A

Dissertation Report on

Elimination of Electromagnetic Interference and Control of Variable Frequency Drive

Submitted

in partial fulfilment of the requirements for the degree of

Master of Technology

in

Electrical Power System

by

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CERTIFICATE

This is to certify that, Mr.Suraj Shankar Salunkhe (Roll No-1729002.) has successfully completed the dissertation work and submitted dissertation report on "Eliminating Electromagnetic Interference from Variable Frequency Drive and its Control" for the partial fulfillment of the requirement for the degree of Master of Technology in Electrical Power System from the Department of Electrical, as per the rules and regulations of Rajarambapu Institute of Technology, Rajaramnagar, Dist: Sangli.

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ABSTRACT

Control part of varibale frequency drive protects and controls the speed, torque and position of an AC induction motor. A VFD controls the speed of the motor during the start and stop cycle as well as throught the run cycle. The control of VFD is done using a programmable logic controller (PLC). Using the programmable logic controller (PLC) VFD control is done with the proper and required operation according to the logic. VFD include the forward rotation start, reverse rotation start, high speed, low speed, medium speed, high starting torque and low starting torque according to the inputs given by PLC logic. Control system of VFD includes a main controller i.e. VFD and first interface PLC. The motor controller (VFD) is coupled to the PLC and controls the electric motor according to the application. PLC is further coupled to Human Machine Interface (HMI) to show the operation visually. An input to VFD is given from the PLC over communication lines to run the motor and outputs from the VFD is controlled frequency and voltage, which control the speed and torque of a motor. From the proposed topology the control of VFD is done using PLC.

Mitigation of electromagnetic interference (EMI) is important aspect in the VFD applications. VFD serves to regulate position, motor's speed and torque by manipulating input frequency and voltage being supplied to motor. VFD uses high-speed semiconductor switches (IGBTs) and pulse width modulation (PWM) techniques to generate fast-rise voltage pulses of appropriate duration and polarity. This creates a huge number of problems. The problems arrived at input side of inverter are inrush and peak currents, harmonics, commutation notches, low frequency interference. Also, problems at output side are peak dv / dt, parasitic earth currents, eddy current loss in motor, bearing currents, acoustic motor noise.This all problems leads to generate EMI in drive system. In this dessertation work, sine wave filter is placed in between inverter and motor to eliminate electromagnetic interference and dv/dt filter is placed in between main supply and rectifier to mitigate harmonic distortion and rate of rise of current.

Keywords: Variable Frequency Drive, Programmable Logic Controller, Electromagnetic Interference Mitigation, EMI Filter, Induction Motor.

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ABBREVIATIONS

VFD	Variable Frequency Drive
PLC	Programmable Logic Controller
HMI	Human Machine Interface
PWM	Pulse Width Modulated
SPM	Special Purpose Machine
SMPS	Switched Mode Power Supply
VTL	Vertical Turning Lathe
HMC	Horizontal Machining Centre
CNC	Computer Numerical Control

Chapter 1

Introduction

1.1 General

Nowadays the demand for Variable Frequency Drive (VFD) and servo drive is increasing rapidly. Industrial automation is basically used of the various new control techniques and systems such as electrical drives, electronic circuits, PLCs, Computer numerical controls, Microcontrollers, Microprocessors etc. These control techniques are used to operate and control pieces of machinery and industrial processes to reduce human efforts and time. Development of industrial product quality and production precision require new breeds of accurate and efficient equipment. This leads to the line increase of nonlinear loads which, in turn creates a rapid worsening of power quality in multiple industrial fields. VFD is among the most prominent sources of poor power quality including electrical devices, excessive fluctuation and abnormal electric arc furnaces and induction furnaces. VFD is typically used in speed control, HVAC, flow rate control, factory packaging and transportation.

Induction motors are widely used in industrial applications that require accurate control of the acceleration, speed and torque. They are used in the industrial machines, compressors, rolling machines, vertical turning lathes (VTL), horizontal machining center (HMC), industrial robots etc. The speed of the squirrel cage induction motor can be controlled by various methods such as voltage changing, connecting a resistance in rotor circuit, mechanical coupling to the shaft and pole changing. The most efficient and cost-effective method for controlling an induction motor is changing the supply voltage and frequency to motor.

Various types of VFDs are available in the market which has different methods for sending or receiving data from the controller. VFD is coupled to the PLC over a communication line. The coupling of VFD to PLC executes a motor control that determines motor parameters such as, start or stop of a motor under the normal or faulty condition, turn on or turn off the motors, acceleration and deceleration rate of the motor, torque shaft speed. PLC gives the desired parameter signals to VFD over the communication line and then VFD determines the frequency, voltage and/or pulse width modulated (PWM) signal to supply electric motor over a power line to achieve desired motor output . Human Machine Interface (HMI) include a display, LCD screen, cathode ray tube, LED, use keypad, a graphical user interface to enable an operator to control the operation. Display of HMI includes various display functions and icons that operator touch to initiate, control or stop various operations. The PLC transmits the desired parameter signals to the VFD on the RS-422, and then the VFD provides the frequency, voltage, and / or pulse width (PWM) modulated signal to power the electric motor on a feed line to obtain the desired output of the motor. The HMI display includes various functions and icons that the operator can touch to initiate, control or stop various operations.

In the earlier time, VFD use mechanical moving parts for the short period of time which results in equipment failure due to friction from mechanical constant motion. Many problems occur when starting of the large motors via direct connection to the utility power source is obtained. As we know AC motors draw three to five times its rated current with low power factor at the startup and this may cause sub-transient voltage drops in the network of utility source and they may adversely affect other system and equipment connected to it. AC motors undergo several thermal and mechanical stresses during the direct start, which affects lifespan and limits the number of starts in a specified time. VFD basically controls the voltage magnitude and frequency which give rise for smooth starting of the motor.

The pulse-width modulated (PWM) high peak voltage waveform on the power supply leads to the control motors by varying the frequency and voltage to control torque, speed and position. High voltage distortion, harmonics, and fluctuations are observed in the variable frequency drive of the induction motor powered by the PWM modulated voltage source converter. The motor power frequency is

modulated at a much higher rate using PWM techniques. This modulated PWM frequency has a very high dv / dt and di / dt. This high voltage and high edge current waveform generate electromagnetic interference (EMI) that damages motor bearings, mechanical noise, sensor measurement and output errors, overvoltage's, and associated insulation damage. as well as the overheating of the motors One of the oldest solutions to this problem is a common mode inductor or a current-compensated inductor to limit the rise rate of the currents as well as the switching noise of the rectifier side. The common mode choke is essentially an inductive circuit. A sinusoidal filter or three-phase low-pass LC sine filter is generally used to smooth the PWM waveform of the voltage and current of the sine waveform.
This dissertation report describes EMI filter which is a combination of sine wave filter and dv / dt filter. This presents studies of motor performance with and without EMI filter fed VFD. Also, it describes the effect of switching pulse width modulated frequencies on the motor performance and how to filter switching frequencies into sinusoidal waves by using appropriate EMI filter with the help of hardware result analysis.

1.2 Motivation of the present work

Variable frequency drive produces PWM high voltage waveforms overpower leads to control speed, torque and position of the motor. High voltage stress, harmonics as well as distortions are seen in the pulse width modulated voltage source inverter fed induction motor variable frequency drive. Also high di/dt and high dv/dt in the motor terminals due to the higher switching frequency, motor bearing damage, severe electromagnetic interference problems occur by using different PWM techniques. High voltage and high edge current waveform generate electromagnetic interference (EMI) that damages motor bearings, mechanical noise, sensor measurement and output errors, overvoltage's, and associated insulation damage as well as the overheating of the motors. Thus, a technique is proposed to enhance the output of the VFD and power quality.

1.3 Layout of the thesis

Based on the thesis work objectives, flow of dissertation work is distributed in the following chapters:

Chapter 1: In this chapter, current scenario of the VFD system, PLC controlling, VFD related problems are discussed.
Chapter 2: Literature review about VFD and EMI filter is discussed in this chapter. All published documents on EMI filter and VFD control topology are discussed. Also, objectives of research work are discussed in this paper.
Chapter 3: Description of proposed system is discussed in this chapter. This includes a detailed description of VFD control system and EMI filter.
Chapter 4: Operation and implementation of proposed VFD control topology and EMI filter are discussed in this chapter. The designing and working of all circuits with their components and features used in the hardware are discussed.
Chapter 5: In this chapter, hardware implementation and simulation results are explained. All hardware results with and without EMI filter are discussed.
Chapter 6: In this chapter, thesis conclusion and future scope are discussed.

1.4 Closure

In this chapter, a generalised concept of VFD, PLC controlling and EMI filter is discussed. Several EMI filters and control techniques are discussed with its requirements. The layout of project work is presented.

Chapter 2

Literature Review

2.1 Introduction

This chapter consists of a detailed literature review of control techniques of VFD used till date. there are different control techniques proposed by several researchers which are used in EMI mitigation filter. This chapter gives a brief summery of all these research documents.

2.2 Literature Review

Richard H. Osman et.al proposed concept of soft starting a large AC motor with the variable frequency drive configured to be coupled to utility power source and to provide an output voltage having a variable frequency and variable peak magnitude.VFDs are used to soft start the induction motor having the same rated voltage as AC motor. [1]

Chun-Lien Su proposed Variable frequency driven central seawater cooling system that uses the programmable logic controller (PLC) which gives the control signals according to the requirement of torque and speed of motor . The adjustable speed control of motor is an important measure for the effective management of electrical energy efficiency of marine vessels.Energy savings benifits with VFD control on seawater cooling pumps is analysed with PLC control technology and HMI visualisation. [2]

Joseph Song-Manguelle et.al has proposed the analytical reversible propagation of electrical and mechanical components in motors air gap. These results can be used to emulating dynamic loads such as oil and gas processes, industrial machines,

