furthermore, the VFD also enables a gradual increase in motor speed, thus reducing the inrush current during startup. This reduction in current results in a smoother motor operation during start and stop. Overall, the VFD is an efficient and effective solution for controlling the speed of motors.

Chapter 2

Adjustable Speed Drive

2.1 Introduction to VFD

Variable Frequency Drives, better known as VFDs, vary the frequency of the motor's power input, resulting in a change in the motor's speed.
There are two types of control Frequency control and Voltage control. As far as speed is concerned, frequency control is the better option since it gives better control over the flux density, which is constant with frequency control. To control the smooth speed change of motors, industries use variable frequency drives.[4]
So, we can say VFD is basically a device which convert the motor's input power's frequency and voltage into variable ones.

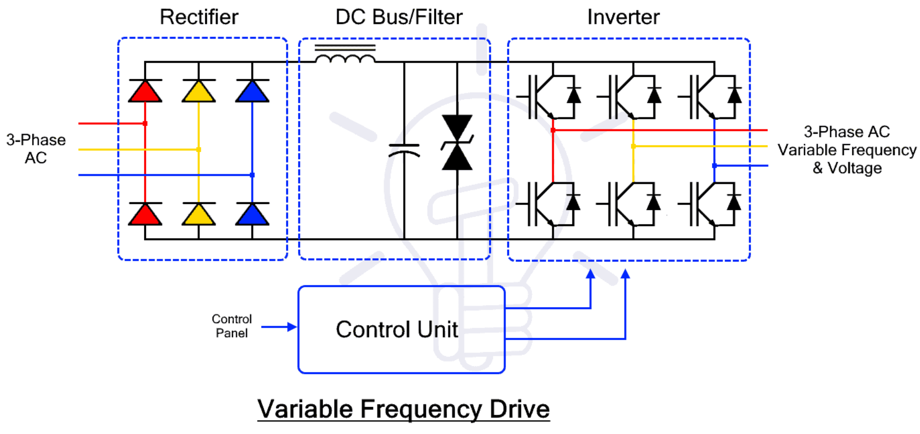

Figure 2.1: Circuit Diagram of VFD.

The speed and torque of AC motors can both be adjusted with a VFD. VFDs, therefore, provide smoother and continuous motor speed changes than gearboxes and eliminate a motor's inrush start current, which it draws at the start of the motor. They also provide smoother start of motors. VFDs are also called variable speed drives.

2.2 Operating Principle of VFDs

Various frequency drives have the main feature of allowing the speed to be adjusted as well as the ability to stop and start the motor softly. Additionally, VFDs eliminate starting inrush current draws by the motor. The aforementioned characteristics are the primary reasons why VFDs are considered to be useful and powerful speed controllers.

There are four parts to a typical VFD, as follows:

1. A rectifier (Bridge Type)
2. A DC link also called DC filter(Capacitor and Inductor)
3. An inverter(Switches i.e., IGBTs or FETs)
4. A control circuit(Usually a microprocessor)

2.2.1 Rectifier

The initial stage of a Variable Frequency Drive (VFD) involves the use of rectifiers. These rectifiers serve the purpose of converting the alternating current (AC) voltages to direct current (DC) voltages. Depending on the specific product design and specifications, rectifiers can be either half-bridge or full-bridge. Diodes, transistors, or silicon-controlled rectifiers (SCRs) are utilized in the rectifiers to achieve this conversion. This DC voltage is then passed through an LC filter to minimize ripples before being sent to the inverter segment for conversion to AC voltage. The efficiency and performance of the motor are enhanced by using VFDs to regulate its speed, which ultimately leads to energy savings and increased productivity.

- When a diode is used as a rectifier, DC power output is uncontrolled and dependent on the diode
- In the case of SCR, gate terminal is used to control the power output in DC.

For a three-phase conversion of AC voltages to DC Voltages rectifier use six diodes.[5] So when using six diodes that kind of rectifier is known as six-pulse-converter.

2.2.2 DC bus/Filter

After the rectifier stage of a Variable Frequency Drive (VFD), the resulting DC power output contains ripples that can impact the performance of the motor. To eliminate these ripples, DC bus or DC filters are employed to smoothen the DC output. These filters consist of inductors and capacitors that work together to reduce the ripples present

in the DC power output.
The inductors filter out the high-frequency ripples, while the capacitors filter out the low-frequency ripples. This process of smoothing out the DC output is crucial in ensuring that the inverter receives a stable and consistent DC voltage input. The filtered DC output is then sent to the inverter segment, where it is converted into AC voltage for the motor to operate at the desired speed. The use of DC filters is a vital component of VFDs, as it not only helps in eliminating ripples but also improves the overall performance and efficiency of the motor.

2.2.3 Inverter

The inverter is a device that converts DC power to AC power, which is essential for the operation of the motor. The inverter contains electronic switches such as transistors, IGBTs, or FETs that convert the DC power into AC power.
Pulse width modulation (PWM) is a technique used by inverters to control the frequency of the AC power and thus control the speed of the motor.[4] This process of changing the frequency according to the needs of the motor allows for efficient and precise speed control. Inverters play a crucial role in the performance of induction motors, as they ensure that the motor runs smoothly and with optimal energy efficiency.

2.2.4 Control circuit

The Control Circuit, as the name suggests, is responsible for controlling the overall operation of the VFD. Microcontrollers are an integral part of this circuit and are used for controlling and communicating with various devices, as well as detecting and reporting any fault conditions that may occur during operation.
In the case of VFDs, the microcontroller receives feedback signals from the motor and updates the output continuously according to the provided algorithm. The control circuit is responsible for ensuring that the motor operates at the desired speed and power output

2.3 Types of VFDs

There are different types of VFDs available that vary the speed of a specific motor based on their operating principles.
Those are:

1. Voltage source inverter (VSI)
2. Current source inverter (CSI)
3. Pulse width modulation (PWM) inverter
4. Space vector modulation (SVM) inverter
5. Matrix converter
6. Multilevel inverter

2.3.1 Voltage-Source Inverter

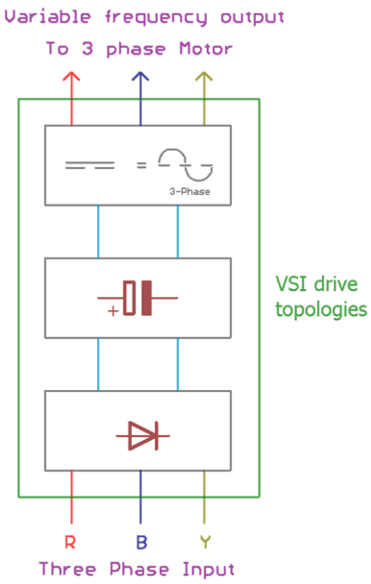

Figure 2.2: VSI drive topologies

One type of Variable Frequency Drive that is commonly used is known as Voltage Source Inverter (VSI). A basic configuration of diode bridge is used to convert AC power into DC power. A capacitor is used in the DC bus or DC filter section to store this energy. Following the Rectifier and DC Filter, an inverter is utilized, and the stored energy in the DC filter section's capacitor is supplied to the inverter. The inverter, through switching, generates output.

2.3.1.1 Advantage of VSI

High-efficiency: VSI provides high efficiency due to the conversion of DC to AC power using high-quality switches and control strategies.

Flexible speed control: VSI can provide precise and flexible speed control for induction motors with a wide range of speeds.

Smooth operation: VSI provides smooth operation due to its ability to control the frequency and voltage of the motor output.

Improved power factor VSI can help improve the power factor of the induction motor by reducing the reactive power.

Reduced mechanical stress: VSI can reduce the mechanical stress on the induction motor by gradually increasing the motor speed during startup and eliminating large inrush current spikes.

2.3.1.2 Disadvantages of Voltage-Source Inverter

- Cogging effect is one of the disadvantages of VSI Type VFD as in cogging effect there is a jerking in the motor when motor starts or stops.
- VSI type VFD's output delivers noises.
- In VSI type VFD there are harmonics at its output.
- Variation of Power Factor with varying the speed of the motor is high.

2.3.2 Current Source Inverter

Another kind of Variable Frequency Drive is CSI or Current Source Inverter.
In Voltage Source Inverter (VSI) type VFDs, a simple bridge of diodes is used to convert the AC power input into DC power. However, when the output current needs to be smoother, Current Source Inverter (CSI) type VFDs are employed. In CSI type VFDs, the design is based on current rather than voltage as in VSI type VFDs.
Unlike diodes, SCRs are used in the Current Source Inverter type VFDs. Moreover, in the DC bus or DC filter section, inductors connected in series are utilized to filter out the power coming from the SCRs. The Current Source Inverter works just like a constant current generator, and it produces the square wave output of the current instead of the voltage, which is produced in VSI.

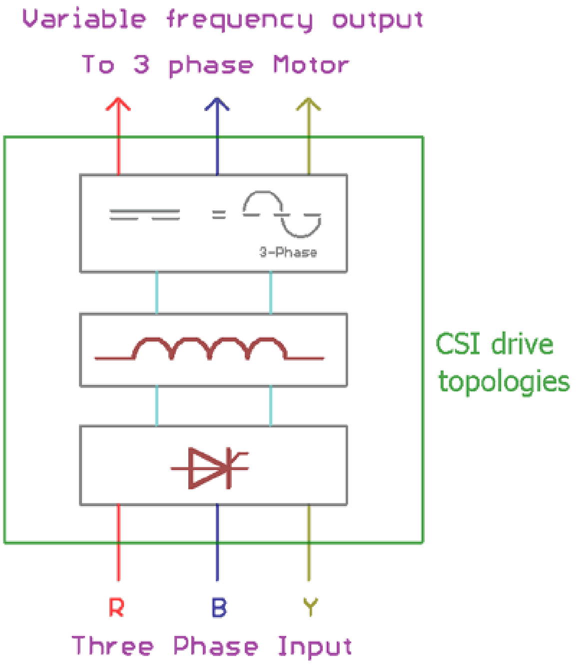

FIGURE 2.3: CSI drive topologies

2.3.2.1 Advantages of CSI

Good for high torque applications: CSI is preferred for high torque applications as it can provide a more stable and smoother output current compared to VSI.

Better performance in variable speed ranges: CSI has better performance in variable speed ranges and can adjust to the motor's requirements more effectively.

Improved power factor: CSI has a better power factor than VSI which means it operates more efficiently and can save energy.

Improved overload capacity: CSI can handle higher overload capacity and can provide better protection for the motor.

Better fault tolerance: CSI can handle faults better and can operate safely even when there are issues with the power supply or the motor.

2.3.2.2 Disadvantages of CSI

- Power Factor when using Current Source Inverter type VFDs is usually poor when dealing with the motor at low RPM.
- Cogging effect is one of the disadvantages of Current Source Inverter Type VFD too because cogging effect make motor's shaft throb.
- As more than one motors can be controlled using only one Voltage Source Inverter type VFD but in case of Current Source Inverter type VFDs we cannot control more motors with one Current Source Inverter type VFD.

2.3.3 Pulse Width Modulation

Pulse Width Modulation, also known as PWM, is an advanced technique used in Variable Frequency Drives that provides several advantages over the traditional Voltage Source Inverter VSI. One of the key benefits of PWM is that it maintains a constant VOLTS/HERTZ ratio, making it more efficient in controlling motor speed.
The basic design of a PWM includes a rectifier with diodes that convert AC power to DC power. The pulse duty cycle is then controlled by switching IGBTs or FETs, which are adjustable over a range of frequencies. Additionally, a regulator is employed to ensure stable output of voltages and currents for the load.
Another advantage of PWM is that it reduces harmonic distortion, which can cause damage to the motor and other connected equipment. PWM also provides better control of motor speed, torque, and direction, making it an ideal choice for applications that require high precision and accuracy.
Overall, PWM technology is becoming increasingly popular in Variable Frequency Drives due to its superior performance and efficiency compared to other types of VFDs.

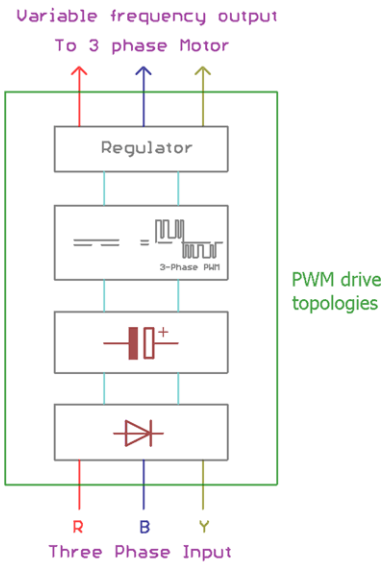

FIGURE 2.4: PWM drive topologies

2.3.3.1 Advantage of PWM

- Through Pulse Width Modulation clogging effect is minimized
- Wide range of the speed of motor can be controlled through Pulse Width Modulation technique.
- Provide better protection than CSI and VSI.
- Power factor variations does not occur i.e., it remains constant.
- Efficiency is higher as compared to VSI and CSI.

2.3.3.2 Disadvantages of PWM

- Design is not simple as compared to the design of CSI and VSI
- Complex in respect of the implementation.
- Requires additional hardware.
- VFDs using Pulse Width Modulation techniques' output delivers noises.
- Not very economical financially as compared to the design of CSI and VSI.

2.4 Applications and Advantages of VFDs

2.4.1 Applications of VFD

VFDs are most commonly used in industrial applications that include induction motors. There are numerous applications where VFD can be used productively which are listed below:

- Cooling tower
- Boilers and Forced Draught Fan
- Constant Air Volume (CAV) System
- Pump control
- Screw Press
- Elevators

2.4.2 Advantages of VFD

Benefits and advantages of Variable Frequency Drives are listed below,

- Using Variable Frequency Drive motor start smoothly.
- smooth acceleration deceleration time
- Methods to stop the motors are provided by Variable Frequency Drives[6]
- Variable Frequency Drive provides protection from the flow of reverse current of the motor.
- Harmonics through Variable Frequency Drive can be eliminated up to much extent
- Variable Frequency Drive provides stable Power Factor
- Financially efficient

Chapter 3

Control Techniques for VFDs

Two methods of variable frequency control have been introduced. They are as follows

- Scalar Control Method
- Vector Control Method
- Direct Torque Control (DTC)
- Sensorless Control
- Space Vector Modulation (SVM)

3.1 Scalar Control Method

This technique is also known as V/f (Voltage to Frequency) control. It involves maintaining a constant ratio of voltage to frequency. This technique is simple and cost-effective, but it may not be suitable for high-performance applications. It has two types.