Pouring Machines, electric and hybrid vehicles emulation etc. By using parallel connected PWM VSI inverter which is supplying an induction motor minimizes the torque components which is transferred from mechanical to electrical side. [3]
Ephrem Ryan Alphonsus et.al gives review on the application of PLC in our current scenario. applications of PLCs are widely spread in various fields such as energy research, engineering studies, industrial control applications, and monitoring of various plants. Also it gives the limitations of PLC, but findings of PLC indicate that PLCs have more advantage than its limitations. [4]
Warren Neil Rattan et.al propses VFD is coupled with the PLC over a communication line. VFD is a motor controller the is coupled to and drives an electric motor by varying frequency voltage and/or pulse width modulated signal (PWM) supplied to electric motor. The motor control PLC gives the ladder logic such as: how the motor is stared or stopped under normal condition , in the faulty condition, the acceleration or deceleration rate of motor, torque, shaft speed. The VFD PLC provides frequency, voltage, and/ or PWM signal to supply to electric motor. [5]
Mahesh Nandaniya proposed on the automatic gate control of canal using VFD. PLC is used to give the commands to VFD. VFD achives the required voltage and frequency to start and stop the motor. gate will open or close as per command and after that system will automatically stop. [6]
Spyridon V. Giannoutsos proposed Variable frequency drive topology for large motors in the marine vessel are used for the energy saving applications. However due to such large motors in the vessels power distribution network introduces harmonics, which can be controlled by using harmonic attenuation filters including AC, DC chokes, ferrite core and frequency tuned filter. [7]
Prasun Mishra High voltage stress, harmonics as well as distrotions are observed in the pulse width modulated voltage source inverter fed induction motor variable frequency drive. Sinusoidal LC filters are placed between the inverter and the induction motor to smooth the PWM waveform. [8]
Mahesh Swamy passive harmonic filter of reduced size and weight which can significantly reduce the distortions of input voltage and current waveforms caused by variable frequency drive. [9]
Dinesh Kumar performance and analysis of three phase induction motor with VFD

and VFD with filter. VFD used for the speed control of induction motor injects harmonics within the circuit and they lead to peaky rotor and stator current and oscillations in the torque. [10]

Fang Z. Peng proposes Z source inverter system and variable frequency drive. the Z source inverter employs a unique LC network coupled to the inverter main circuit used as a filter. [11]

Xie Wenhao Electromagnetic interference (EMI) in the application of the variable frequency drive creates the noise in the motor. EMI passive filters which can suppress the noise from the VFD. [12]

Erik Velander proposes novel dv/dt filter for voltage source converters using silicon carbide devices. Concept used for filter is to provide inductance between power devices and converter output with RC link. [13]

Donald J. Lucas proposes RFI/EMI filter for a variable frequency motor drive system includes a VFD, common mode choke, motor and cable including plurity of power leads. the importance of cable grounding is given. Motor cable ground shield is connected to the motor ground and main ground. [14]

Vladimir Kraz VFD and servo drive having the PWM switching pulses and due to this pulses the electromagnetic interference will cause the noise problem. The motor filters such as sine wave filters, DV/DT filters are used to reduce the noise problems. [15]

2.3 Objectives of Research work

In this dessertation work,it is proposed to develop a system for mitigationg electromagnetic interference from varaible frequency drive and its control by using PLC.The objectives of proposed work are:

1. To study convetional VFD control and EMI elimination techniques.

2. To develop PLC program for VFD control.

3. To model proposed EMI filter system in MATLAB-simulink.

4.To develop hardware of VFD control and proposed filer.

Chapter 3

System Description

3.1 Introduction

This chapter introduces different system components used for the dissertation work. The block diagram of proposed system is shown in figure 3.1

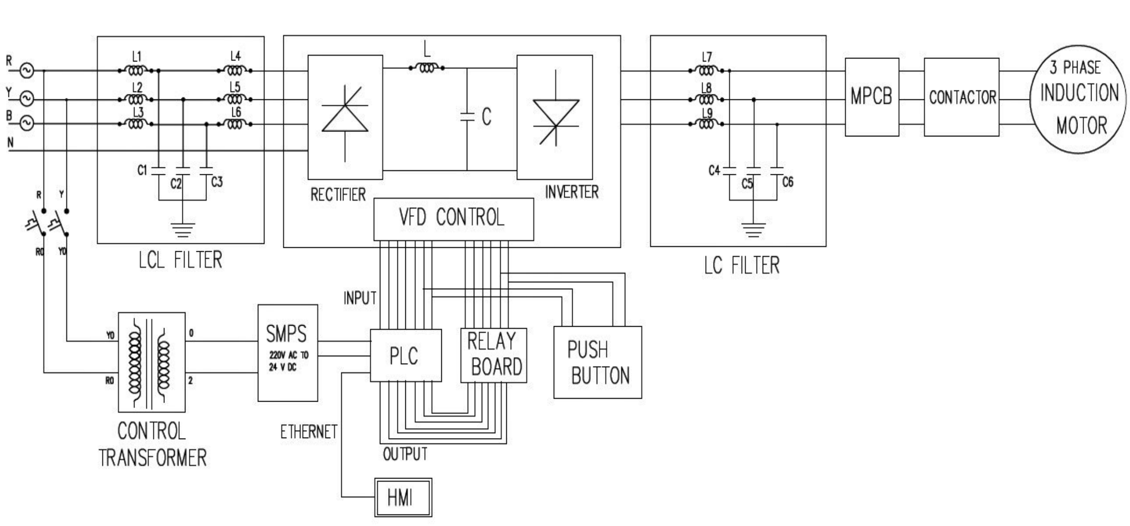

Figure 3.1: Block diagram of proposed system.

Thus, the major components of the proposed system are:

1. Variable frequency drive
2. Programmable logic controller
3. Switched mode power supply
4. Human Machine Interface
5. Sine wave filter

6. dv/dt filter
7. EMI filter

The components are described in the following sections

3.2 Variable Frequency Drive

Variable frequency drives convert constant voltage and frequency input power to variable voltage and frequency source for controlling AC induction motors speed. The frequency and voltage from inverter applied to an AC motor decides the motor speed.

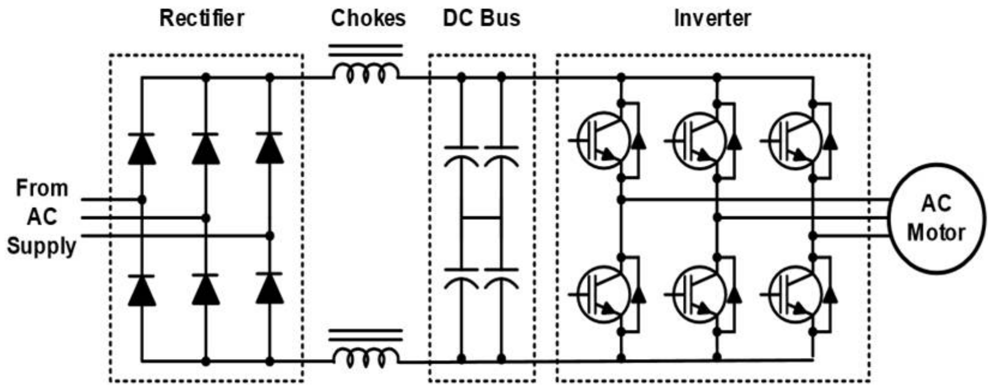

Figure 3.2: Circuit diagram of VFD

Figure 3.2 shows typical circuit diagram of VFD. The main components of variable frequency drive are voltage-controlled inverter, DC bus and controlled rectifier. The controlled rectifier in a VFD is basically a converter which convert Ac voltage into DC voltage. One of the half-bridge rectifiers only allows the power supply to pass when the voltage is positive. Another half-bridge rectifier will allow the current to pass through only when the voltage is negative. These two rectifier bridges are necessary for each phase of power. Since most power supplies are in three phases, at least six rectifiers will be used. Thus, the term "6 pulses" is used to choose a drive with 6 rectifiers.

A VFD also has various rectifying pulses, with 6 rectifiers per section, allowing a VFD to be 12 pulses, 18 pulses or 24 pulses. Rectifiers use transistors, diodes and silicon rectifiers to rectify power. The SCR contains a gate circuit that allows a microprocessor or microcontroller to control the start of the current. The transistors contain a gate circuit that allows a microprocessor or microcontroller to switch a gate pulse at any time. A VFD using transistors in the rectifying unit is known to have an active front end.

The rectified DC voltage from the rectifier is further stored in the DC bus. The DC bus has capacitors for storing and accepting the rectifier power supply, and then transferring power to the inverter. The DC bus also contains inductors, DC links, a ferrite core, a choke or similar elements, so that it adds an inductance, which smooth the power supply of the DC bus. The last unit of the VFD is called ”inverter”. The inverter has transistors that transfer power to the motor. The ”Isolated Gate Bipolar Transistor” (IGBT) is commonly used in upgraded VFDs. The IGBT switching time (on and off) is several thousand times per second and it will control the power transferred to the motor. The IGBT uses the ”Pulse Width Modulation” (PWM) technique to control a sinusoidal wave of current and voltage at the frequency desired by the motor [12]. The PWM technique is called the process involved in converting DC voltage to variable frequency AC voltage in the inverter unit of the VFD. PWM controls the transistors that turn on and off the DC voltage in one pulse required to produce the AC output voltage and frequency. A VFD with a 440 VAC input AC power supply converts it into a DC power supply of approximately 600 VDC. Thus, ”pulse” is defined as the activation and deactivation of transistors generating a voltage pulse with a maximum amplitude of approximately 600VDC. Figure 3.3 shows the Pulse width modulated (output) voltage waveform of VFD.

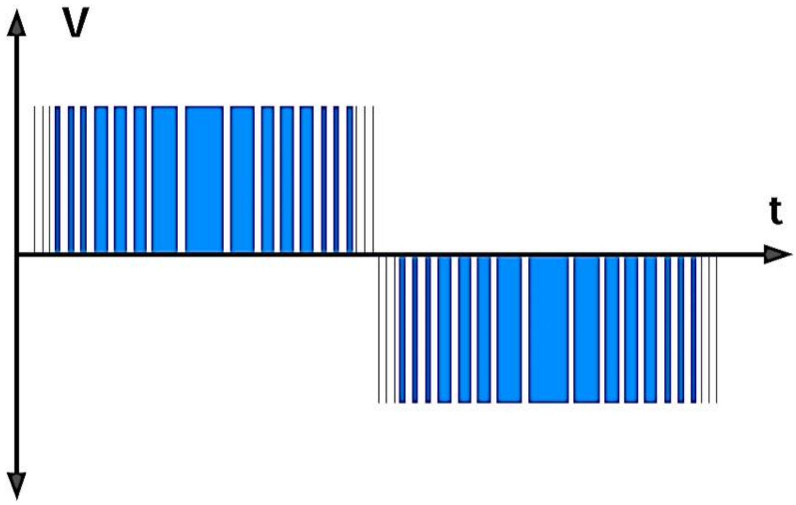

Figure 3.3: Pulse Width Modulated Voltage Waveform

In the case of modern VFDs controlled by the PWM technique, this control is completed by modifying the motor rms voltage. By controlling the time required to switch the pulse, the resulting rms voltage of the motor phases is controlled. By controlling the pulse width on each half-wave, the rms voltage across the motor phases is controlled. The controlled variable RMS voltage decides that the VFD is changing the amount of current required between the motor phases. The current waveform transferred via the PWM process is also affected by the IGBT switching pulses.