- Open loop scalar control
- Closed loop scalar control

3.1.0.1 Open Loop Scalar Control

Open loop scalar control is a widely used technique in industry which doesn't require a desired output signal, hence the name "open loop". It is a simple and cost-effective method as it doesn't require any feedback signal. The motor speed is controlled by varying the frequency and voltage at the same time.[7] This open loop control scheme does not take into account the torque control, which makes it less desirable or important.

3.1.1 Close Loop Scalar Control

This scalar control method provides accurate and precise control over both speed and torque. Torque can be controlled directly or indirectly. In indirect torque control, torque is controlled by controlling the slip as it is directly proportional to the torque. Unlike open loop scalar control, this type of control incorporates feedback signals to obtain the current speed value, which can then be compared to the desired speed. If the difference between the two is not zero, controllers are used to make it zero and bring the motor to the desired value.

3.2 Vector Control Method

The Vector Control Method is a control technique used in variable-frequency drives (VFDs) where the currents in the stator of a three-phase AC electric motor are separately identified as two orthogonal components, forming a vector. One of these components represents the motor's flux, while the other defines its torque. This allows independent control of the torque and magnetic flux since the currents inducing flux and torque can be controlled separately.[8]

Two types of vector control methods are:

- Direct Torque Control (DTC)
- Force Oriented Control (FOC)

3.3 Direct Torque Control

In this type of control, we select stator flux as reference frame. In this technique, it is considered that rotor current always remains same throughout the time of interest. As for stator resistance, we consider it to be zero and its voltage remains constant throughout the time interval. If switching frequency of the inverter is compared with sampling frequency of the system, it turns out to be very low. The main objective of DTC is to control particular value of torque generated by particular value of voltage obtained from three phase inverter.

3.4 Sensorless Control

This technique eliminates the need for position sensors by using advanced algorithms to estimate the motor's position and speed. It reduces costs and improves reliability, but it may not be suitable for all applications.[9]

3.5 Space Vector Modulation (SVM):

This technique involves generating three-phase voltage signals by combining two-phase signals. It offers high efficiency and low harmonic distortion, making it ideal for high-performance applications.

3.6 Pulse Width Modulation (PWM) and its Advantages

As previously noted, Pulse Width Modulation (PWM) is an enhanced and more efficient version of the Voltage Source Inverter (VSI).

Pulse Width Modulation (PWM) is an advanced control technique used in various applications, such as motor control, power inverters, and lighting systems. It is a method of controlling the average voltage or current of a signal by varying the duty cycle of a pulse waveform. The duty cycle is the ratio of the ON time of the signal to its total period. The higher the duty cycle, the higher the average voltage or current. The PWM control method ensures that the output voltage or current is stable and regulated, which leads to better efficiency and performance of the system. In addition to the rectifier and regulator, the PWM design includes a microcontroller that generates the control signals for the IGBTs or FETs based on the input signal and the desired output. This enables the PWM to provide precise control of the output voltage or current, resulting in a high-quality output waveform.[10]

The Pulse Width Modulation (PWM) technique allows the control of analog circuits using digital outputs from a microprocessor. Unlike traditional methods that require Digital-to-Analog conversion, PWM keeps the signal digital, which reduces noise effects. Instead of a continuously varying (analog) signal, PWM distributes energy through a series of pulses. By adjusting the pulse width, the energy flow to the motor shaft can be effectively controlled. This method is widely used in various applications such as motor control, power supplies, and lighting.

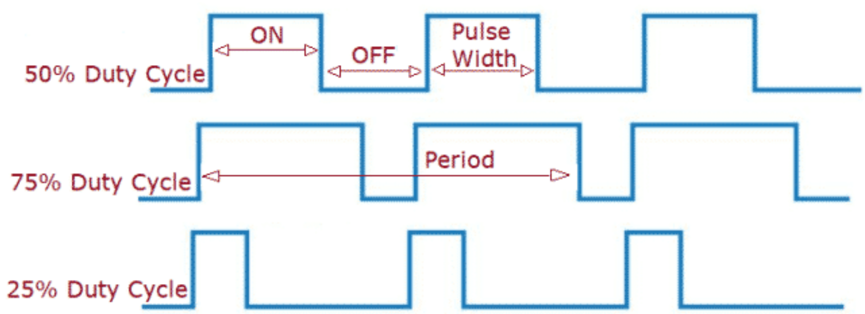

FIGURE 3.1: Pulse Width Modulation (PWM)

Figure illustrate PWM Waves with 50%, 75% and 25% of duty cycles.[11]

By changing the pulse's width, we can control or regulate the applied voltages. This changed voltage is basically average voltages. And the time at which the output wane has at HIGH, if varied we can vary the voltages. i.e., the average voltage. And this average value of the voltage is dependent on the value of the duty cycle. we can see from the Fig. b below, that when the wave remain at the time at HIGH i.e., ON was more the average value of the voltage was more and vice versa.

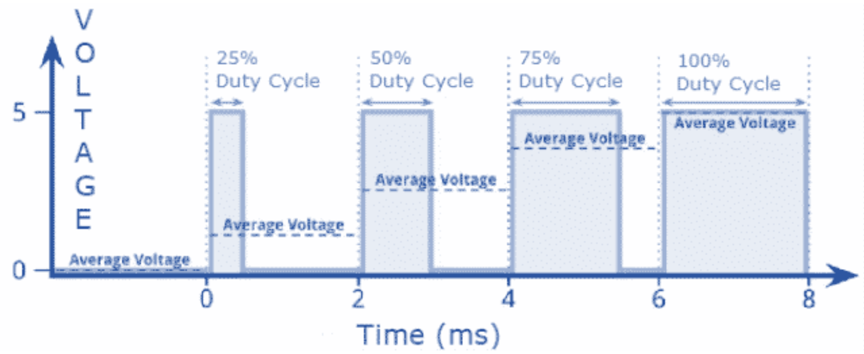

FIGURE 3.2: Illustration for Average value of Voltage

The performance of most six-step inverter systems is limited at low speeds and often considered unacceptable.
The torque produced by the stator's field of rotation in a six-step system is more pulsating due to its stepwise nature. Therefore, these systems have a limited range where acceptable performance can be achieved.
The Pulse Width Modulated PWM technique is also used for the purpose that it improves the performance of the DC filter.
The advantage is that switching at high speed is achieved which will make the wave more sinusoidal even when the speed of the motor is low hence giving the motor a smooth operation.
Obtained result can be an extremely good performance at low speeds as well as high and the ability to control the motor accurately around zero speed.
As the technique is basically electronic its cost has been reducing steadily as large-scale integrated circuits and microprocessors have tumbled in price, so this system is nowadays very popular. Although this system is by no means new, having been used certainly in the late 1960's, its use has increased recently because of the availability of faster switching devices like transistors and gates turn off thyristors. This technique involves switching the inverter at a rate at least ten times the maximum output frequency desired and hence good switching performance is essential for this system.

3.6.1 PWM signal formation

A pulse width modulating signal is generated using a comparator. The modulating signal forms one part of the input to the comparator, while the non-sinusoidal wave or sawtooth waveforms the other part of the input. A comparator compares the two signals

and generates a PWM signal as its output waveform. If the sawtooth signal is greater than the modulating signal, the output signal is in the "high" state. The magnitude value determines the comparator output which defines the width of the pulse generated at the output.
A comparison circuit is utilized for generating PWM as illustrated in Figure c. Two inputs are provided to the comparator, where one is fed to the comparator and the other one is supplied by a wave that is different from the sinusoidal wave, which could be a sawtooth wave. The process of modulation is performed at the carrier frequency. The comparator functions by comparing both waves and generating the output pulse width modulation wave, resulting in a modulated pulse signal as shown in the figure. The pulse width modulation signal at the output is high when the sawtooth signal is greater than the modulation signal and vice versa. Thus, the output of the comparator is determined by the applied signal at the input, i.e., the sawtooth wave, which describes or indicates the width of the modulated pulse signal.
Pulse Width Modulation signal at the output will be HIGH when from both the input signals,

Sawtooth Signal > Modulation Signal and vice versa. Therefore,

The output of the comparator is defined by the applied signal at input i.e., saw tooth. Which will then describe or tell the width of the Modulated Pulse Signal.

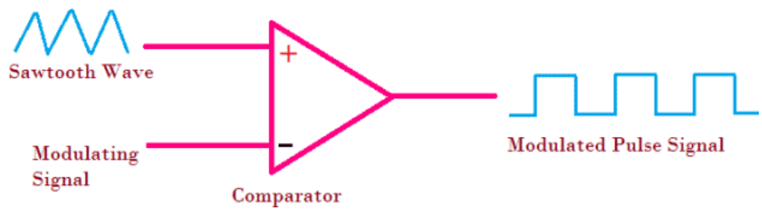

FIGURE 3.3: Comparator

3.6.2 Duty Cycle

In signals, we define logic high as "on time". We use the concept of a work cycle to express "on time". Simply put, the duty cycle describes the percentage of time a digital signal is "on" during an interval or period. It is expressed as a percentage (%).
Let's take a signal with a maximum voltage of 10V. If our signal takes one second to complete a cycle and the signal is on for 0.5 seconds and off for another 0.5 seconds, this is called a 50% duty cycle and we get 5V as the average output voltage. If the signal is on for 0.75 seconds and off for another 0.25 seconds, that will be a 75% duty cycle and the output will be 7.5V. Signals having different duty cycles are shown in the figure

given below: By varying the duty cycles, we got the different signals as shown above.

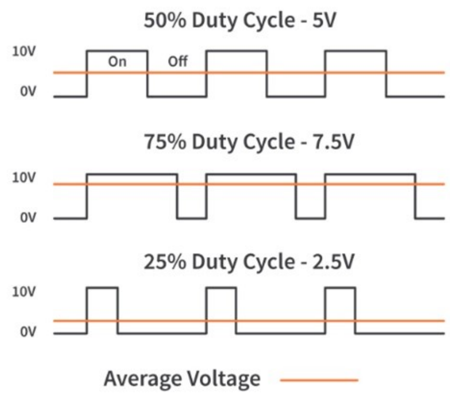

FIGURE 3.4: Single PWM Technique

The duty cycles can be calculated by the formula:

$$D = T_{ON}/(TotalTimePeriod) \times 100$$

where

D = Duty cycle in percentage (%) T_{ON} = Time Duration of the signal being in the 'ON' state Total time = Time is taken to complete one cycle ($T_{ON} + T_{OFF}$)

As we have calculated the duty cycle, we can also calculate the average voltage of the signal:

$$V_a vg = D/100 \times V_{max}$$

where D = Duty cycle in percentage (%)
V_{avg}= Average Voltage of the signal
V_{max}= Maximum voltage of the signal

3.6.3 Advantages of PWM

The following are the advantages of Pulse Width Modulation:

1. As we discussed earlier, the cooling of motherboard process by the help of small fans that operate through of PWM techniques are helpful for maintaining the temperature of the motherboard to normal.

2. PWM technique facilitates in preventing LED's overheating while maintaining and keeping its brightness.

3. Accuracy is achieved by using PWM.

4. Through Pulse Width Modulation clogging effect is minimized
5. Wide range of the speed of motor can be controlled through Pulse Width Modulation technique.
6. Power factor variations does not occur i.e., it remains constant.
7. Efficiency of PWM technique is high.

3.6.4 Applications of PWM

The applications are:

- PWM techniques are used in programming or encoding.
- PWM is used where regulating the voltage is required.
- PWM is used in VFDs to control the motor's speed linearly.
- In cooling process of the motherboard or other appliances like chips etc. Fans are operated through PWM technique.
- Different amplifiers also use Pulse Width Modulation technique.

3.7 PWM Techniques

There are different ways to generate a PWM signal. We can use a 555 Timer IC or even a comparator circuit to generate it. But the easiest way to see PWM in action is with a microcontroller. We can generate a PWM signal with popular microcontroller boards like the Arduino Uno by just entering a few lines in our code! The PWM circuit present on microcontrollers uses timers in the backend, but they are internally connected to pins to make our work easier. For example, if we want to generate a PWM signal to change the speed of a DC motor with our Arduino Uno, we can use Arduino's analogWrite() function. In the case of the Arduino Uno, there are only 6 I/O pins (3,5,6,9,10,11) and the frequency at pin9, pin10, pin11, and pin3 is 490 Hz, and the frequency at pin5 and pin6 is 980 Hz that support PWM generation and are marked with a tilde ( ) before the PIN on the board. The analogWrite() function, which is available by default in the Arduino IDE, is used to generate the PWM signal. The function can generate PWM with the default frequency of each pin. A fixed frequency PWM waveform can be generated on each of these pins using the analogWrite() command. The first argument to analogWrite() is the PIN from which we want to get the PWM signal. The second argument is the duty cycle. The duty cycle can range from 0 to 255, which corresponds to a 0 to 100% duty cycle in percent, where a pass of 0 represents a 0% duty cycle and 255 represents a 100% duty cycle. However, it is crucial to note here that not all Arduino Uno pins are capable of generating a PWM signal.

The different techniques of PWM are given below:

- Single-pulse width modulation technique
- Third harmonic injection pulse width modulation
- Multiple-pulse width modulation
- Sinusoidal pulse width modulation
- Hysteresis band pulse width modulation
- Space vector pulse width modulation

3.7.1 Single Pulse Width Modulation Technique

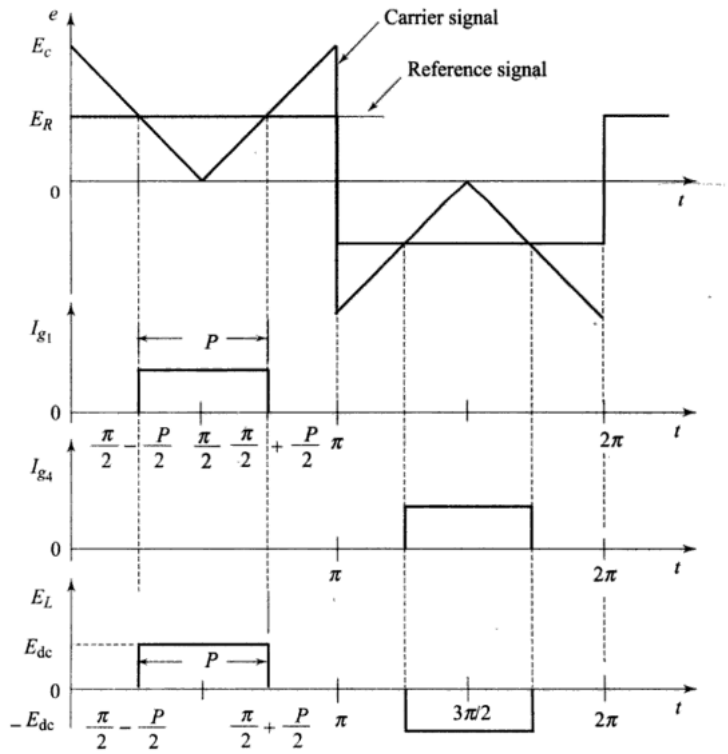

FIGURE 3.5: Single PWM Technique

For single-phase circuits, the output voltage of the inverter can be adjusted by modifying the pulse Duty Cycle, which controls the signal width. Altering the width of the carrier signal can change the ON time of the transistor, resulting in a variation of the inverter output voltage as the transistor time is adjusted.