3.3 Pulse width modulation

The process involved in inverting the DC voltage to the variable voltage variable frequency (VVVF) AC voltage in the inverter section of the VFD is called pulse width modulation or PWM. Pulse width modulation uses transistors which switch the DC voltage on and off in a defined sequence to produce the AC output voltage and frequency. Most VFD's today utilize insulated gate bipolar transistors or IGBT's. The transistors act as a switch connecting the DC bus across the windings of the motor. A VFD with a 480VAC input will have a DC bus of approximately 678VDC. Thus the 'pulse' refers to the switching on and off of the transistors producing a pulse of voltage with an amplitude of approximately 678VDC. In the case of a VFD that utilizes PWM technology, this is done by varying the RMS voltage to the motor. By controlling the amount of time each pulse is on and off, the resulting RMS voltage across the motor phases can be controlled. The 'width' of the pulse factors into the resulting RMS voltage output.

Figure 3.4 shows a longer 'ON' time of the pulse results in a higher RMS voltage across the phases. Figure 3.5 shows a shorter 'ON' time of the pulses results in a lower RMS voltage across the motor phases.

So by modulating the pulse width over each successive half wave, the RMS voltage across the motor phases can be controlled. The resultant variable RMS voltage allows the VFD to vary the amount of current flowing between motor phases. The current waveform produced through the PWM process is also influenced by the IGBT switching frequency.

The ability to control the torque and speed of an AC motor opens up the application possibilities for machine designers. Motor speeds can be optimized for the

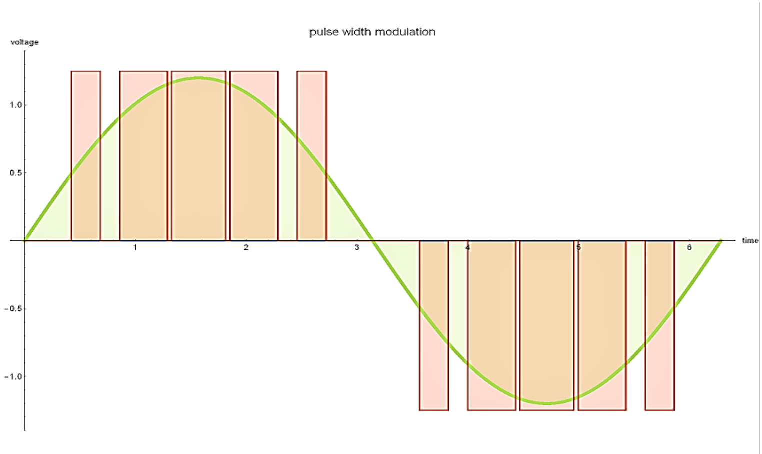

Figure 3.4: PWM representation with longer “ON” time

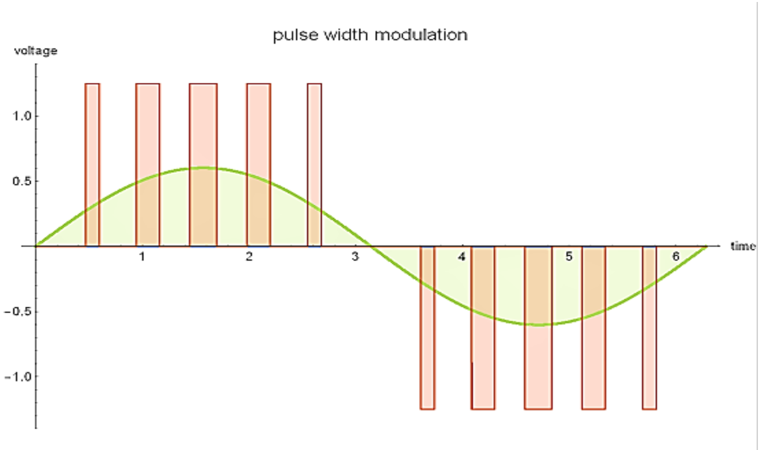

Figure 3.5: PWM representation with shorter “ON” time

application to achieve higher system efficiency (i.e. fan control). Motor speeds can be increased above the nominal motor speed to increase production rates. Motor torque can be limited to help protect mechanical components of the system. Controlled starting and stopping of motors can eliminate mechanical components that may wear over time.

Motor speed (rpm) is dependent upon frequency. Varying the frequency output of the VFD controls motor speed:

Speed (rpm) = frequency (hertz) x 120 / no. of poles

3.4 Programmable Logic Controller

Programmable logic controllers [PLC] are computer-based, solid-state, single processor devices that emulate the behaviour of an electric ladder diagram capable of controlling many types of industrial equipment and entire automated systems. The term logic is used because the programming is primarily concerned with implementing logic and switching operations. Input devices such as switches, and output devices such as motors, being controlled are connected to the PLC and then the controller monitors the inputs and outputs according to the machine or process. All PLC systems are comprised of the same basic building blocks that detect incoming data, process it, and control various outputs.

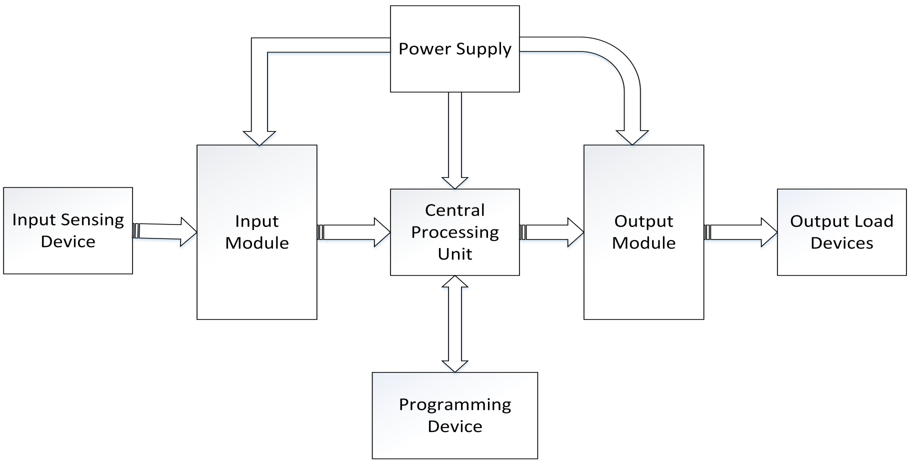

Figure 3.6: Block Diagram of PLC

The basic blocks are:

1. Rack Assembly
2. Power Supply
3. Programming Device
4. Input/output Section
5. Central Processing Unit (CPU)

3.4.1 Rack Assembly

Most programmable controllers that have a large number of input and output terminals are constructed by using a variety of modules. These modules include the power supply, processor unit, and input/output modules. Allen-Bradley controllers make a distinction between a PLC chassis and rack. The hardware assembly that houses input/output (I/O) modules, processor modules, and power supplies is referred to as the chassis. The modules are installed in a rack. The PLC rack serves several functions. It physically holds the modules in place, and it also provides electrical connections between the modules by using a printed circuit board at the back or the rack assembly. The modules are easily inserted into channels on the rack. They fit into sockets mounted on the motherboard to make electrical contact with the other circuitry. The ability to plug modules into the rack allows maintenance personnel to replace defective units quickly.

3.4.2 Power Supply

The power supply supplies direct current (DC) power to other modules that plug into the rack, With larger systems, power to field devices is provided by external alternating current (AC) or DC supplies. For some small micro PLC systems, the power supply may be used to power field devices.

3.4.3 Programming Device

The programming terminal or loading terminal is used to program the CPU. The type of terminal used depends on the manufacturer and often the preference of the customer. Some are small handheld devices that use a liquid crystal display or light emitting diodes to show the program. Some of these small units will display one line of the program at a time and other required the program to be entered in a language called Boolean. Many industries prefer to use a notebook or laptop computer for programming. An interface that permits the computer to be connected to the input of the PLC and software program is generally available from the manufacturer of the PLC.

3.4.4 Input/ Output Section

The I/O section of a PLC is the section to which all field devices are connected and provides the interface between them and the CPU. Input/output arrangements are built into a fixed PLC while modular types use External I/O modules that plug into the PLC. The fixed type is associated with the small or micro PLC system where all of the features are integrated into a single unit. The number of I/O ports is fixed within each model and cannot be changed. The modular types use a rack to hold the I/O modules so the number and type of I/O modules can be varied.

3.4.5 Central Processing Unit

The CPU coordinates and controls the operation of the entire programmable controller system. A processor module is usually located at one side of the rack assembly. It contains integrated circuit chips that include one and more microprocessors, memory chips, and circuits that enable data to be stored into and retrieved from memory. The processor is composed of three main sections: the central processing unit (CPU), the arithmetic logic unit (ALU) and the memory. The principle function of the CPU is to interpret and execute computer-based programs that are permanently stored in the processor's memory. These programs are written by the PLC manufacturer to enable the PLC to perform ladder logic instead of other programming languages. The CPU coordinates the operation of the ALU and the memory. The function of the ALU is to perform mathematical calculations and make logic functions. The memory function of the processor stores programs and data that the CPU needs to perform various operations. The memory is organized into several sections according to the function they perform.

3.5 Switched Mode Power Supply

SMPS is used to power a wide variety of equipment such as PLCs, relay modules, sensors, proximity switches, solenoid soils, thermo sensors, load sensors, HMI supply. In VFD control topology some of the inputs and outputs are working on 24V DC supply. Also, some of PLC input voltages are 24 V DC. SMPS is the device converts 230 VAC supply into 24V DC supply for reliable operation.

3.6 Human Machine Interface

HMI is a certain device that is capable to display human-machine interactions. Interface mainly consist of software and hardware that gives the user inputs to be converted as signals for the machines that, in turn, provide required output to the user. HMI technology is basically of two types i.e., machine to human and human to machine. HMI contains a USB interface to connect a personal computer and transfer data. Also, Ethernet interface, RS-422/485, RS-232 interface to connect the various industrial device, barcode readers and serial printers.

3.7 Sine Wave Filter

Sine wave filters are low pass frequency filters which convert the rectangular PWM output signal of motor drives into a smooth sine wave voltage with low residual ripple. Sine wave filters, also known as LC-filters or named sinusoidal filters, are mainly used in combination with variable speed drives to protect the motor against excessive voltage spikes and overheating. As a result, insulation stress and losses in AC motors are reduced and prolongate the motor life time. Figure 3.7 shows typical block diagram of sine wae filter arrangement.

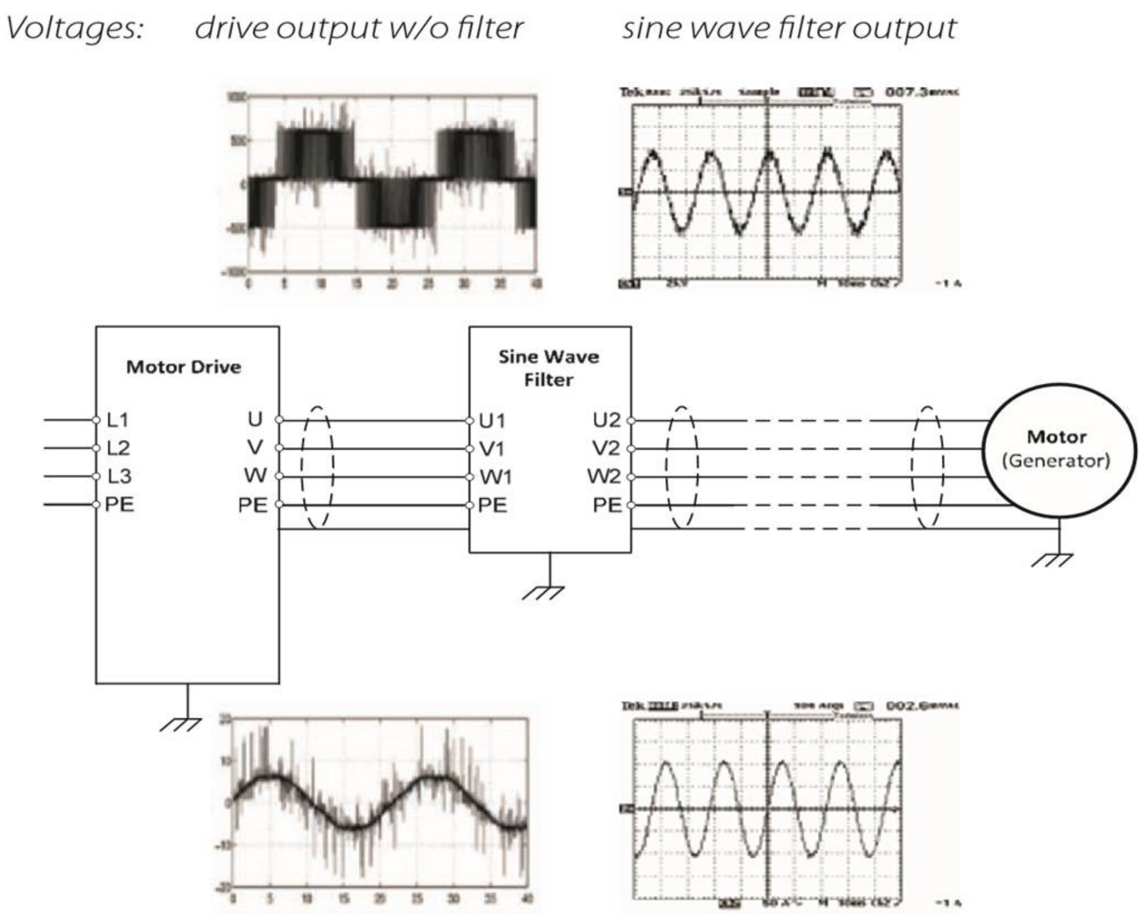

Figure 3.7: Block Diagram of typical sine wave filter arrangement

The residual ripple of the signal can be adjusted by using the values of the L and C. Optimum cost-benefit ratio is often reached at a ripple voltage of 3 % to 5 %.

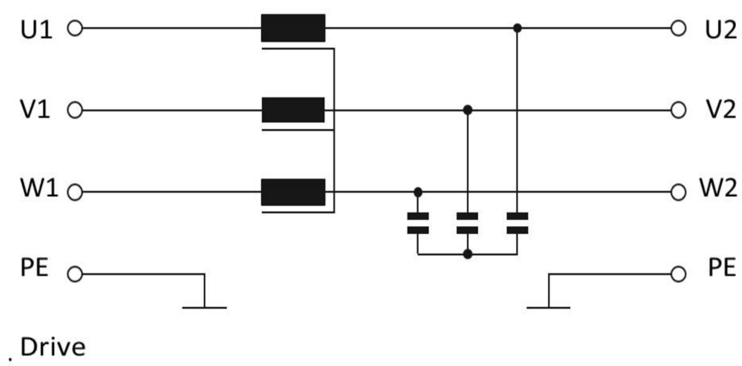

Figure 3.8: differential mode LC sine wave filter

3.8 Sine wave filter selection

It is recommended that the rated current of the sine wave filter shall be equal to or greater than the nominal motor current and should correspond and be compatible with the ratings and duty cycle capability of the motor drive. For motor drives feeding isolation transformers select a sine wave filter with a current rating equal or greater than that of the transformer primary current. With regard to the voltage, Schaffner offers sine wave filter for 400 VAC, 500 VAC, 600 VAC and 690 VAC applications. Even for short cable installations, at voltages 500 VAC sine wave filter are recommended, to protect the motor winding insulation against high voltage peaks. In cases the motor drive selection has been made prior to the sine wave filter selection, the usual way is to size the sine wave filter to the corresponding motor drive. Nevertheless, the proper power selection depends on one side upon the drives related specifications, e. g. rated current, voltage, line frequency, motor drives switching frequency, motor frequency, the ambient conditions (temperature, altitude) and on the other side on the motor and application performance requirements. In addition, the motor cable length, cable type, motor type, and some particular application requirements needs to be considered.

3.8.1 Frequency

The frequency is an important factor when selecting output filter. Depending on the type of filter, three different frequencies are relevant.

• Supply frequency. The frequency of the AC mains supply network, typically 50 or 60 Hz. The operating frequency of the filter is determined by the behaviour of the capacitors. Depending on the voltage/frequency characteristic of the capacitor, it might be possible to operate a filter at a higher frequency but with a reduced input voltage.

• Switching frequency. The frequency used to switch the IGBTs in the output stage of a frequency converter. This frequency has a direct relation to the power loss in the converter and to the output components.

Higher switching frequencies have following effects:

– increasing the switching losses of the semiconductors

- temperature rise of motor drive and derating to be considered

– reducing the audible noise level

– increasing the leakage currents

– reducing the harmonic motor current and motor temperature

Generally speaking, lower frequencies result in lower motor drive losses and lower leakage currents.

For an output filter, it is also necessary to consider the relation between the motor drive switching frequency and the resonance frequency of the sine wave filter. The Schaffner sine wave filters are always designed in such a way that the resonance frequency is at least 2.5 times lower than the lowest switching frequency. It is important that the minimum switching frequency adjusted in the motor drive is respected according to the specified minimum switching frequency of the sine wave filter.

3.8.2 Required drives settings

The nominal switching frequency of the motor drive can vary or be adjusted and therefore need to be considered from the beginning for the sine wave filter selection. The motor drive must be suitable to be operated with sine wave filter and therefore shall be adjusted with a constant switching frequency. The mode of operation must be “scalar“ (V/Hz) with a fixed switching frequency. Check the drives manufacturer manual whether special settings are necessary. In any doubt contact the drives manufacturer. Ensure the drives switching frequency is set to the required minimum switching frequency.

3.9 dv/dt filter

Motor drives switching frequencies of 16 kHz or more can generate dv/ dt values of up to 12 kV/us. Depending on the output voltage of the motor drive, the cable length and type as well as the layout do influence the voltage rise time. High dv /dt levels can damage the motor windings. According to EN 60034 voltage rise times of 500 to 1000 V/us are permissible depending on motor types. Figure 3.9 shows the block digaram of dv/dt filter arrangement.

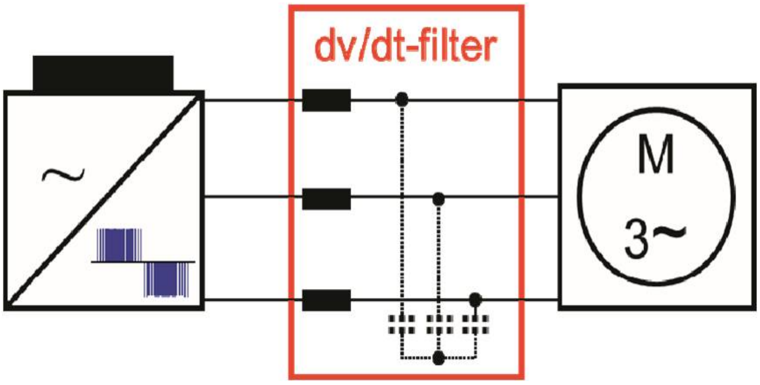

Figure 3.9: block diagram of arrangement of dv/dt filter

The dv/dt filters are low pass filter built with inductors, capacitors and power resistors. The nominal switching frequency of the motor drive shall be below the typical cut off frequency of the dv/dt filter (typical <10 kHz). The sine wave filter has higher L and C values, therefore dv / dt filters are lower in cost and smaller in size. With a dv/dt filter the output current ripple is lower but the voltage is still PWM pulse pattern shaped. The output pulse voltage waveform with and without filtr is shown in figure 3.10.

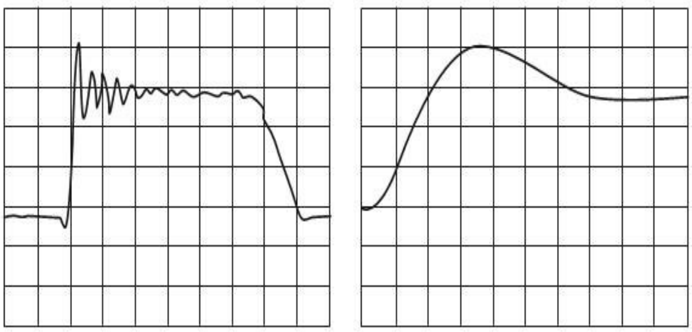

Figure 3.10: Waveform of voltage pulse with and without dv/dt filter

The Filter reduces the high output voltage dv/dt from IGBT motor drives and limits the peak voltage to 1000 V. It protects the motor insulation windings from premature aging and destruction and increases significantly the service life of electric motors. In addition, less interference propagation towards neighbouring equipment or lines are occurring. The typical cable length used is $\leq$ 80 m at a maximum switching frequency of 16 kHz at 400 VAC. Side effect of the use of a dv/dt filter: the frequency of the pulse ringing voltage oscillation is reduced below 150 kHz. Mainly for high power motors, the motor bearing stress is slightly reduced, but dv/dt filters do not eliminate the acoustic switching frequency noise from the motor.

3.10 EMI Filter design

For reasons of cost efficiency, required time and space, a trial is generally first made to eliminate motor drive issues without any additional components. Also, the subsequent cost that result from motor or system failures are far lower than initial cost of preventive output filter cost. According to the operational safety and installation lifetime the following types of passive filter components have installed to mitigate EMI.