3.7.2 Third Harmonic Injection Pulse Width Modulation

Adding a 3rd harmonic signal to a sine wave reference signal of low frequency can increase the amplitude of the output voltage signal without causing any distortion on the phase voltages. This is because the absence of the 3rd harmonic voltage on the phase voltages and the line to line for a three-phase load with a floating-point neutral point.

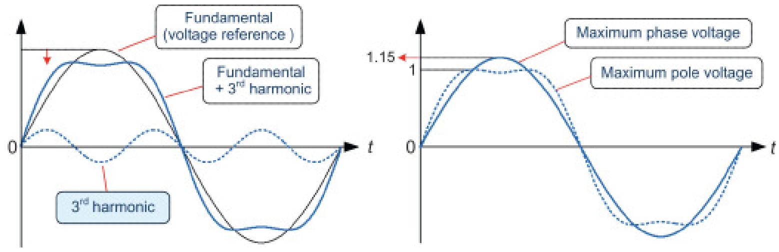

FIGURE 3.6: Principle of THIPWM

3.7.3 Multiple Pulse Width Modulation

The pulse width modulation technique is called a Multiple PWM when output voltage is each half cycle consists of more or multiple number of pulses. By varying the carrier signal eac pulse will vary.
Triangular wave's frequency > Triangular wave's frequency of SPWM,
Through multiple PWM, the harmonics can be decreased. The frequency determines the number of pulses per half cycle.

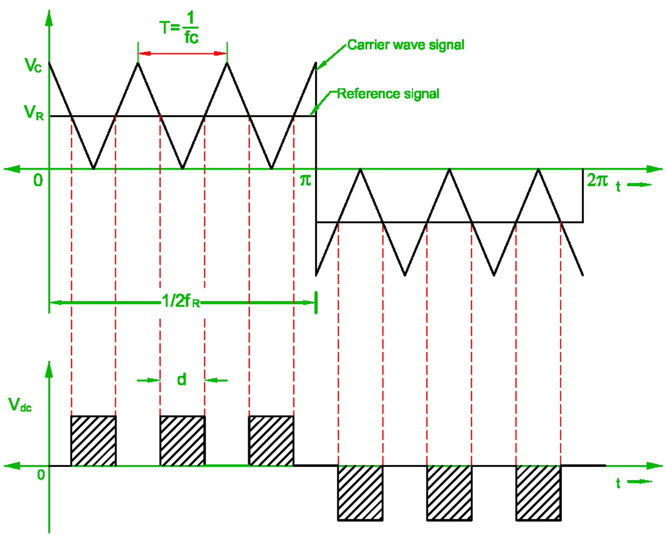

FIGURE 3.7: Multiple Pulse Width Modulation

3.7.4 Sinusoidal Pulse Width Modulation

As the name implies the modulating signal will be sinusoidal and the output of the PWM will be a sine wave. We compare triangular wave with sine wave called the reference wave (sinusoidal). This Sinusoidal Pulse Width Modulation technique eliminate the harmonics which are less than a specific value.

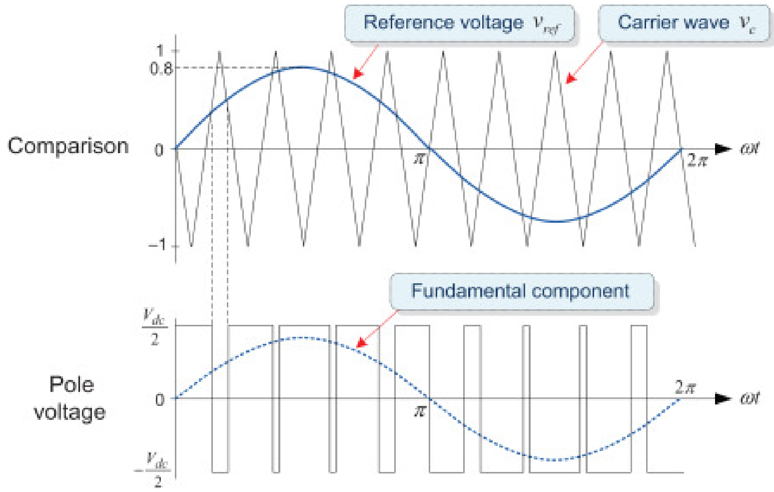

FIGURE 3.8: Sinusoidal PWM

3.7.5 Hysteresis band pulse width modulation technique

Hysteresis PWM refers to a technique where the output can freely oscillate within a predefined error band, known as a "hysteresis band". Switching moments in this case is generated from the peaks of the triangle wave. Hysteresis PWM techniques do not rely on any inverter load information Properties. If the reference signal is known and the inverter output voltage is not saturated, the inverter output will always follow the reference path band. For this technique, the switching frequency of the power supply is not fixed and will vary accordingly on the size and frequency of the reference. So, the switching losses with this technique can be higher than with other techniques. The PWM hysteresis band

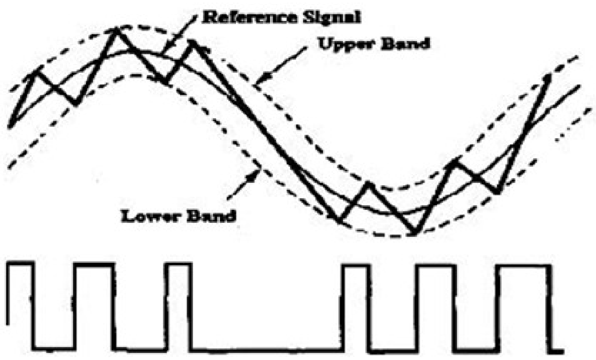

FIGURE 3.9: Sinusoidal PWM

is described as instantaneous feedback PWM current control method where current the current smoothly follows the command currently in a specified hysteresis band.

3.7.6 Space vector pulse width modulation technique

Space Vector PW Modulation (SVPWM) is a pulse width modulation (PWM) control algorithm. Used to create alternating current (AC) waveforms, it is most commonly used to drive three-phase AC motors at different speeds from DC using multiple class D amplifiers. The harmonics present at the output are reduced and therefore this vector modulation method offers optimum output current or voltage.

Chapter 4

Fundamentals of Microcontrollers

4.1 Introduction to Microcontrollers

A Microcontroller is a computer on a chip.
A Micro-controller is a small computing device that can be designed as a single-chip computer. It is called a "controller" because its purpose is to control or regulate a particular function. These devices are often referred to as embedded controllers because they are typically manufactured or assembled within the electrical appliance they are designed to monitor. With the increasing use of micro-controllers in various devices we use on a daily basis, they have become an essential component of modern technology.
Micro-controllers possess a wide range of attributes including assessing, saving, supplying, controlling, regulating, evaluating, and displaying information. These devices find extensive usage in various industries, with the automotive industry being a significant beneficiary of their capabilities.

4.2 PID, PD, PI ,and P Controllers

The initial type of micro-controller is the P controller. Its output is the result of the product of the error signal and the proportional gain. K_p.

$$p(t) = K_p * e(t)$$

The P controller fails to reduce the steady state error. To overcome this limitation, the PI controller is employed. This Micro-controller type can effectively reduce the error. K_p.

$$i(t) = K_i \int e(t)dt$$

One approach to address the steady-state error limitation of P controllers is by using a PI controller, which employs integral techniques. However, this method may introduce stability and final response issues. To counter these problems, a PD micro-controller is often used to minimize stability errors.

$$i(t) = K_i \int e(t)dt$$

However, the PD controller alone may not be the optimal solution for Variable Frequency Drive (VFD) applications. While it can improve the value of the differential gain K_d, it may not be sufficient to address all the issues mentioned earlier. To achieve comprehensive error reduction, the final controller used is the PID controller, which incorporates all the aforementioned functions.
For this project, we have chosen to implement a PID micro-controller as it offers all the necessary solutions to the problems we have identified.[12] Testing has been performed on ARDUINO UNO board.

4.3 Overview of ARDUINO UNO Microcontroller

The Arduino Uno is a microcontroller that is free to use and open-source. It is based on the Microchip ATmega328P microcontroller and was created by Arduino.cc. This board provides a software and hardware environment that is designed to facilitate easy and efficient programming based on Harvard architecture. The user manual for the Arduino Uno is simple and its programming is considered easy when compared to other microcontrollers, which makes it a popular choice for testing and project development.

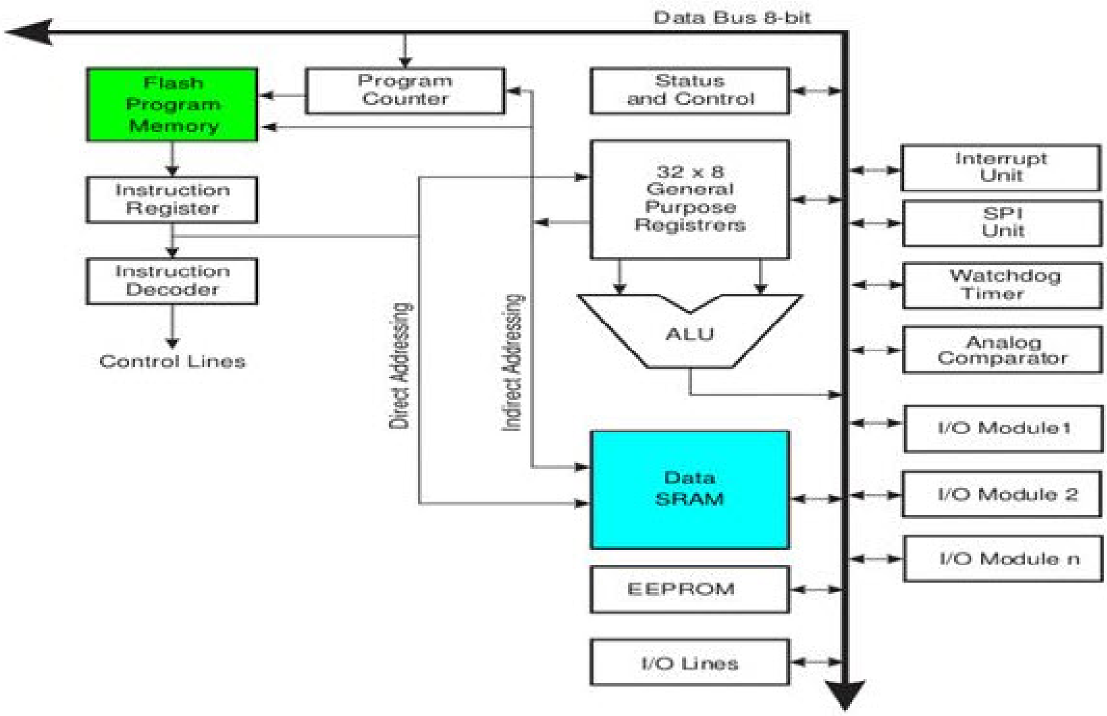

Figure 4.1: Arduino UNO Architecture

4.4 Overview of ARDUINO NANO Microcontroller

The Arduino Nano is a compact and versatile microcontroller board based on the ATmega328P microcontroller. It is part of the Arduino family of boards and is widely used in hobbyist projects, prototyping, and educational settings. Despite its small size, the Arduino Nano offers a wide range of features and capabilities, making it a popular choice among makers and electronics enthusiasts.

At its core, the Arduino Nano is built around the ATmega328P microcontroller, which operates at a clock speed of 16 MHz. This microcontroller provides 32KB of flash memory for storing the program code, 2KB of SRAM for variable storage, and 1KB of EEPROM for non-volatile data storage. The Nano also includes a USB interface for programming and serial communication, as well as various digital and analog input/output pins that can be used to interface with sensors, actuators, and other electronic components.

One of the key advantages of the Arduino Nano is its small form factor, which measures only 18x45mm. This compact size allows for easy integration into projects with space constraints, making it ideal for applications where size and portability are important factors. Despite its small size, the Nano retains compatibility with the standard Arduino Uno, which means that most Arduino Uno shields and libraries can be used with the Nano without any modifications.

The Arduino Nano can be programmed using the Arduino software, which provides a user-friendly and beginner-friendly integrated development environment (IDE). The IDE allows users to write, compile, and upload their code to the Nano with ease. Additionally, a vast community of Arduino enthusiasts and developers provides extensive documentation, tutorials, and sample code, making it easier for beginners to get started and for experienced users to explore advanced projects.

With its compact size, rich feature set, and extensive community support, the Arduino Nano is a powerful and versatile microcontroller board. It offers a wide range of applications, including robotics, home automation, sensor interfacing, and many more. Whether you are a beginner or an experienced maker, the Arduino Nano provides a great platform for exploring and bringing your electronic projects to life.

4.5 Hardware and Software Specifications of ARDUINO Microcontrollers

Some of the hardware specifications of the Arduino board are discussed here in detail.

4.5.1 Hardware Specifications

- It has Atmega32 micro-controller embedded on board.
- It is based on Harvard Architecture.

- The clock is controlled by 16MHz clock oscillator.
- Connector for connection with computer and power to LEDs and board itself.
- A serial connector for communication of the board with computer.
- It has a reset button to before an upload of a program.
- It has 14 digital pins.
- The pins are to read the ON or the OFF state.
- It has 6 analogue pins, which are responsible to read analogue input.
- A 5V power jack for extra power input.

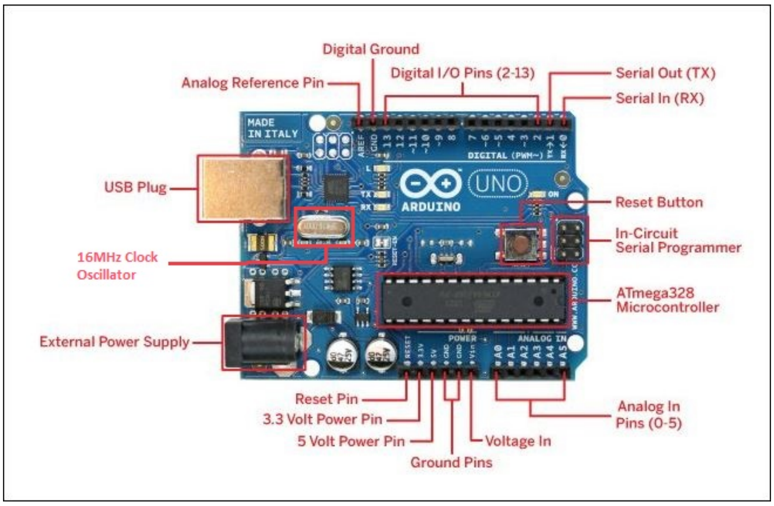

FIGURE 4.2: Arduino UNO

4.5.2 Software Specifications

Here are some software specifications of Arduino UNO board.