- dv/dt Reactors (filter)
- Sinusoidal output filter
- EMI filter

The EMI filter is essentially a combination of dv / dt reactor and sinusoidal filter. dv / dt reactor on line side of VFD protects the electronic components of VFD from input line (supply) disturbances and protect power supply from disturbances created by VFD. Sine wave filter converts the PWM signal to the corresponding sine waves with approximately the same rms voltage as the original PWM signal. Also, EMI filters have the advantage of significantly reducing electromagnetic interference in all aspects. They can also be installed later in existing installations. Just like a reactor, they require no tests or periodic maintenance. Sine wave filters, however only work with certain types of motors (that is, they cannot be used with servomotors); cannot be used at lower switched frequencies due to possible damage to the internal capacitor and are bulky.

In process of designing we have to take all information about the available power system, including environmental condition, is required. Power system data contains nominal line-to-line voltage, current, fundamental frequency, system description, and impedance of all system components. A clear description and circuit diagram of VFD, equipment location (i.e. indoor or outdoor), operating parameters, switching and controlled operation rates, environmental data (such as temperature and wind condition), harmonics rates and characteristics, is important to consider before starting the EMI filter designing.

Table 3.1 shows the information about the power system including environmental

Table 3.1: Power system data

Voltage	415 V
Rated current	17 A
Motor Rating	10 KW
Ambient Temperature	50
Rated Frequency	50 Hz
Max. switching Frequency	4 kHz
Power Factor	0.6

data. From the above ratings the calculation for filter is decided.

EMC filters are designed in order to decide circuit values for L and C are optimized for lowest power at the fundamental frequency and also able to effectively attenuate up to 50 KHz. The technical design usually requires a high reactive component, so that its impedance will be critically damped at about 0.707.

$$\zeta = \frac{L}{2R\sqrt{LC}} \tag{3.1}$$

Where,

L= Inductance (mH)

C= Capacitance (μf)

R= Resistance (Ω)

Under-damped filter (<0.7) can cause a ringing sound or tend to oscillate. An over-damped filter (>1) that can reduce the cut off frequency and increase power loss in the filter. EMI filters depend so much on the input side impedance (source impedance) needed to get the best results. By placing an additional impedance in relation to the required impedance, the EMI filter loses its effectiveness. In addition, adding more L and C from other filters will unbalance the EMI filter and its critical damping. The efficiency of the filters could cause ringtones or power oscillations for the VFD.

Percentage impedance for the EMI filter can be calculated as,

$$\%Z = \frac{\sqrt{3}LI2\pi f}{V_L L} \times 100 \tag{3.2}$$

Where,

Z= Impedance of filter

I= Rated current of VFD

L= Inductance of reactor

VLL=Line voltage

Value of capacitor can be calculated as,

$$C = \frac{KVAR}{2\pi f V^2} \tag{3.3}$$

Where,

KVAR= Total KVAR rating of VFD

V= line to line voltage

Total harmonics distortions (THD) is used to define the effect of harmonic order in the waveform. It is calculated as,

$$THD = \sqrt{\frac{sum of squares of amplitudes of all harmonics}{square of amplitude of fundamental}} \tag{3.4}$$

Percentage THD value decides the total harmonic distortions affected by the VFD. Table 3.2 shows different ratings of inductor and capacitor used for filter.

Table 3.2: Different ratings of inductor and capacitor used for filter

Inverter current rating (A)	Inductor (mH)	Capacitor (μF)	% Impedance
5	7.11	82.26	7
7.5	5.33	123.36	7
10	3.55	164.49	7
12.5	3.14	205.62	7
15	1.22	246.75	7

3.11 Closure

This chapter elaborates a brief description of VFD and its working and PLC with its internal basic blocks. The Sine wave filter and dv/dt filter is explained and sine wave filter selection requirements. Also, HMI and SMPS description is given. EMI filter design is described in detail.

Chapter 4

Methodology

4.1 Introduction

An eliminating electromagnetic interference from VFD ansd its control is proposed. VFD control using PLC works efficiently by controlling speed, torque and position required according to application. EMI filter eliminate issues such as output current, common mode noise, high edge voltage waveform, high di/dt and high dv/dt. The proposed system controls the VFD using PLC and EMI filter mitigates above issues.

4.2 VFD control system

VFD control apparatus mainly includes the variable frequency drive for motor control and PLC to control the overall processes of the machine. Such apparatus may reduce the number of cables used to control the electric motors. Different brands/types of VFDs are available in the market may have different sending and receiving digital data to the PLC from the VFD. According to the PLC and motor controlling requirements which brand/type of VFD should be selected is decided. Figure 4.1 gives detailed information about the control and operation of the motor that is used in the industrial machines. The various industrial applications such as drilling, tapping, milling, boring, finishing of the cast material (i.e. job) require an accurate torque, speed, and position. Speed and torque can be controlled in a number of ways with the VFD.PLC is an industrial computer is used to monitor the inputs, process it in the CPU, and gives the output according to the electrical ladder logic. The program in the ladder logic or in simulation logic can be designed

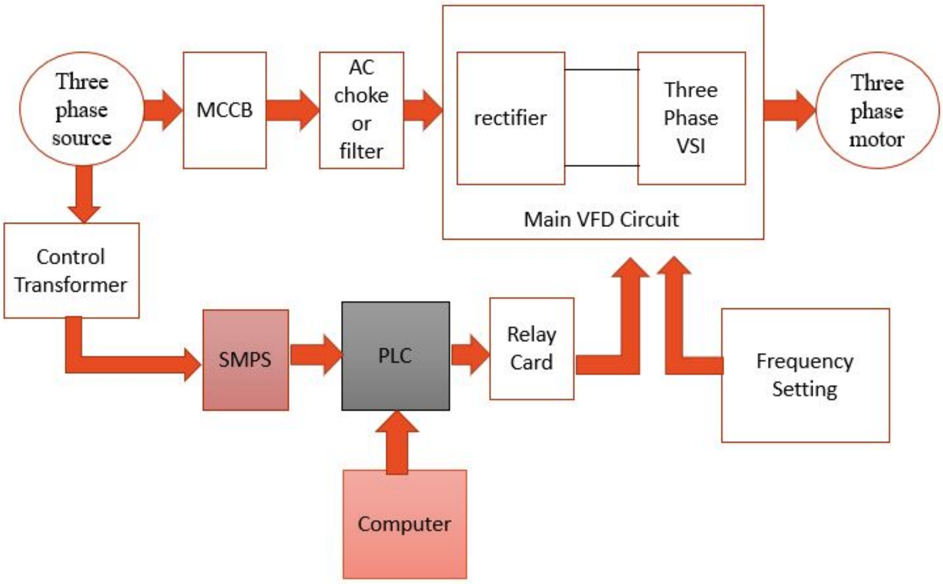

Figure 4.1: Block diagram of VFD control system

and usually checked before installing to the PLC. PLC can be communicated to the computer over RS-422 serial communication line.

Relay modules (card) are electronic boards with an array of relays and switches. They have input and output terminals and are designed to control the output voltage supply. Relay boards with opt isolators or fuses provide isolation between control signals (output signal from PLC) and output controls.

For simple variable speed operation of the inverter, the initial set of parameters is used. Necessary parameters are set to meet the load and operational specifications. Parameter setting, change, and check can be made from the operational panel. VFD has no. of parameter setting to control the speed, torque, Acceleration, Deceleration, and also having the electrical thermal overload relay. For the proper operation to select the different speeds for that to select the parameters P4, P5, P6 and set the required frequency.

Figure 4.2 shows PLC ladder logic for VFD control. Ladder diagram of PLC is modelled in the codesys software. Tha parameter settings of VFD gives accurate speed control. Some of the important parameter settings are shown in table 4.1.

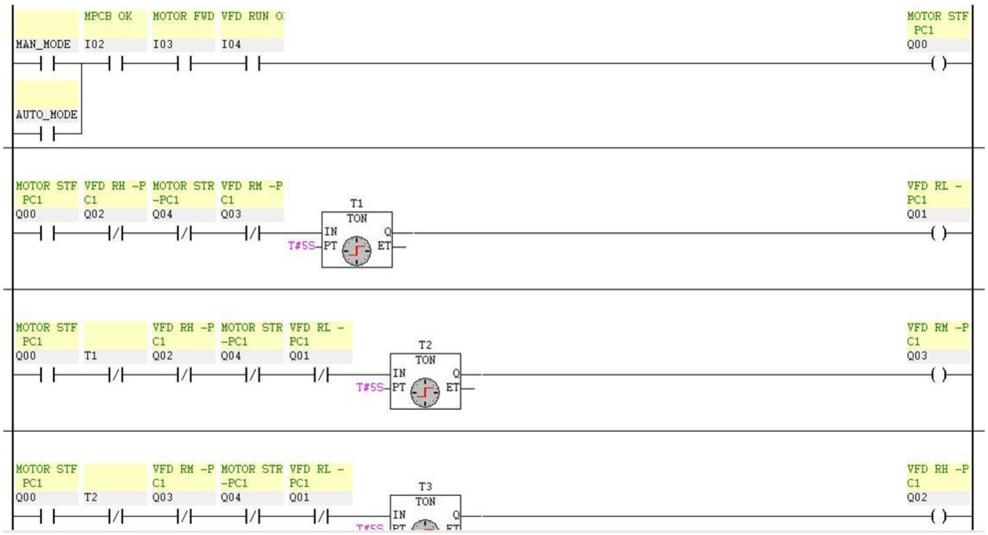

Figure 4.2: PLC ladder logic for VFD control

Table 4.1: Parameter setting of VFD

Parameter No	Parameter selection	Description
P79	No.3	Mode selection (STF, STR)
P3	50 HZ	Base Frequency
P4	0 to 400 Hz	High-speed setting
P5	0 to 300 Hz	Medium Speed Setting
P6	0 to 200 Hz	Low-speed setting
P7	0 to 120 sec	Acceleration time setting
P8	0 to 120 sec	Deceleration time setting
P9	0 to 100 A (set at rated inverter current)	Electrical thermal O/L relay

4.3 Simulation model of Proposed EMI filter

Figure 4.3 illustrates the MATLAB-Simulink simulation model of proposed filter. The system involves a LC sine wave filter having rating of 5 HP. The rated current of system is about 8 A. the ratigs of inductance and capacitance calculated values are 5.33 mH and 123.36 μF. Simulation model consist of inductor and capacitor connected at output side of inverter.

A sinusoidal filter or three-phase low-pass LC sine filter is used to smooth the PWM waveform of the voltage and current of the sine waveform. They are basically of two types, “Common mode” and “Differential mode”. VFD system are works on differential mode i.e. symmetric sine wave. . As a result, insulation stress and losses in AC motors are reduced and prolongate the motor life time.

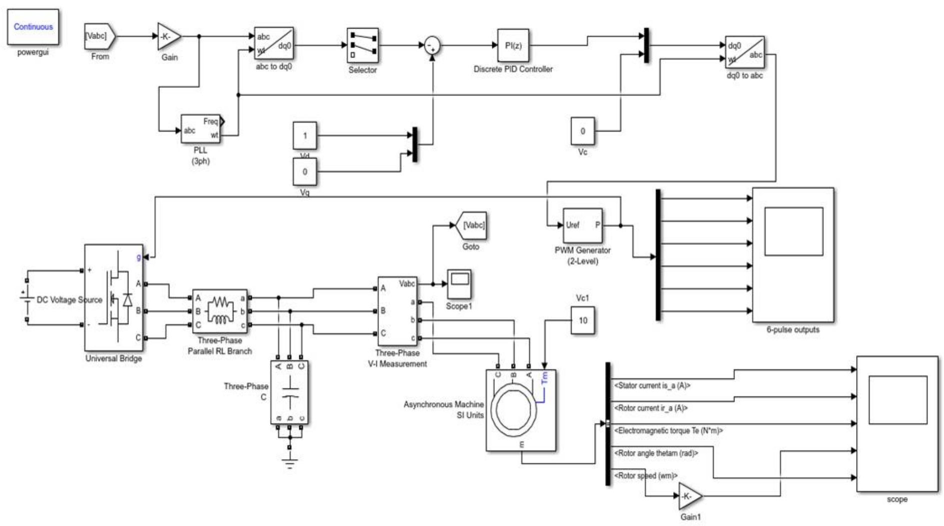

Figure 4.3: simulation of LC filter connected to VFD

The residual ripple of the signal can be adjusted by using the values of the L and C. An optimum cost-benefit ratio is often reached at a ripple voltage of 3 % to 5 %. The study system contains a variable frequency drive of 5HP 7.5 A and connected to a 3.7 KW with and without EMI filter.

4.4 Experimental setup

Following subsection gives the information about components of proposed experimental setup.

4.4.1 Variable frequency drive

Figure 4.4: VFD

Variable frequency drive used for experimental setup is of 10 HP. The current rating of this VFD is 17 amp. it consists of rectifier, DC bus and inverter. Also, Mitsubishi make VFD having various parameter setting to control various operation. Figure 4.4 shows the VFD.

4.4.2 PLC

PLC used for experimental setup is of 16 input and 16 outputs. Mitsubishi make nexgene 2k model is used for experimental setup. PLC is interfaced with computer by using RS-232 and Rs-422 communication cable. The software used for the programming is codesys. Figure 4.5 shows the PLC.

Figure 4.5: PLC

4.4.3 SMPS

SMPS used for experimental setup is of 230V input supply and +24V DC supply. It gives constant +24V DC supply which is given to run the components such as PLC, Sensors, limit switch and proximity switch. Figure 4.6 shows SMPS.

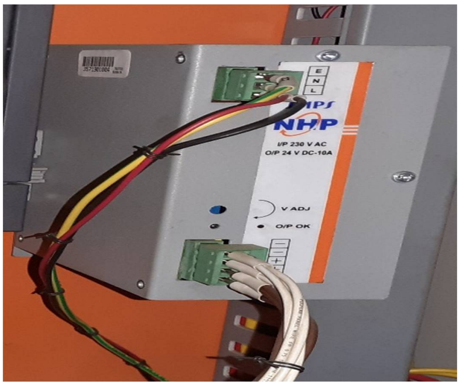

Figure 4.6: SMPS

4.4.4 Control Transformer

A control transformer is very often designed to produce a high level of secondary voltage stability during brief periods of overload condition, otherwise typically known as inrush current. Control transformers are used in an electronic circuit that requires constant voltage or constant current with a low power or volt-amp rating. Various filtering devices, such as capacitors, are used to minimize the variations in the output. Figure 4.7 shows control transformer.

Figure 4.7: Control Transformer

4.4.5 Relay Board

Relay boards are computer boards with an array of relays and switches. They have input and output terminals and are designed to control the voltage supply. Relay boards provide independently programmable, real-time control for each of several onboard relay channels. Each channel has a relay switch with an output rated up to a limit such as 250 VAC / 5 amps. Figure 4.8 shows relay board.

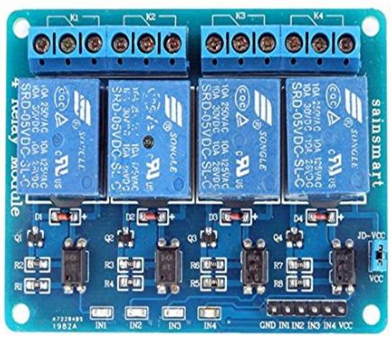

Figure 4.8: Relay Board

4.4.6 EMI filter

EMI filter is designed by calculating inductance and capacitance according to the rating of VFD. Figure 4.9 shows the typical LC filter which is used to smooth the sine wave. The hardware mainly concludes the VFD and EMI filter. The rating of VFD used for demonstration is 10 KW. The current rating of system is 17 A. The values of inductance and capacitance calculated for filter are 246.75 μf.The EMI filter is essentially a combination of dv/dt reactor and sinusoidal filter. dv/dt reactor on line side of VFD protects the electronic components of VFD from input line (supply) disturbances and protect power supply from disturbances created by VFD. Sine wave filter converts the PWM signal to the corresponding sine waves with approximately the same rms voltage as the original PWM signal. Also, EMI filters have the advantage of significantly reducing electromagnetic interference in all aspects.

Figure 4.9: EMI filter

4.5 Experimental installed control panel

For experimental purpose, PLC based VFD controller special purpose machine was used. This Machine panel mainly consist of VFD, PLC, motor protection circuit breaker, relay board, line reactor & capacitor.

Figure 4.10 shows various components of PLC controlled panel with VFD for SPM and EMI mitigation. For implementing the PLC program CODESYS software is used which is interfaced with RS-422 communication. The inputs from various sensors such as temperature sensor, limit switch, pressure sensor, level sensor &

Figure 4.10: PLC controlled panel with VFD control for special purpose machine (SPM)

photo sensor read by the PLC and according to program appropriate outputs given. Detuned inductor and capacitor filter used to mitigate EMI from VFD. For this experimental setup, 10 hp Mitsubishi make VFD inverter is used. The current rating for this inverter is 17 A. The interface for communication with PLC is done using ethernet. VFD has no. of parameter setting to control the speed, torque, Acceleration, Deceleration, and also having the electrical thermal overload relay. For the proper operation to select the different speeds for that to select the parameters and set the required frequency.

4.6 EMI filter Installation Guidelines:

• Ensure that all protective earth and ground connections are made at the lowest possible impedance. Remove paint or other isolation materials to achieve good electrical contact. To keep common mode/high frequency effects low a proper large surface connection is required.
• LC sine wave filters must be mounted in a clean, dry location which protects the product from any liquids, corrosive vapours, dust, abrasive debris and aggressive gases.
• Output filters must be mounted in a clean, dry location (enclosures, cabinets, closed rooms). Contaminants such as oils, liquids, corrosive vapours, abrasive debris, dust and aggressive gases must be kept away of the filter and enclosure.

• Always remove power before touching energized and electrical conductive parts of the filter, and let ample time elapse for the capacitors to discharge to safe levels (<42 V). Residual voltages are to be measured both line to line and line to earth.
• Always connect the filter to protective earth (PE) first, and then continue with the wiring of phase terminals. When decommissioning the filter, remove the PE connection at the end. The sine wave filter must not be operating without connected motor.
• Ensure that cooling slots (if any) are free from obstructions that could inhibit efficient air circulation. Operate the filter within its electrical, mechanical, thermal and ambient specifications at all times.
• Special attention should be paid to cable dimensioning, fuses, grounding, shutdown, disconnection, and overcurrent protection.
• Output filters are lossy electrical components. Filter surfaces and terminals may get hot under full load operating conditions and can exceed surface temperature >80 ° C.

4.7 Closure

The detailed overview of a proposed system is described in this chapter. the proposed system is presented in detail. The different experimental setup components with EMI filter installation guidelines are discussed.

Chapter 5

Result and discussion

5.1 Introduction

In this chapter, the proposed filter is implemented in MATLAB Simulink and simulation results are discussed. Simulation result are presented in two ways, out of which one way is without filter and another way is with filter. these results are compared and discussed. The hardware implementation and hardware results also discussed.

5.2 Simulation results

Consider a model of variable frequency drive connected to the motor without and with sinusoidal LC filter. Performance analysis of simulation is done using MATLAB/Simulink. The study system contains a variable frequency drive of 5 HP 7.5 A and connected to a 3.7 KW with and without sine wave LC filter.

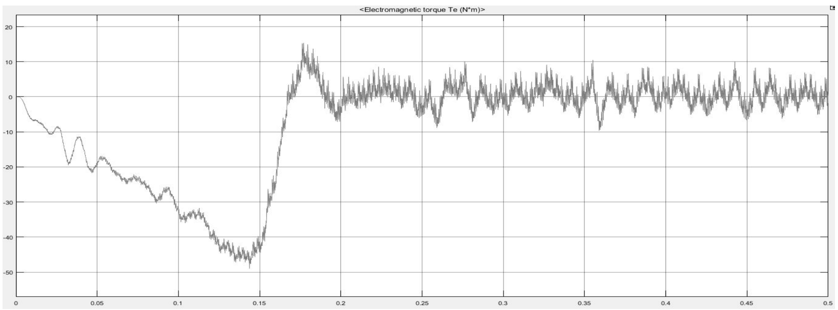

Figure 5.1: Electromagnetic Torque without a filter

Figure 5.1 shows the output waveform of electromagnetic torque without a filter.

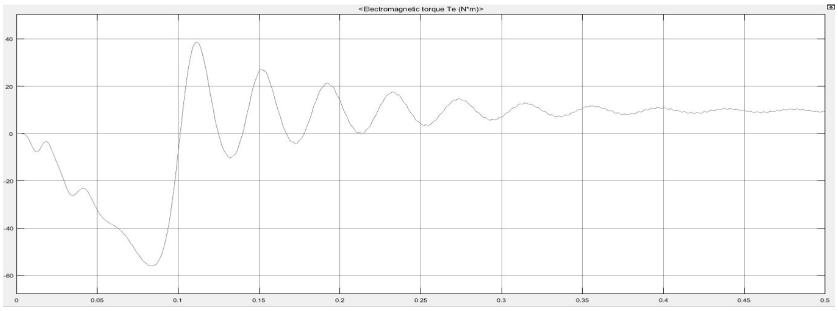

Figure 5.2: Electromagnetic Torque with filter

Electromagnetic torque waveform shows the pulsating torque even after the steady state condition is reached.