- **SPI** Serial peripheral interface which works to send and receive data between different peripherals. These peripherals can be external devices like camera, SD cards etc.
- **ATmega328p Controller** It starts with intake of instructions from input devices and then by decoding it into machine language it is fed to instruction set register, which converts it into the instructions with same clock pulse.
- **Analogue Comparator** Function of analogue comparator in any micro-controller is to compare the analogue value with high or low state. It sets positive if analogue input is high and negative if low.

- **General purpose register** When instructions are decoded by instruction set register, there are two general purpose registers (8 bit and 16 bit) which store data for normal calculations and data of timer counters for high and low values of registers.
- **I/O pins** Input and output pins are main connectors sources of internal registers with output devices to receive commands from user as per requirement.
- **Interrupt Unit** Interrupt service routine detects all the interrupts and executes the given instructions.
- **Status control register** Status control register is responsible of controlling the execution of all instructions at specified time and interval with predefined sequence.
- **EEPROM** Electrical erasable programmable ROM which is responsible for storing the data. It keeps it safe even when power is off.
- **Watchdog timers** It has watchdog timers to watch over any misbehavior or malfunction of results.
- **ALU** Arithmetic logic unit is connected with all registers. It performs all calculations and it is composed of 3 main functions: arithmetic, bit operations and logics.

Chapter 5

Electric Motors and Three-Phase Induction Motors

An electric motor is a piece of equipment that converts electrical energy into mechanical energy using an electrical mechanism. Typically, electric motors operate through the interaction between the magnetic field of the motor and the current flowing through a wire winding. As a result of Faraday's Law, which describes the force produced by the interaction between the magnetic field and current, a torque is generated that is delivered to the motor shaft.[13]

1. Electrical machines that transform electrical energy into mechanical energy are known as electric motors, and they operate through the interaction between a magnetic field and current.
2. The process by which electric motors function involves the interaction between a magnetic field and the current flowing through a wire winding, which results in the generation of torque according to Faraday's Law.
3. Electric motors are devices that convert electrical energy to mechanical energy by means of an electrical mechanism, and they rely on the interaction between a magnetic field and a wire winding to operate.
4. By converting electrical energy to mechanical energy through an electrical mechanism, electric motors operate by creating torque as a result of the interaction between a magnetic field and current flowing through a wire winding.
5. The ability of electric motors to convert electrical energy into mechanical energy is made possible through an electrical mechanism that relies on the interaction between a magnetic field and current flowing through a wire winding.

Electric motors can be powered by direct current (DC) sources such as rectifiers or batteries, as well as alternating power sources (AC) like electric generators, inverters, or power grids.

5.1 Categorization of Electric Motors

Different types of motors are mentioned below:

1. Synchronous Motor
2. Single Phase Induction Motor (Asynchronous Motor)
3. 3 Phase Induction Motor
4. DC Motor

DC motors are exclusively designed to operate on DC voltage supply, as the name suggests. These motors are operated by inducing rotating torque in the motor through the flow of current in a wire or conductor. Conversely, all other types of motors operate on AC power supply and usually rotate at a speed known as synchronous speed.
In synchronous AC motors, the rotor is composed of an electromagnet that is magnetically locked by the rotating magnetic field of the stator and thus rotates at the same speed as the rotating magnetic field. The speed of these motors is determined by the number of poles (P) and frequency (f) of the electrical supply.
The relation between speed of the motor with the frequency and poles are as.

$$N_s = 120f/P$$

The Induction Motor, also known as the Asynchronous Motor, is an electrical motor that rotates at a speed slower than the synchronous speed of the motor. It is characterized by the term slip, which refers to the difference between the rotor speed and the synchronous speed of the motor. The rotor speed is denoted as Nr while Ns is used for the synchronous speed of the motor. The Induction Motor operates based on the principle of electromagnetic induction, whereby the emf is induced in the motor by varying the value of the flux density.
Single-phase induction motor and three-phase induction motor are the two types of induction motors available. The main distinction between the two is that a single-phase induction motor operates on a single-phase power supply, while a three-phase induction motor operates on a three-phase power supply.
The process of starting a motor is usually of utmost importance, and there are two theories for the motor starting method for single-phase motors: Crossfield theory and Double revolving field theory. Apart from the four basic types of motors, there are also various other types of electric motors referred to as special electric motors.

These special electric motors are,

1. Stepper Motors
2. Linear Induction Motors (LIM)
3. Hysteresis Motors
4. Servo motors

These special devices as a name implies exhibits unique characteristics, attributes and qualities which have been built regarding the requirements of the industries or for use in a certain machine. i.e., because of the compact and small nature of design, hand watches typically use a hysteresis motor.
In this project, we will take into consideration three- phase induction motor.

5.2 Three phase Induction Motor

The 3-phase AC induction motor is a widely used electrical motor in various industries and has been the standard for AC power transmission since the early 1900s.
The induction motor is designed to be simple, with power supplied to the stator winding directly without the need for any secondary supply. Its uncomplicated design makes it a cost-effective option that is highly efficient. The induction motor is known for its durability and strength, making it a reliable choice that can perform well even in challenging conditions.[14]

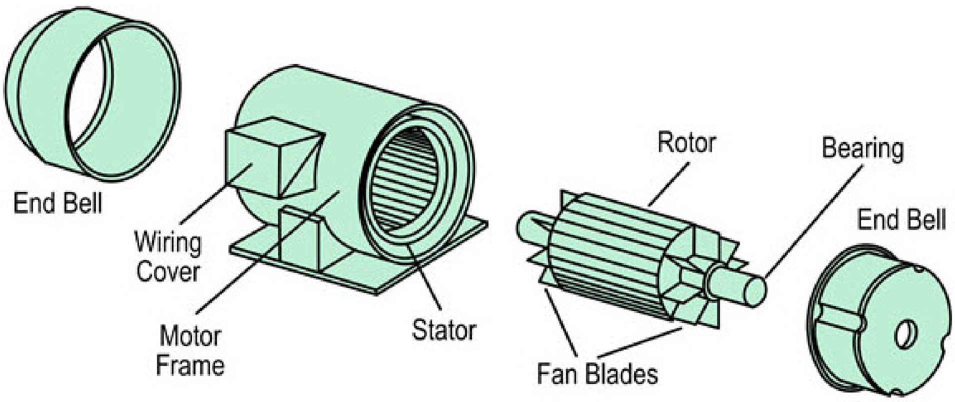

FIGURE 5.1: Induction Motor Components

One of the unique characteristics of induction motors is their self-starting ability, which eliminates the need for any external prime mover to initiate motor operation from a stationary position. Due to their robust design, induction motors are capable of withstanding high overload conditions without suffering significant damage to their winding. In their normal operation, induction motors function at a fixed speed when supplied with

a constant frequency. However, sudden changes in the motor load or torque may cause slight variations in their speed. This dependability and ability to function effectively even under challenging conditions have made induction motors a cornerstone of many industries. As a result, a significant portion of the world's power generation is utilized to power millions of these motors in various industrial settings.
It is, therefore, essential to consider operating such motors at variable speeds with suitable variable frequency controllers, as they become available in the market.[15],[16]

5.3 Working Principle and Advantages of Three-Phase Induction Motors

The basic principle of the three-phase induction motor is that the stator winding is to produce a continuously rotating field in the iron and air gap, thus inducing currents of the rotor conductors such that they produce a torque to turn the rotor, allowing electrical energy to be converted into mechanical rotational energy that can then be provided by the stator.

5.3.1 Working Principle

5.3.1.1 The stator

The stator windings can be of different designs, but the principle is that every winding phase occupies two 60 electric grade sections of the iron border, and those two sections are divided by 180 electric grades. The 3 phase windings are then positioned in a sequence, as shown in Figure 1.2, the physical winding sequence corresponding to the phase voltage vector rotation sequence. Fig. 1.3 shows the layout of a typical winding stator of one layer to explain how such windings are implemented. This diagram shows a two-pole stator section which is flattened to make it clear. This sequence is repeated with more poles in the stator with the coils connected in series in each phase.

The winding of the stator is for the purpose to induce the current and the voltages in the rotor's conductor by generating a flux of the field that will be rotating around the air gap smoothly.
If such a winding is provided with three phase currents, displaced at 120 electrical degrees from each other and sinusoidally changing, then it will produce opposite polarity of just two flux poles which moves along the curve and therefore rotates in the space of the air gap with the speed that relies on the currents' cyclic frequency.

5.3.1.2 The rotor

The rotor of an induction motor consists of a set of rotor conductors which may be connected together as a 3-phase winding similar to the stator as in the case of a wound

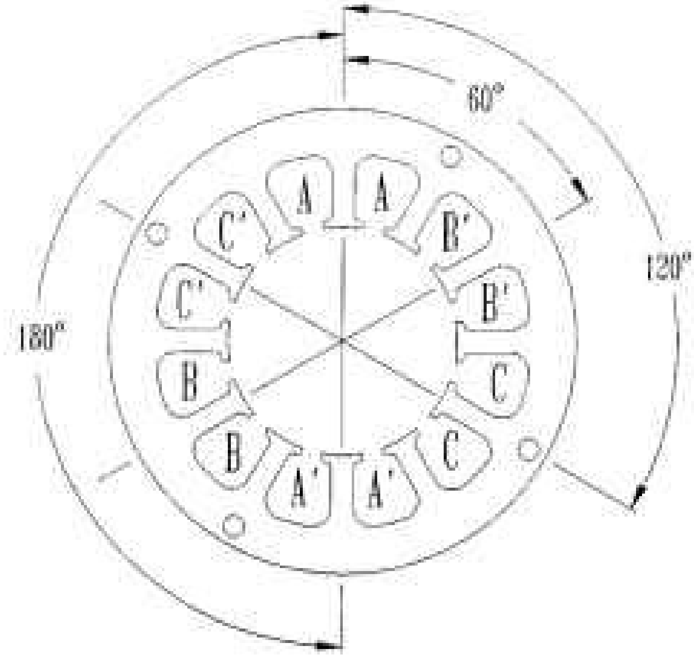

FIGURE 5.2: Two pole stator winding space allocation

rotor with connecting slip rings. In most cases, however, it just consists of a set of conductors which are all short circuited together at both ends of the rotor iron core. In this case the three phases can only be distinguished in the rotor by the pattern of rotor conductor currents.

5.3.2 Advantages

- The main advantage of this induction is that the design of the induction motor is not complicated rather it is very easy and simple. The construction of stator is all same for both synchronous motors and. On the Other Hand, in order for the rotor to get a DC supply a slip ring is required in the case of a Synchronous Generator. Although the induction motor i.e., squirrel cage type motor does not need the slip rings this is for the reason that the windings are constantly short circuited by a squirrel cage type motor.

- The induction motor has no brushes and thus their maintenance is not very high, as comparable with that of DC motor which contains brushes.

- Environmental condition usually does not effect the operation of induction motors that give it a positive edge.

- The induction motors are very vigorous and strong which makes them reliable and effective as per industrial aspects.

- Induction motors are cost effectives as they does not require slip rings or brushes in their construction and design.

- As Induction motor does not contain any brushes in their design which will makes them free from any sparks. This property of induction motors makes them useful for operating in severe or dangerous conditions.
- Induction motors specially three-phase induction motor exhibits high starting torque which makes them useful for those applications which require high torque at the start.
- An induction motor is an effective motor because their efficiency is high. i.e., 80% and above.

Chapter 6

Methodology and Project Details

6.1 Methodology

1. **Power Source** In this case, we are using 220-volt AC single-phase power directly from the plug.

2. **Rectifier** Passing the 220V AC through a full bridge rectifier circuit results in the conversion of AC voltage into DC voltage.

3. **DC Filter** The DC voltage obtained after rectification contains ripples, which can be eliminated by passing it through an LC filter.

4. **Inverter** After passing through the filter, the DC voltage is directed to the 3-phase inverter which transforms it into a variable 3-phase voltage that can be supplied to the motor.

5. **Driver Circuit** The microcontroller's safety and prevention against reverse current necessitate the use of a driver circuit. Additionally, the driver circuit precisely triggers the FETs or IGBTs by providing the required current.[17] IC IR2110 is utilized for the driver circuit since it offers isolated internal grounds, which prevent the switching sequence from overlapping.

6. **SPWM** The switching of FETs or IGBTs installed in the 3-Phase inverter is achieved through the use of SPWM.

7. **Micro-controller** We use the Arduino UNO for speed display using a hall sensor and Arduino NANO for speed control microcontroller for our project.

8. **Open Loop Control** Our VFD design employs an open loop control approach to regulate the motor's speed by linearly varying the frequency.

9. **Power Source** In this case, we are using 220-volt AC single-phase power directly from the plug.

6.1.1 Block Diagram

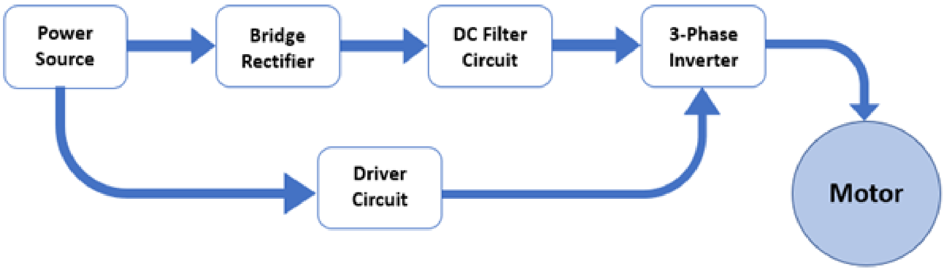

FIGURE 6.1: Block Diagram of the Project

For Simplification The Project is divided in different stages

6.2 First stage of the project

Prior to hardware implementation, the project underwent simulation using MATLAB and Proteus software. While the simulation provides ideal values, the final voltage values observed during hardware implementation are typically lower due to factors such as friction and hysteresis losses.

6.2.1 MATLAB Simulation

During the MATLAB simulation, the SPWM is generated by combining three reference sine waves and a triangular carrier wave. This 6-pulse SPWM signal is then utilized for switching the MOSFETs of the 3-phase inverter. It should be noted that the simulation results may differ from the actual hardware implementation due to various losses such as friction and hysteresis losses.

6.2.1.1 SPWM Generation

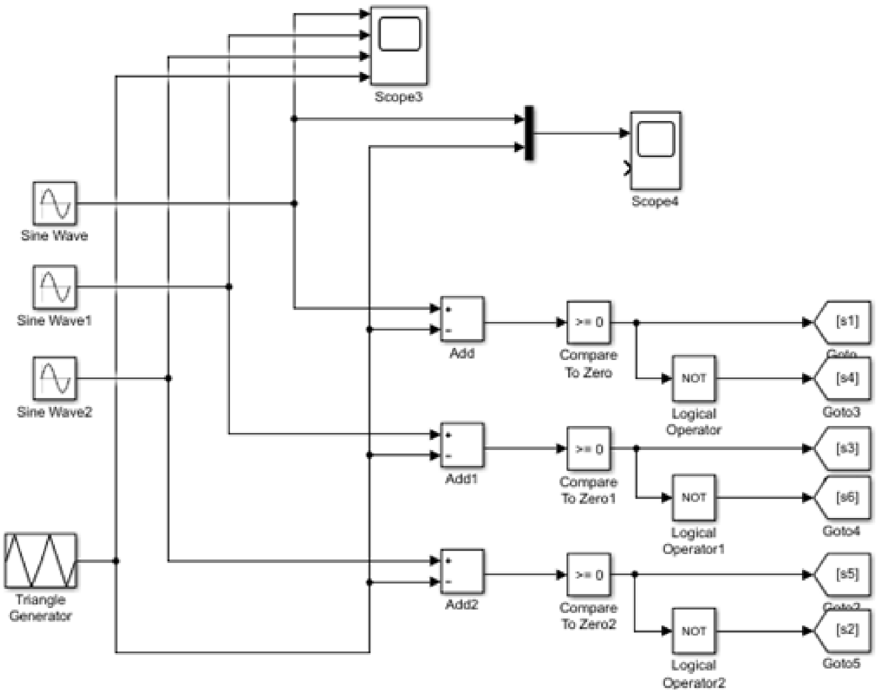

FIGURE 6.2: SPWM generation in MATLAB

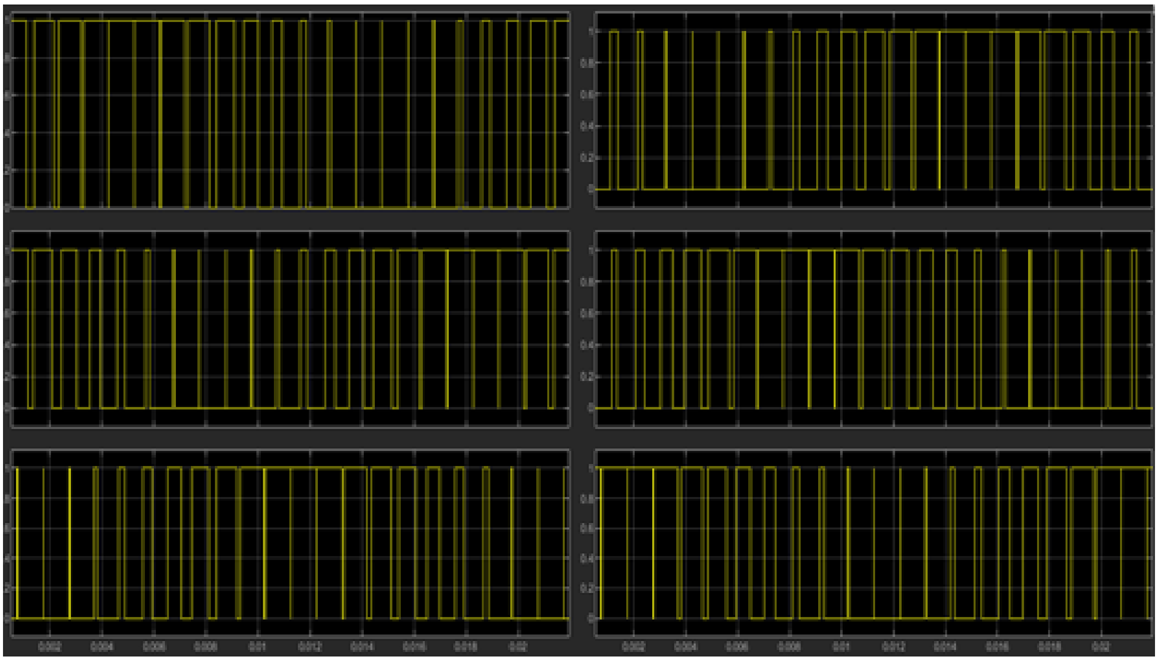

FIGURE 6.3: 6-Pulse of SPWM

6.2.1.2 3-Phase Inverter

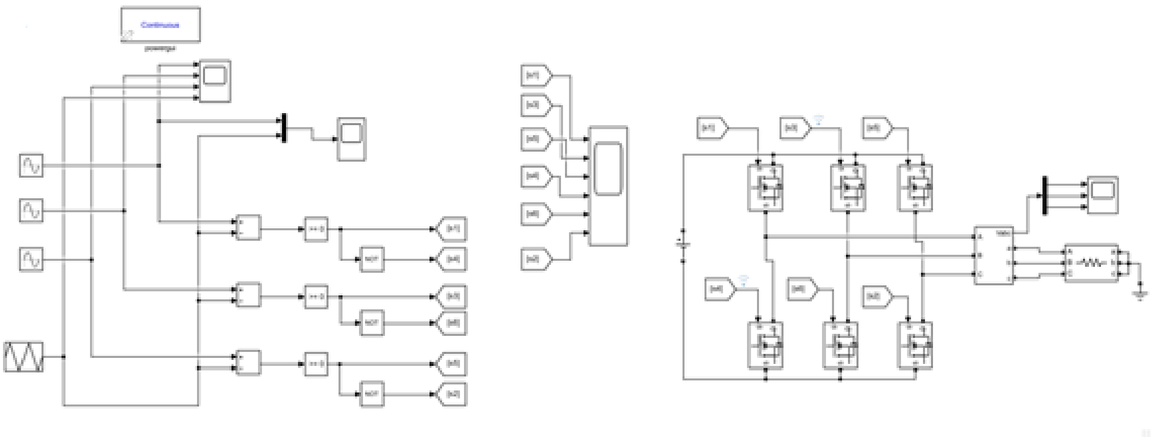

FIGURE 6.4: 3-Phase Inverter simulation with SPWM

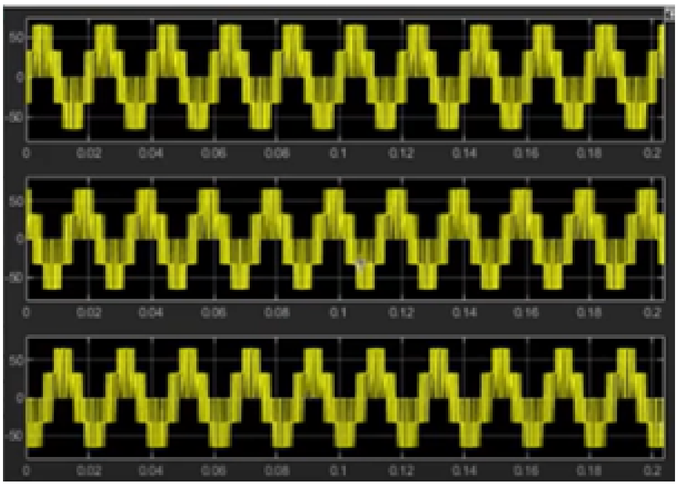

FIGURE 6.5: Phase to Phase output Voltage

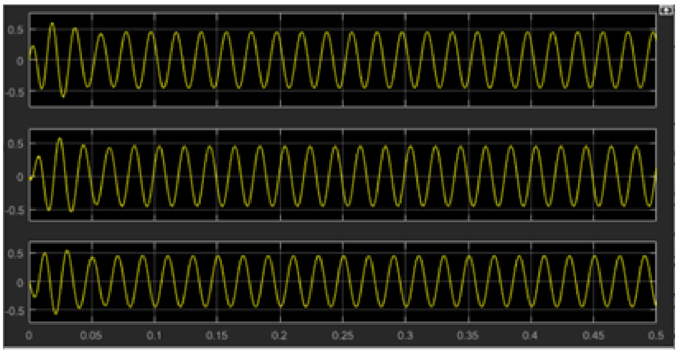

FIGURE 6.6: Output voltage with filter

6.2.2 Proteus Simulation

The Arduino programming for this project involves dividing a single sine period into 256 values, using two timers, Timer0 and Timer1. A potentiometer is connected to the A0 pin of the Arduino, which is used to vary the width of the PWM signal. A 5V power supply is used to power up the potentiometer. The output pins of the Arduino, which carry the PWM signal, are connected to the driver ICs. These ICs take the PWM signal to the MOSFETs of the 3-Phase inverter.

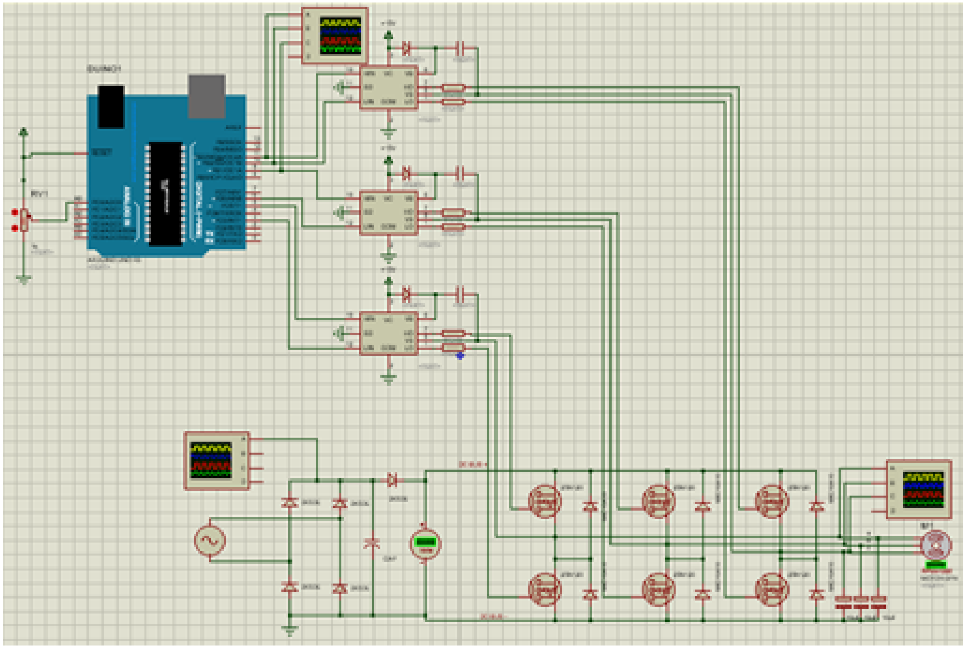

FIGURE 6.7: 3-Phase VFD Circuit

6.2.2.1 Results

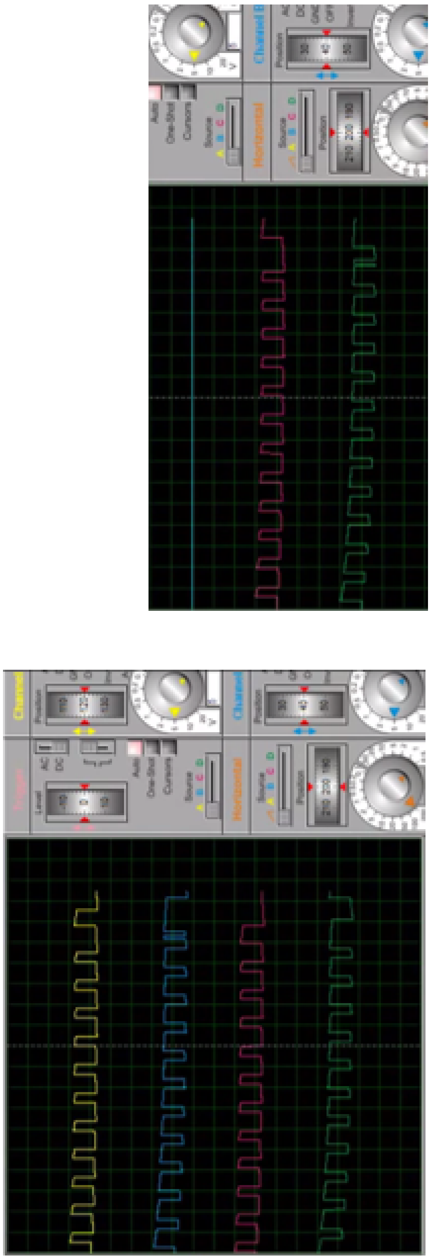

FIGURE 6.8: 6-Pulses SPWM generation in Proteus

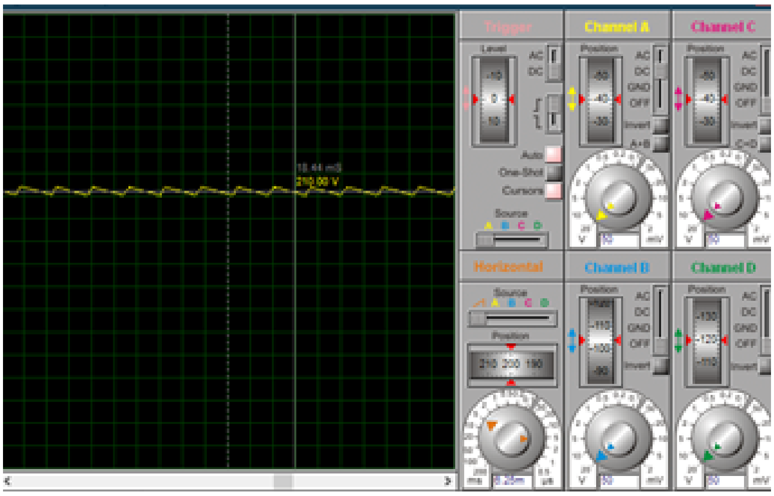

FIGURE 6.9: Rectified Input

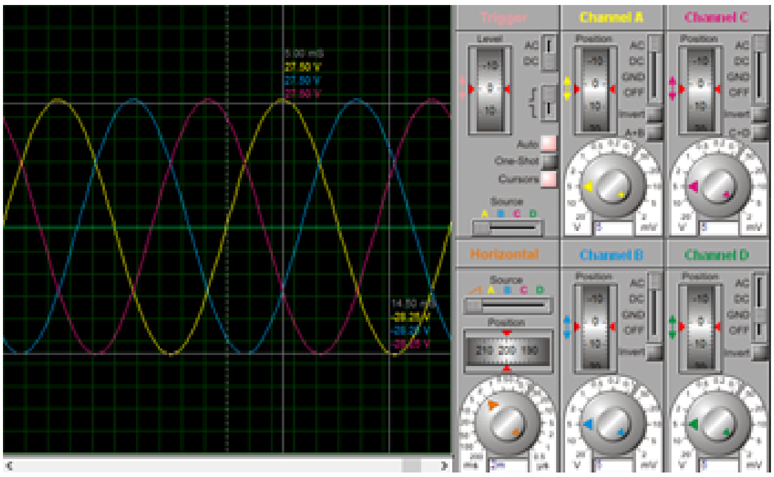

FIGURE 6.10: 3-Phase Output of Inverter

6.3 Second stage of the project

After performing testing on Proteus and MATLAB, we designed the PCB layouts and then assembled the components on a PCB and created a prototype of our project, which was a variable frequency drive (VFD) for an induction motor.
PCB designs for both the PCBs are below