Figure 5.2 shows the output waveform of electromagnetic torque with a filter. As when the filter is used it gives improved electromagnetic torque waveform with less pulsation electromagnetic torque on the rotor.

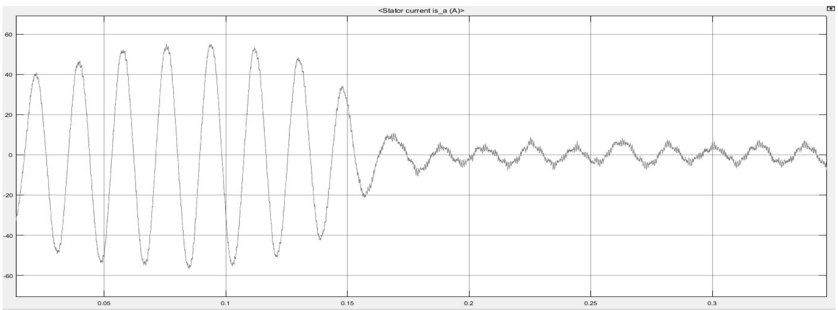

Figure 5.3: Stator Current without Filter

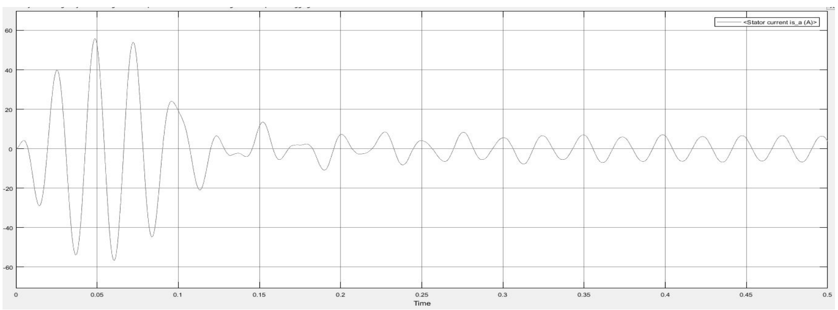

Figure 5.4: Stator Current With Filter

Figure 5.3 and Figure 5.5 shows the output waveforms of stator current and rotor current without a filter. Stator current and rotor current waveforms show the pulsating nature due to the switching frequencies and PWM supply to the motor.

Figure 5.4 and Figure 5.6 shows the output waveforms of stator current and rotor

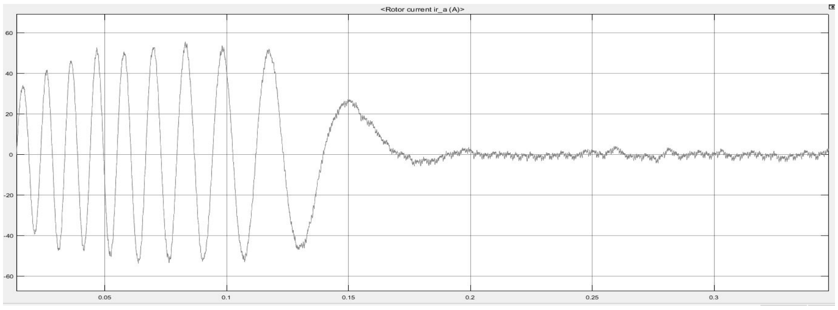

Figure 5.5: Rotor current without Filter

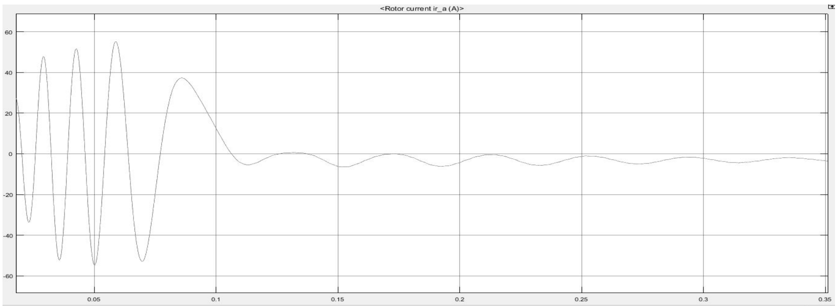

Figure 5.6: Rotor Current with Filter

current with a filter. It shows an improved waveform with fewer ripples and the smooth current waveform.

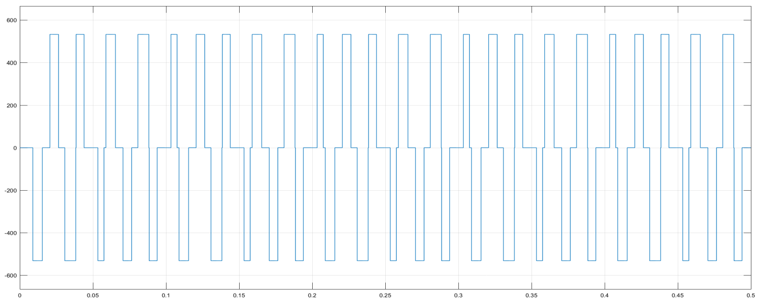

Figure 5.7: Voltage waveform without a filter

Figure 5.7 shows the supply voltage waveform of the motor from the inverter which gives the pulse width modulated waves to the motor. Motor bearing damage, Insulation damage, Noise, harmonics are observed by supplying PWM voltage to the motor.

Figure 5.8 shows the inverter output voltage waveform with smoothen sinusoidal waves removing all the pulsating waves. When this output is supplied to the motor then the performance of the motor is improved. By connecting proper capacitance and inductance the inverter output waveforms can be improved.

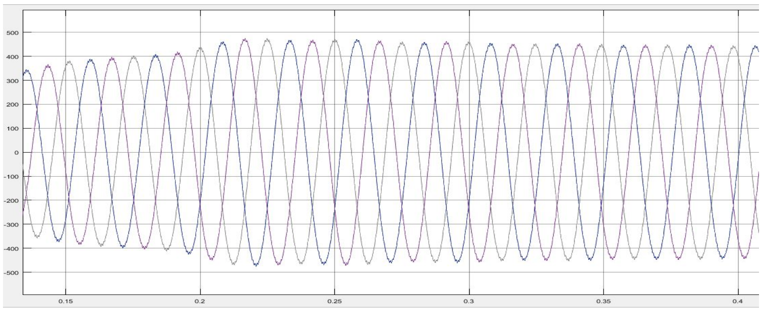

Figure 5.8: Voltage waveform with a filter

5.3 Hardware Results

The hardware mainly concludes the VFD and EMI filter. The rating of VFD used for demonstration is 10 KW. The current rating of system is 17 A. By using power analyser different power system measurements are taken. Result analysis involve measurements of output drive voltage, input drive current, output drive current and voltage harmonics.

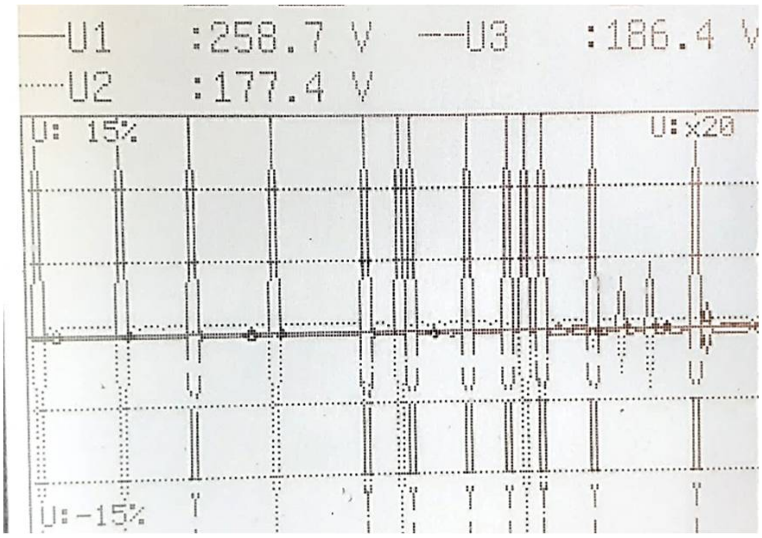

Figure 5.9: VFD output voltage waveform without EMI filter

Figure 5.9 shows output voltage waveform of VFD without using EMI filter. It is clearly seen form the waveform that voltage is unbalanced and distorted. The notches and fluctuations are higher. This results in insulation stress and losses in AC motors, motor heating, acoustic noise of the motor, Higher motor bearing current and electromagnetic emissions on motor cables.

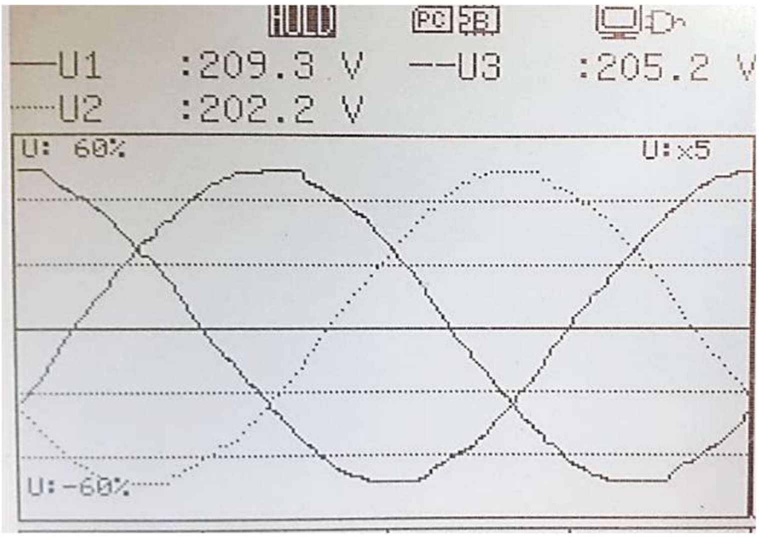

Figure 5.10: VFD output voltage waveform with EMI filter

Figure 5.10 shows output voltage waveform of VFD with using EMI filter. From waveform, it is clearly observed that the voltage distortions and fluctuations are mitigated and smoothens the distorted waveform into sinusoidal waveform. Also, voltage is balanced due to EMI filter.