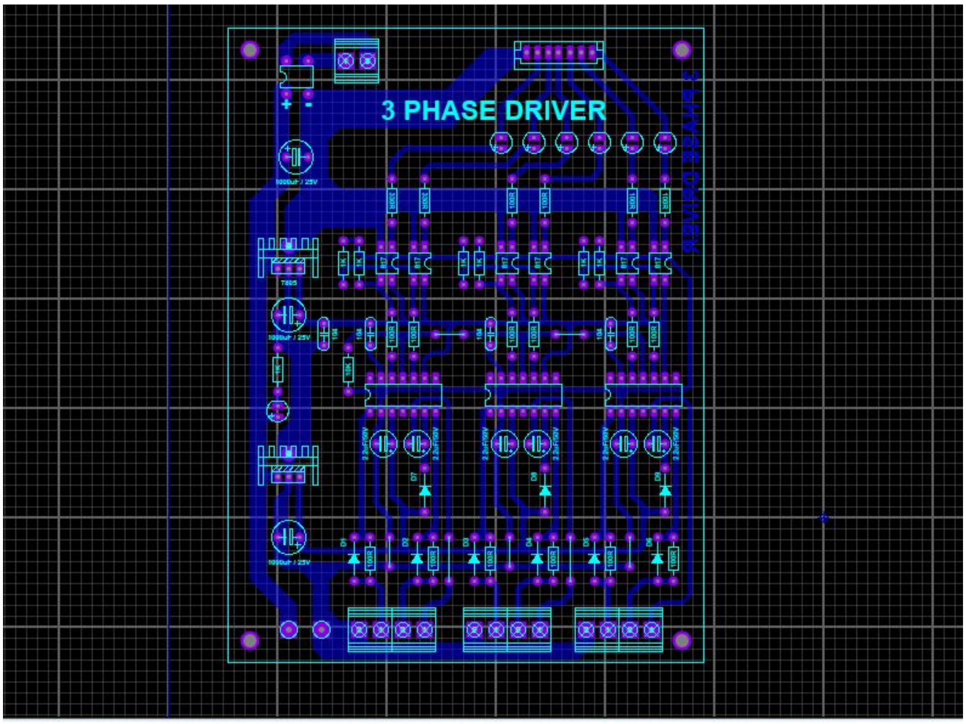

FIGURE 6.11: 3-phase driver circuit PCB design

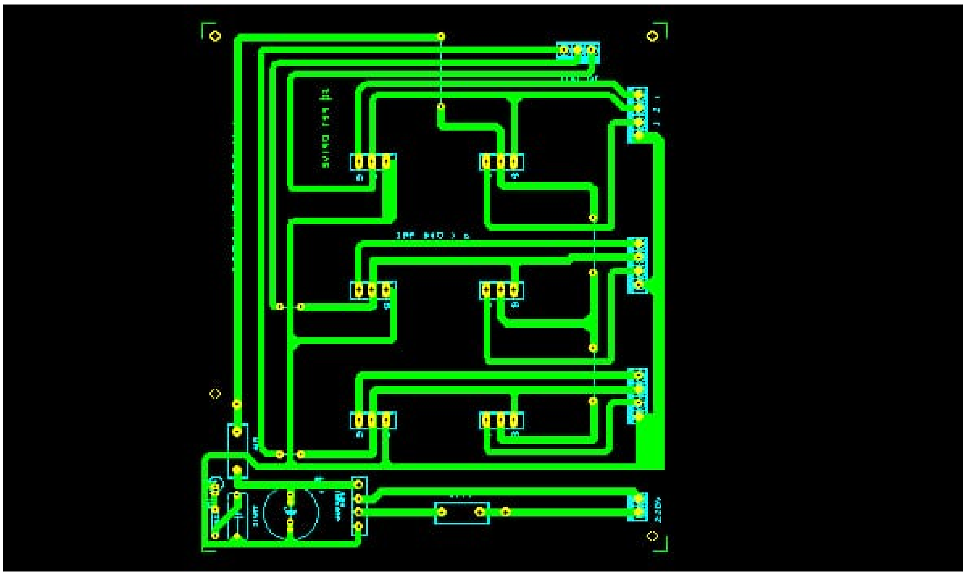

FIGURE 6.12: FET driver circuit PCB layout

The second phase of the project is to design a driver circuit for proper controlling of current and maintaining the required voltage. Driver circuits can be designed using different ICs. TLP250, IR2110, IR2112, PC817C and many other ICs are available for designing driver circuits. IC used in our project is IR2110 because it provides a separate internal ground advantage over other ICs.

6.3.1 Driver Circuit

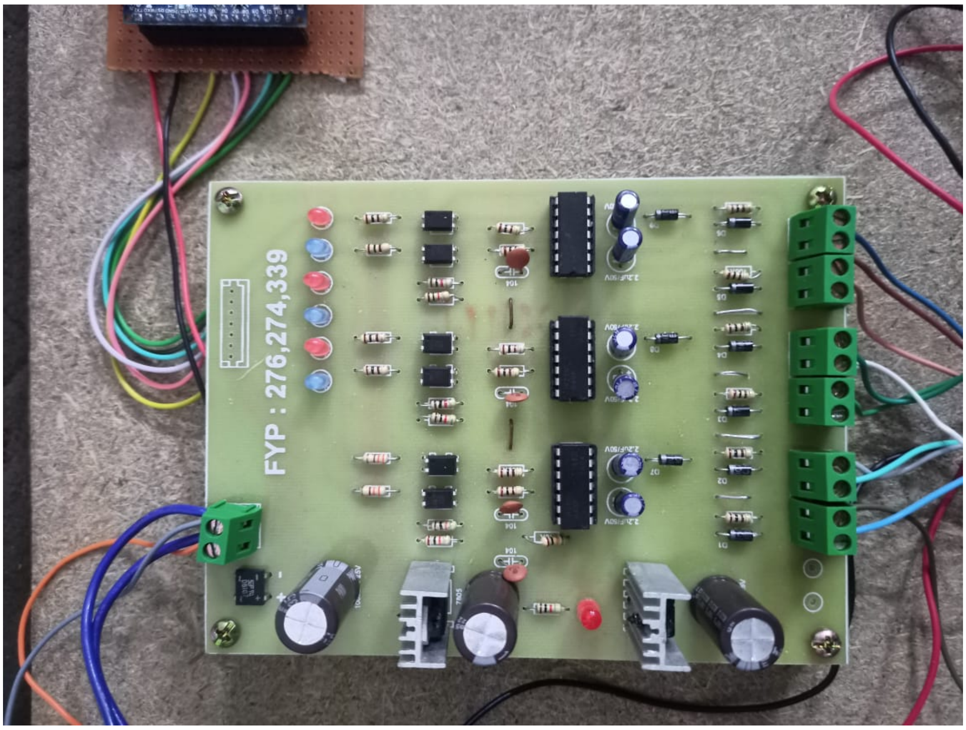

FIGURE 6.13: Driver Circuit

6.3.2 IC IR2110

The IC IR2110 is a popular high-voltage, high-speed power MOSFET and IGBT driver integrated circuit (IC) manufactured by Infineon Technologies. It is commonly used in various applications, including motor drives, switch-mode power supplies, and inverters. The IR2110 provides robust and efficient control of power semiconductor devices by generating the necessary gate drive signals. Here are some key features and functionalities of the IR2110:

1. High and Low-Side Drivers: The IR2110 consists of two independent driver channels—a high-side driver and a low-side driver. These drivers are capable of sourcing and sinking high current pulses to drive the gates of power MOSFETs or IGBTs.

2. Bootstrap Operation: The IR2110 utilizes a bootstrap capacitor to supply the high-side driver with a voltage that is greater than the supply voltage (Vcc). This enables efficient high-side gate drive operation without requiring a separate high-voltage supply.

3. Floating Channel Outputs: The outputs of the IR2110 are floating, which means they can be connected to high-side or low-side devices in a variety of topologies, including half-bridge, full-bridge, and H-bridge configurations.

4. Undervoltage Lockout (UVLO): The IC incorporates an undervoltage lockout mechanism to prevent insufficient voltage levels from driving the power devices. It ensures that the supply voltage is above a specified threshold before enabling the driver outputs.

5. Shoot-Through Protection: The IR2110 includes built-in shoot-through protection to prevent simultaneous conduction of high-side and low-side devices, which can lead to short circuits and excessive power dissipation. This protection mechanism includes a dead-time control feature to avoid any overlap between the high-side and low-side switching signals.

6. Input Logic Compatibility: The input logic of the IR2110 is compatible with both CMOS and TTL (5V) logic levels, making it easy to interface with various control circuits and microcontrollers.

7. Fault Protection and Diagnostics: The IC offers features like fault status output, which indicates fault conditions such as undervoltage, overcurrent, and overtemperature events. These diagnostics aid in fault detection and system troubleshooting.

The IR2110 is a versatile driver IC that simplifies the design and implementation of power control circuits. It provides efficient gate drive signals, protects against faults, and offers flexibility in system configurations. However, it's important to consult the datasheet and application notes provided by the manufacturer to ensure proper utilization and integration of the IC in specific circuit designs.

FIGURE 6.14: IC IR2110

6.3.2.1 Why is a driver circuit required?

Here's why a driver circuit is required in VFD design:

Power conversion: The driver circuit in a VFD is responsible for converting the incoming AC power into DC power. It typically includes rectification components, such as diodes or thyristors, to convert the AC voltage to a pulsating DC voltage. This conversion is necessary because most VFDs operate using DC power to control the motor speed.

Inverter control: The driver circuit also controls the switching of power semiconductor devices, such as insulated gate bipolar transistors (IGBTs) or power MOSFETs, in the inverter section of the VFD. The inverter converts the DC voltage back into an AC voltage with variable frequency and voltage levels, which is then supplied to the motor. The driver circuit generates the appropriate gate signals to control the switching of these power devices.

Motor protection: The driver circuit plays a crucial role in protecting the motor from various faults and abnormal conditions. It monitors parameters such as motor current, temperature, and voltage, and incorporates protective features like overcurrent protection, overvoltage protection, and thermal overload protection. These protective measures help prevent motor damage and ensure safe operation.

Control interface: The driver circuit provides an interface for external control signals, such as speed reference or start/stop commands. It interprets these signals and adjusts the output frequency and voltage accordingly to achieve the desired motor speed and torque control. The driver circuit may also include feedback mechanisms to monitor motor speed and provide closed-loop control if necessary.

Fault detection and diagnostics: The driver circuit may include circuitry for fault detection and diagnostics. It can detect faults like short circuits, open circuits, or component failures, and provide appropriate fault signals or alarms. These diagnostics help in troubleshooting and maintenance of the VFD system.

In summary, the driver circuit in a VFD is essential for power conversion, inverter control, motor protection, control interface, and fault detection. It enables the VFD to efficiently and reliably control the speed and torque of an electric motor while providing protection and diagnostic capabilities.

6.3.2.2 How does IR2110 works?

This I_c has two input pins: Pin 10 has a High side pulse from the microcontroller and Pin 12 has the low or opposite pulse of pin 10. To power up the I_c we need to apply 3.5 volts VDD at Pin 9. A capacitor of 0.01uF in parallel between Pin 5 and 6. This is important that we connect the positive terminal of the capacitor to Pin 5. Pin 3 and Pin 6 meet at the same point through the diode and here we apply the required voltage VCC. This is the voltage that we need to trigger our IGBT or MOSFETs. Two terminals of I_c are connected to the ground: Pin 11 and Pin 2. Two remaining pins are used for output from the I_c. The High terminal output is obtained from Pin 7 and the Low side output is obtained from Pin 1.

A resistor at the input terminal is used to limit the input current for IR2110. Because a sudden inrush current can damage the IC. So selection of a standard value resistor is required. By using Voltage division:

$$V = (5 - 1.8)V = 3.2V$$

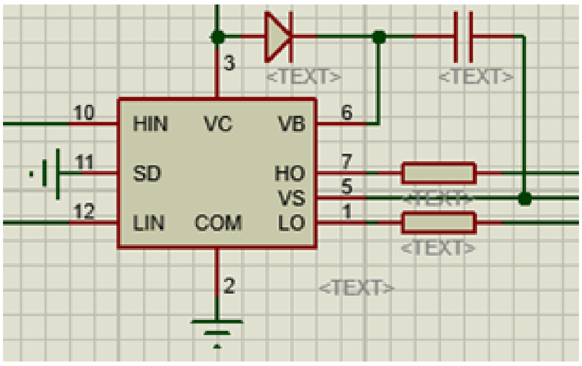

FIGURE 6.15: Pin connection of IR2110

$$R = V/I = 160ohm$$

6.3.3 Inverter Design

The main part of the project is three-phase inverter. This part takes DC as an input and converts it into the 3-phase AC supply for the PMAC motor. MOSFETs or IGBTs are used in inverters for switching purposes. To minimize the switching losses, the SVPWM technique is used which provides the least THD.

6.3.3.1 Three-Phase inverter

A three-phase inverter consists of three legs connected in parallel. Each leg has two switches in each. Two switches on each leg provide one phase of voltage at their junction. The second and Third legs have a phase difference of 120 degrees and 240 degrees with respect to the first phase. DC input is connected at one terminal and output voltage is measured from the second end of the inverter.

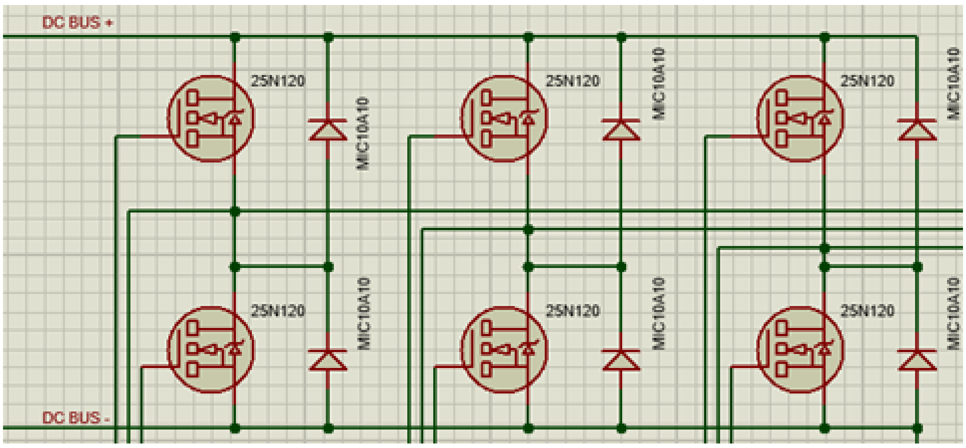

FIGURE 6.16: Proteus Inverter Model

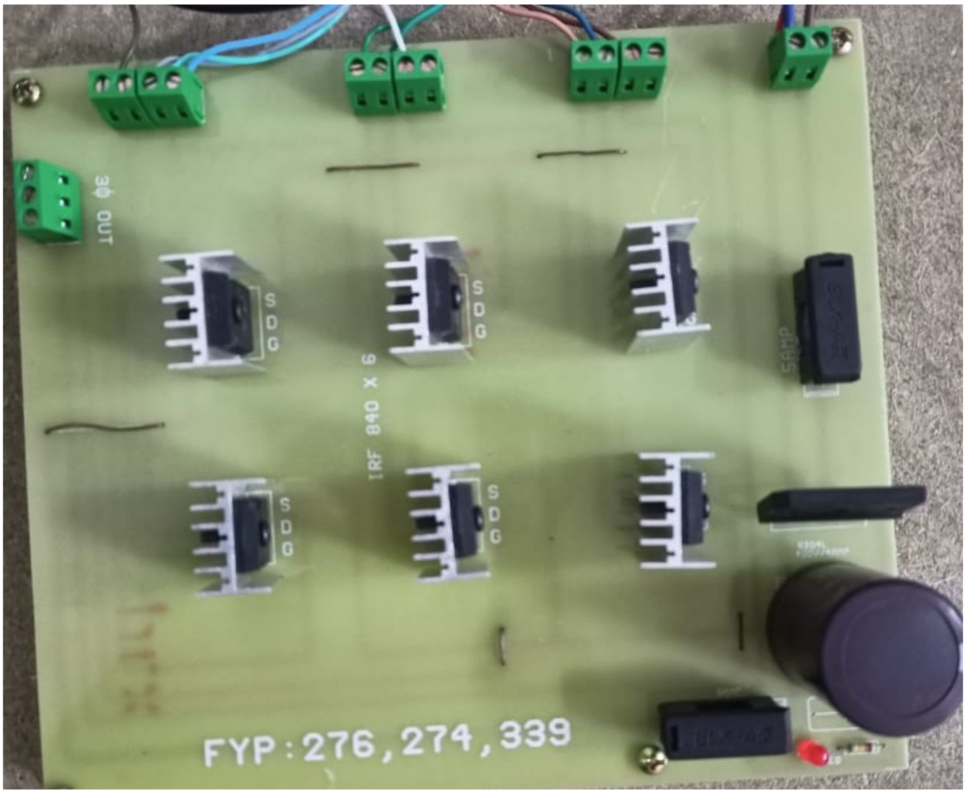

FIGURE 6.17: Hardware Inverter Circuit

6.3.4 IGBTs or MOSFETs

When it comes to selecting between IGBTs (Insulated Gate Bipolar Transistors) and MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors), the choice depends on various factors and the specific requirements of the application. Here are some key considerations for each device:

IGBTs:
1. High Voltage and Current Handling: IGBTs are well-suited for applications that require high voltage and current capabilities. They can handle higher voltages (typically above 600V) and larger currents, making them suitable for power electronics applications such as motor drives, inverters, and high-power switching applications.

2. Switching Speed: Compared to MOSFETs, IGBTs typically have slower switching speeds. They exhibit higher switching losses and longer turn-off times, which can limit their performance in applications that require fast switching frequencies.

3. Robustness and Reliability: IGBTs offer high ruggedness and robustness, making them suitable for demanding industrial environments. They can handle short-circuit conditions and are less susceptible to damage from voltage transients.

4. Cost: IGBTs are generally more expensive than MOSFETs, especially for higher voltage and current ratings. However, the cost difference may vary based on specific device specifications and market conditions.

MOSFETs:
1. Low Voltage and Medium Power Applications: MOSFETs are commonly used in low voltage (up to a few hundred volts) and medium power applications. They are widely employed in applications such as power supplies, DC-DC converters, and low-power motor drives.

2. Switching Speed: MOSFETs have fast switching speeds and lower switching losses compared to IGBTs. This characteristic makes them suitable for applications that require high-frequency switching and efficient operation.

3. Efficiency: MOSFETs generally exhibit higher efficiency due to their lower on-state resistance (RDS(on)) and reduced switching losses. This efficiency advantage becomes more pronounced in low-voltage and moderate-power applications.

4. Cost: MOSFETs are generally more cost-effective than IGBTs, particularly for lower voltage and current ratings. They are available in a wide range of voltage and current ratings, providing options to meet different budget requirements.

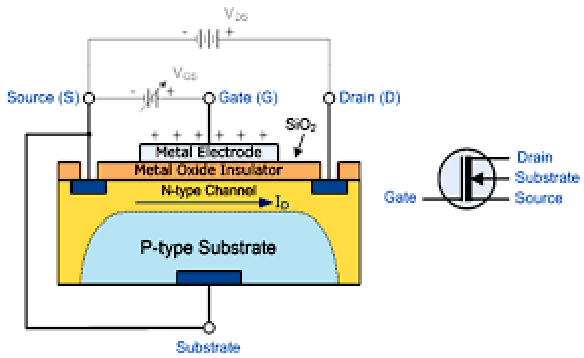

Figure 6.18: MOSFET Circuit

In summary:
IGBTs are preferred for high-voltage and high-current applications that demand robustness and high power handling. They are suitable for applications where switching speed is not the primary concern. On the other hand, MOSFETs are often used in low-voltage and medium-power applications that require fast switching speeds, high efficiency, and cost-effectiveness. Ultimately, the choice between IGBTs and MOSFETs depends on the specific application requirements, including voltage and current levels, switching frequency, efficiency targets, and budget constraints.
In this project, the power source is Max. 201 Volts. So the use of MOSFETs would be suitable.[18]

6.3.4.1 MOSFET

The Metal-Oxide Semiconductor Field Effect transistor also known as MOSFET is a type of transistor i.e., field effect transistor. The MOSFET has no pn junction structure in comparison to another junction-gate field-effect transistor. Silicon dioxide is used to separate the gate terminal of the MOSFET from the channel.[19]

MOSFETs are of two categories namely enhancement and depletion. In which enhancement type MOSFETs are more commonly used as compared to depletion-type MOSFETs.

6.3.4.2 Working of MOSFET

An N-channel MOSFET is preferred over P-channel MOSFET due to the majority electrons. Electrons provide high speed then positive ions. It can be used in depletion or enhancement mode. Both modes have almost the same configuration except for the orientation of the battery. In depletion mode, the gate is supplied with negative volts, which causes the flow of current from drain to source.[20] But due to the depletion layer, ID decreases if we increase VGG. In enhancement mode, we apply positive voltage at the gate instead of negative. Which causes an increase in drain current ID and this current is directly proportional to the applied VGG.[21]

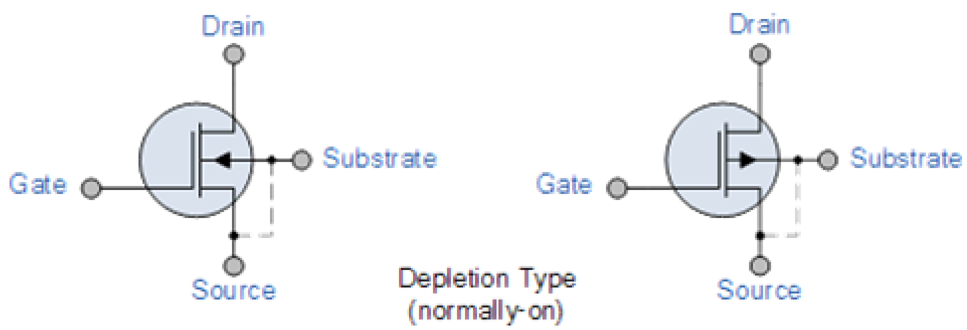

FIGURE 6.19: D-MOSFET

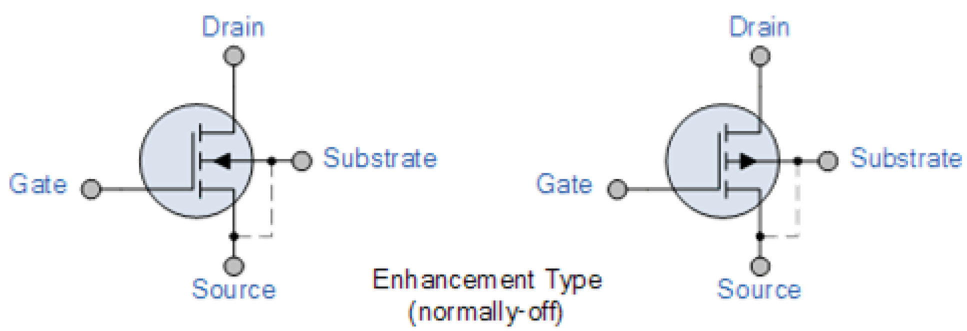

FIGURE 6.20: E-MOSFET

6.4 Capacitive filter

Using a capacitive filter is not necessary. A motor can run on provided SPWM signal by the inverter. But a PWM signal produces Noise and switching state from 0 to 1 rapidly will cause heat losses. It also reduces the rate of rise of inverter output voltage.

Reducing the harmonics in the final output waveform of the SPWM signal results in the smooth performance of the equipment. Designing C Designing of a capacitive filter is necessary, as we cannot select any capacitor randomly for any application. It should be selected according to voltage, current and power rating. As we have a motor as a load which is an inductive load, which means that the voltage of the motor leads to the current of the motor. Capacitive reactance written as Xc depends upon the frequency of the input.

$$X_L = 1/2\pi f L$$

Frequency is inversely related to Capacitive reactance, which means as frequency increases, the capacitor's charging and discharging will take a smaller time to charge and discharge which will decrease the duty cycle and so capacitive reactance.

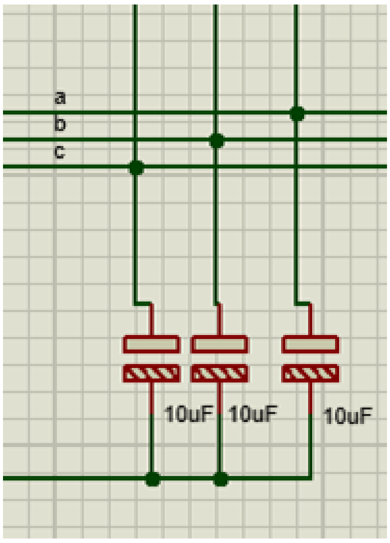

FIGURE 6.21: 3-Phase Capacitive Filter

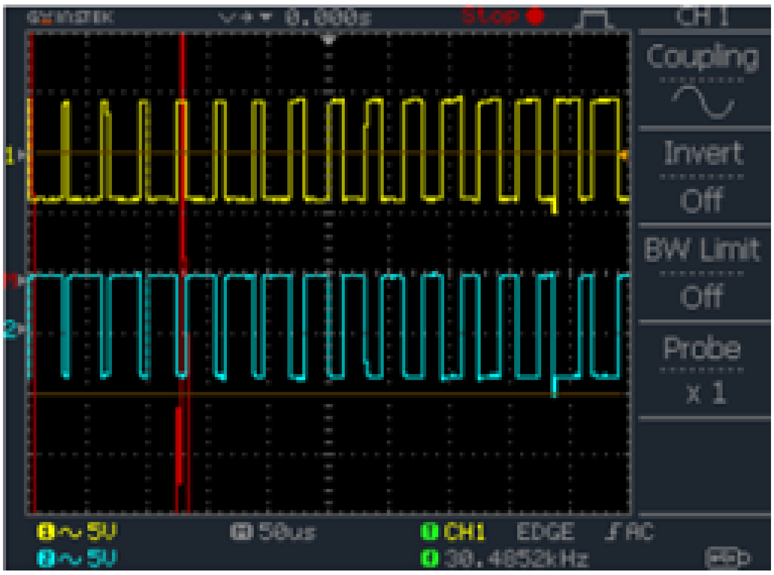

Figure 6.22: Arduino PWm

The project's second stage involves designing a driver circuit that can control current and maintain the necessary voltage. There are various ICs that can be used for driver circuit design, such as TLP250, IR2110, IR2112, PC817C, and many more. In our project, we are using the IR2110 IC due to its unique internal ground feature that sets it apart from other ICs.

6.4.1 IC IR2110

The IR2110 is a high voltage and high-speed power MOSFET with independent referenced output channels of low side and high side. It is a 14-pin IC used in the driver circuit, providing both high and low input pins. The terms high side and low side refer to the upper and lower legs of the inverter, respectively, where each leg of the inverter has opposite PWM signals for its two FETs.

FIGURE 6.23: IC IR2110

6.4.2 Capacitive filter

Although using a capacitive filter is not mandatory for running a motor on the SPWM signal, it is highly recommended. This is because the PWM signal produced by the inverter generates noise and rapid switching from 0 to 1 results in heat losses and a slower rate of rise of the inverter output voltage. Using a capacitive filter can help in reducing the harmonics in the final output waveform of the SPWM signal, resulting in the smoother performance of the equipment.

6.4.3 Designing C

It is important to carefully design a capacitive filter to ensure proper selection of the capacitor for the given application. Factors such as voltage, current, and power rating need to be taken into consideration. Since the motor is an inductive load, the voltage of the motor leads to the current of the motor. Capacitive reactance, denoted as Xc, depends on the frequency of the input signal. A proper value of capacitance is required to ensure that the capacitive filter effectively reduces the high-frequency noise and harmonics in the output signal. Furthermore, a well-designed capacitive filter helps to stabilize the output voltage of the inverter and reduce heat losses in the switching devices.

$$X_L = 1/2\pi f L$$

The capacitive reactance (Xc) is inversely related to the input signal frequency. This means that as the frequency increases, the capacitor takes less time to charge and discharge, resulting in a reduction in the duty cycle and capacitive reactance. It is important to choose a capacitor with suitable voltage, current, and power ratings, particularly when working with an inductive load like a motor where the voltage leads the current.

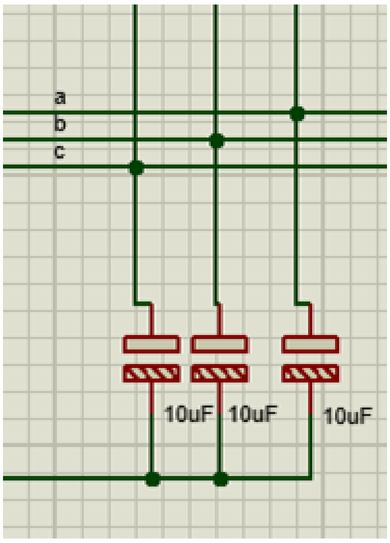

FIGURE 6.24: 3-Phase Capacitive Filter

6.4.4 Speed Control and Measurement

To measure the speed of an induction motor, you can utilize a Hall sensor, which detects the magnetic field changes caused by the rotating motor's magnets. By interfacing the Hall sensor with the Arduino Uno, you can capture these changes and calculate the motor speed.

Hall Sensor Basics: A Hall sensor is a transducer that produces a voltage output in response to changes in the magnetic field. It consists of a Hall effect device, which is typically a semiconductor material, placed in close proximity to a magnetic field source. As the magnets on the rotor of the induction motor rotate, they cause the magnetic field to fluctuate, resulting in a voltage output from the Hall sensor.

Interfacing Hall Sensor with Arduino Uno: To interface the Hall sensor with the Arduino Uno, you'll need to connect the output pin of the Hall sensor to one of the digital input pins on the Arduino board. You may also need to add pull-up or pull-down resistors depending on the sensor's output configuration. Once connected, you can use the Arduino's digital input capabilities to read the voltage changes produced by the Hall sensor.

Capturing Speed Measurements: To measure the speed of the induction motor, you can utilize the Arduino's timekeeping capabilities. You can start a timer when a change is detected by the Hall sensor and stop the timer when the next change occurs. By calculating the time difference between these changes, you can determine the time taken for one complete rotation of the motor. Dividing this time by the number of motor poles, you can obtain the rotational speed in revolutions per minute (RPM).

Displaying Speed: To display the motor speed, you can connect an output device, such as an LCD display or a serial monitor, to the Arduino Uno. Using appropriate libraries and code, you can output the calculated motor speed to the display device. This allows you to visualize and monitor the speed of the induction motor in real-time.

Calibration and Accuracy: It's important to calibrate the system for accurate speed measurements. This involves accounting for factors like the number of motor poles, the resolution of the Hall sensor, and any signal conditioning circuitry used. Calibration ensures that the displayed motor speed corresponds as closely as possible to the actual speed of the induction motor.

Enhancements and Additional Features: Beyond basic speed measurement, you can expand the functionality by incorporating additional features. For example, you can implement threshold-based alarms to detect abnormal speed conditions and trigger alerts. You can also log the speed data to an external storage device or transmit it wirelessly to a computer or a mobile device for further analysis and monitoring.

By leveraging the Arduino Uno's flexibility and the capabilities of the Hall sensor, you can create a reliable and versatile speed monitoring system for your induction motor. The Arduino platform offers ample opportunities for customization, allowing you to add more features and adapt the system to your specific requirements.

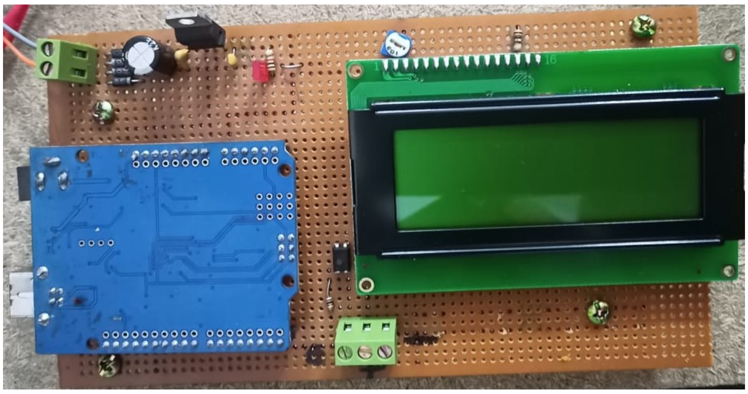

FIGURE 6.25: LCD Display

6.4.4.1 Speed Relations

In an induction motor, the speed of the motor is directly related to the frequency of the power supply and inversely related to the number of poles in the motor. Additionally, the voltage supplied to the motor also affects its speed.

1. **Speed-Frequency Relationship:** The speed of an induction motor is proportional to the frequency of the power supply. This relationship is known as the synchronous speed equation:

   $$N_s = 120 * f/P$$

   Where:
   - Ns is the synchronous speed of the motor in revolutions per minute (RPM).
   - f is the frequency of the power supply in hertz (Hz).
   - P is the number of poles in the motor.

   The synchronous speed represents the theoretical speed at which the motor would rotate if there were no slips. However, due to slip, which is the difference between the synchronous speed and the actual rotor speed, the motor operates at a lower speed.

   By manipulating the frequency of the power supply, you can control the speed of the motor. Decreasing the frequency reduces the speed while increasing the frequency increases the speed. This principle forms the basis of variable frequency drive (VFD) systems used for motor speed control.

2. **Speed-Voltage Relationship:** The voltage supplied to the induction motor also affects its speed. The voltage-speed relationship is defined by the torque equation of the motor:

   $$T = (K * V^2)/R$$

   Where:
   - T is the torque developed by the motor.
   - K is a constant.
   - V is the voltage supplied to the motor.
   - R is the motor resistance.

   From the torque equation, it can be observed that the motor speed is influenced by the square of the voltage supplied. Increasing the voltage increases the motor speed while decreasing the voltage decreases the speed.

   However, it's important to note that altering the voltage alone can result in limitations and may not be sufficient for precise speed control. VFDs are often employed to control both the frequency and voltage supplied to the motor, enabling more accurate and efficient speed control.

In summary, the speed of an induction motor is directly proportional to the frequency of the power supply and inversely proportional to the number of poles. By manipulating the frequency, you can control the speed of the motor. Additionally, the voltage supplied to the motor also affects its speed, with an increase in voltage resulting in higher speeds. The relation between the speed and frequency of the motor is given by the equation,

The frequency of our project ranges from 10 to 60 Hz so the speed of the induction motor varies from 150 to 1800 rpm.
The measured values of frequency and speed are less than the calculated value from the equation it is because of frictional losses. The measured values are:

Sr. No.	**Frequency (Hz)**	**Speed (rpm)**
1	10	278
2	17.5	511
3	31.3	921
4	48.7	1455

Table 6.1: Frequency Speed relation of motor

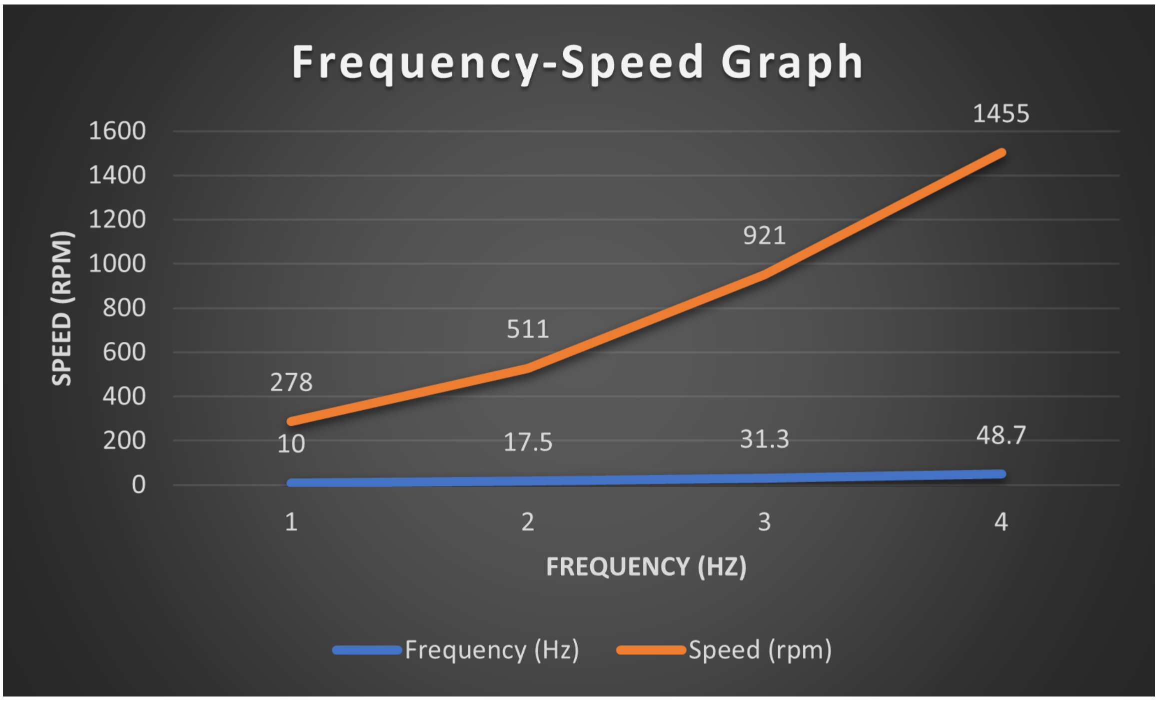

Figure 6.26: Project Model

6.5 Project Model

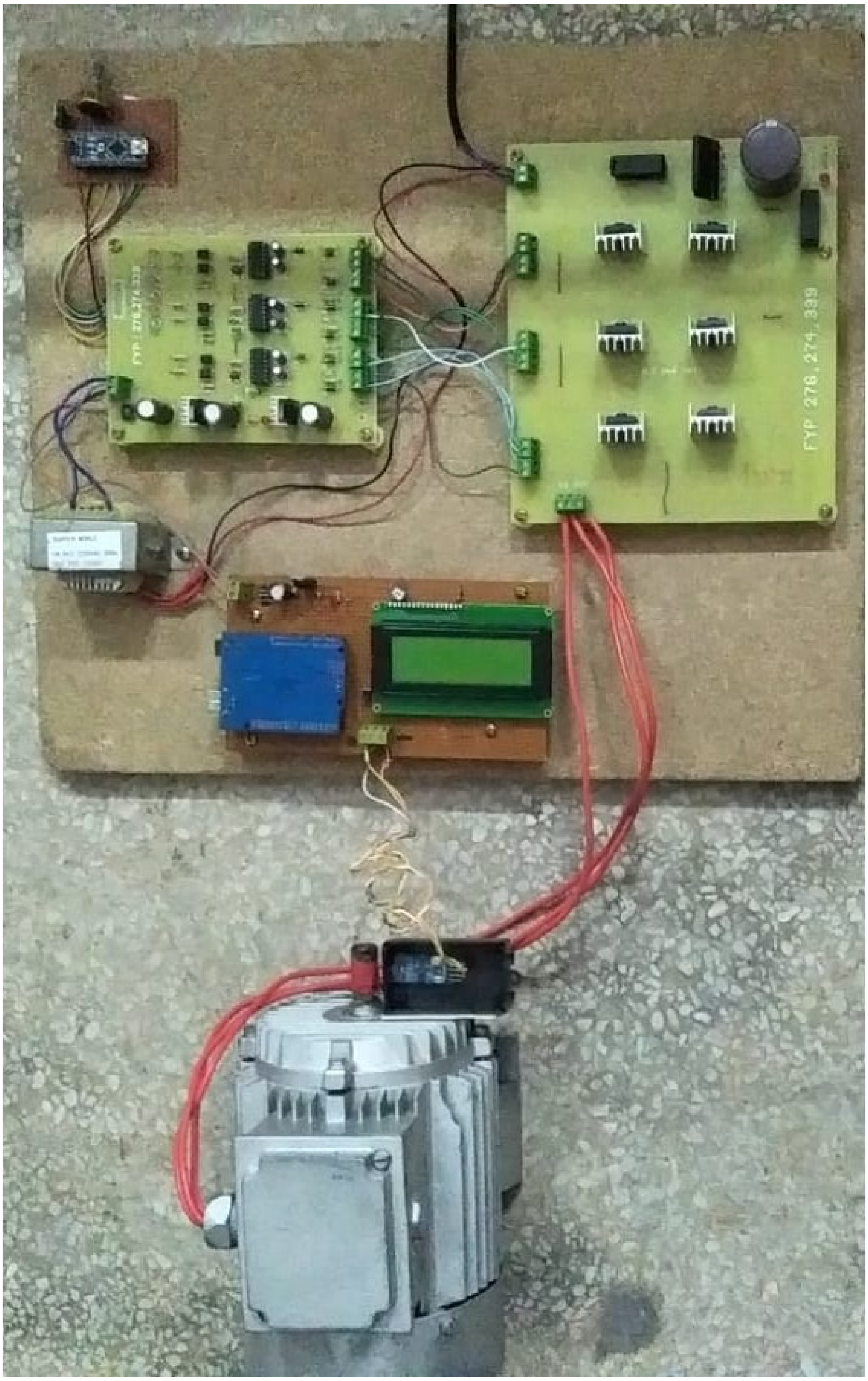

FIGURE 6.27: Project Model

Chapter 7

Conclusion and Final Thoughts

The below points show the conclusion of the above description.

- SPWM technique is the best technique used in most of industrial projects and provides the least THD.
- Inverter in the Variable Frequency Drive provides Pulse Width Modulation signal. If this signal is directly supplied to the motor. It will produce noise. So, for the smooth running of the motor, a capacitive filter should be used to obtain a smooth waveform.
- PMAC synchronous motor provides approximately 93 percent efficiency while induction motor provides 88 percent maximum efficiency.
- Micro-controllers used in this project although are cost-efficient, they have certain computational and operational efficiency problems.
- This project results in the production of the most economical and efficient Variable Frequency Drive, which can be used further for different applications.
- Variable Frequency Drive is basically used to reduce the starting inrush current. Make the motor smooth at the time of start and stop.
- Through Variable Frequency Drive we control the speed of the motor linearly.
- Variable Frequency Drive is better than soft starters i.e., a typical VFD gives a wide range of frequency varying that results in the speed varying of the motor.
- Variable Frequency Drive can be used for small applications as well as large applications.
- By incorporating advanced control algorithms and techniques, such as vector control and pulse width modulation (PWM), the ASD provides precise and flexible

control over motor speed, torque, and direction. This level of control allows for optimal operation of the motor under varying load conditions, resulting in improved energy efficiency and reduced power consumption

- Lastly, the thesis has highlighted the potential for future advancements in adjustable speed drive technology. With the rapid growth of power electronics and digital control systems, there are opportunities to further enhance the efficiency and capabilities of ASDs. Integration with advanced machine learning algorithms, intelligent fault diagnosis and prediction systems, and communication networks can enable smarter and more autonomous motor control, leading to even greater energy savings and improved system reliability.

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