Figure 5.11 shows input current waveform of VFD without using EMI filter. From

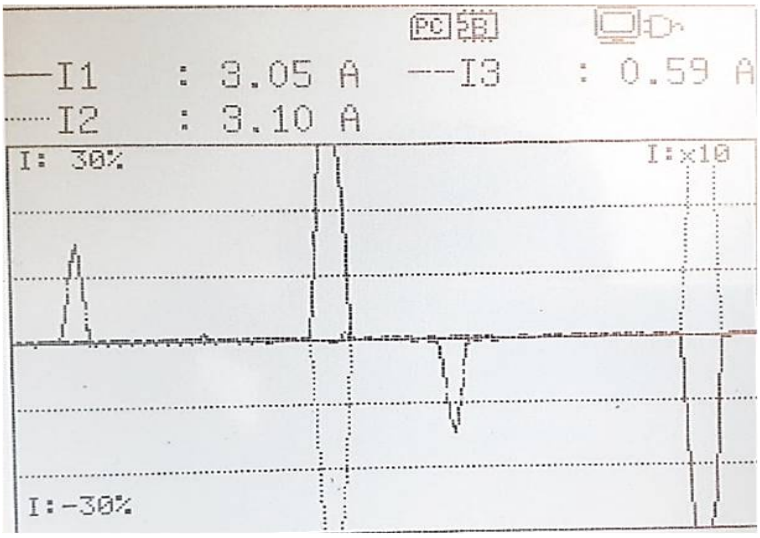

Figure 5.11: VFD input current waveform without EMI filter

waveform it is seen that there are high spikes of current at input side i.e. rate of rise of current (di/dt). This di/dt affect VFD input and increases interference in electronic components.

Figure 5.12 shows input current waveform of VFD with using EMI filter. Form waveform, it is observed that the spikes are reduced and rate of rise of current is

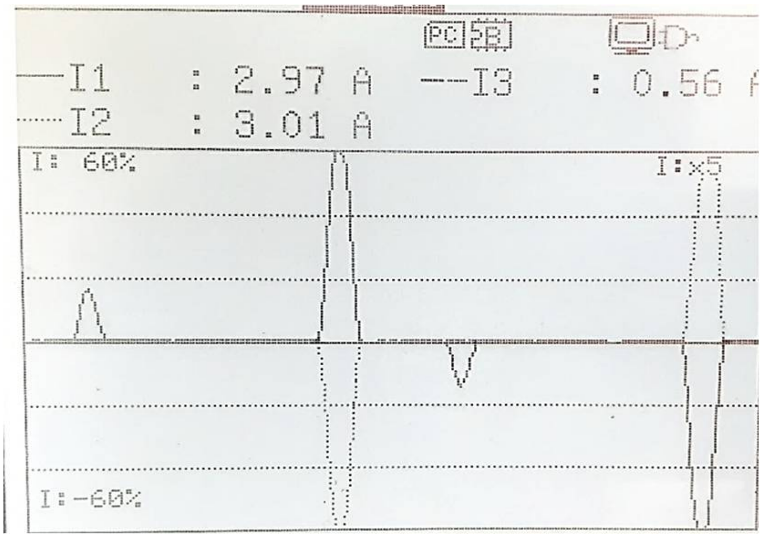

Figure 5.12: VFD input current waveform with EMI filter

limited by using EMI filter.

Figure 5.13 shows output current waveform of VFD without using EMI filter.

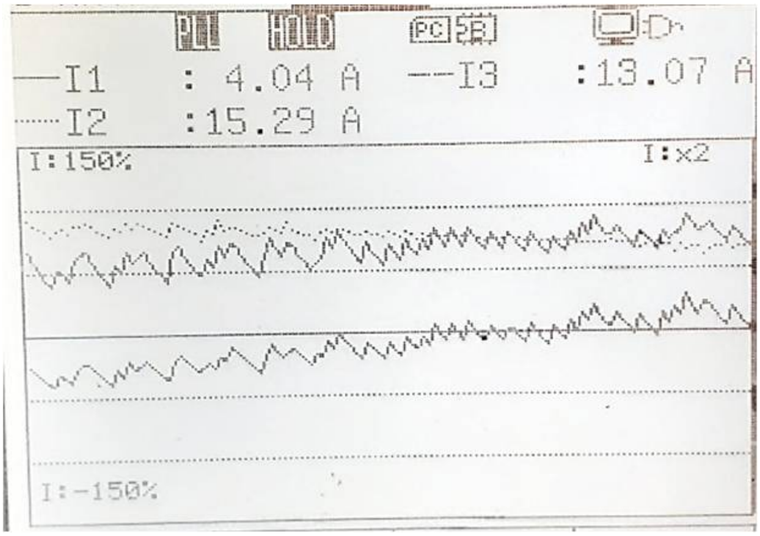

Figure 5.13: VFD output current waveform without EMI filter

From waveform it is seen that current are distorted from each phase and having lot of fluctuations due to EMI. Also current is distorted from each other to all phases. These current waveforms give rise to electrical overstress and leads to electronic equipment damage.

Figure 5.14 shows output current waveform of VFD using EMI filter. Form waveform, it is observed that the fluctuations and distortions in the current is removed in some extent. Also, three phases are balanced and electrical overstress on electronics components due to ground current is minimised. This smooth waveform

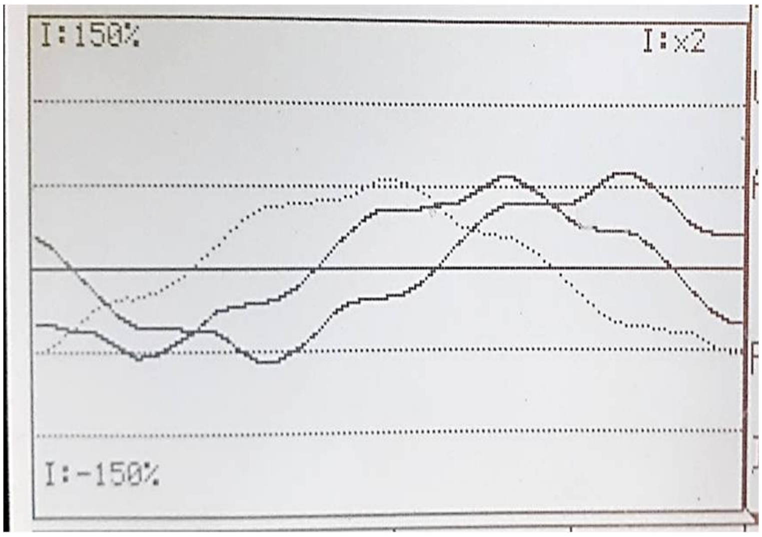

Figure 5.14: VFD output current waveform with EMI filter

leads to control and eliminate electromagnetic interference from VFD.

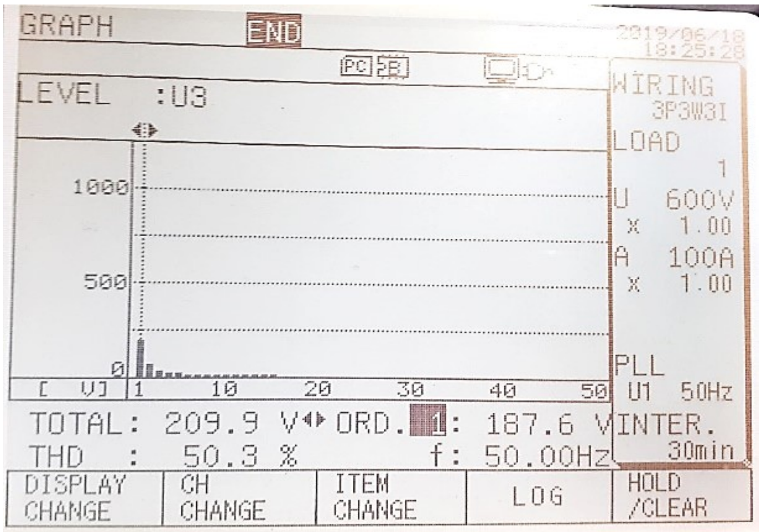

Figure 5.15: Voltage harmonics graph without EMI filter

Figure 5.15 shows voltage harmonic graph without using EMI filter. From graph it is seen that Total Harmonic Distortions (THD) percentage of voltage harmonics is going up to 50%. According to IEEE standards voltage harmonics having THD level should be in between 1 to 5%.

Figure 5.16 shows voltage harmonic graph with using EMI filter. From graph it is observed that Total Harmonic Distortions (THD) percentage of voltage harmonics goes down in prescribed IEEE limits due to EMI filter.

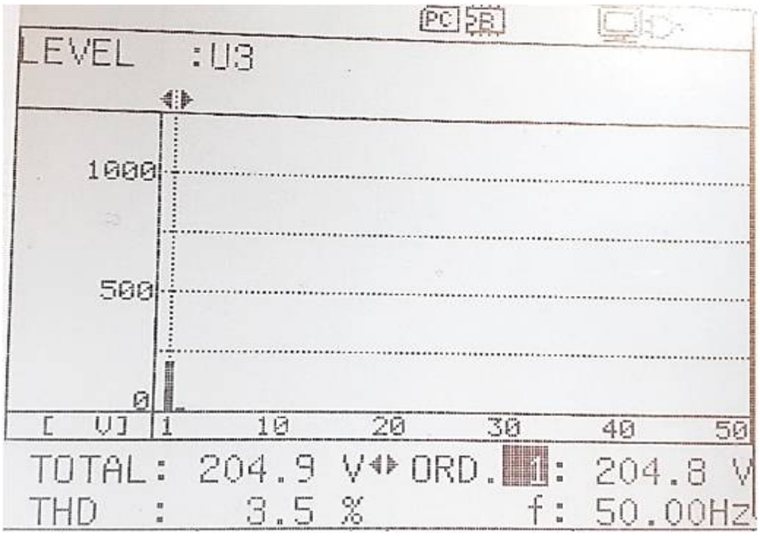

Figure 5.16: Voltage harmonics graph with EMI filter

5.4 closure

The simulation models along with its results are given in this section. Simulation of VFD with filter consist of sinusoidal filter, dv/dt filter and VFD. The simulation of filter is tested with different frequencies. The result of filter is compared with the reactor and choke. This chapter also consist of results of experimental setup of filter and VFD control system. The comparison of VFD results with and without filter are discussed.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

Variable Frequency Drive control using PLC for industrial machines are proposed. The main advantage of this topology is controlling the large motors by using variable frequency drives and controls all the operations using the PLC. In this control topology, VFD is coupled to the PLC over a communication line. The coupling of VFD to PLC executes a motor control that determines motor parameters such as, start or stop of a motor under the normal or faulty condition, turn on or turn off the motors, acceleration and deceleration rate of the motor, torque shaft speed.PLC gives the desired parameter signals to VFD over the communication line and then VFD determines the frequency, voltage and/or pulse width modulated (PWM) signal to supply electric motor over a power line to achieve desired motor output.

The pulse-width modulated (PWM) technique is used to control voltage and frequency for VFD. Due to this,the problems arrived at input side of inverter are inrush and peak currents, harmonics, commutation notches, low frequency interference. Also, problems at output side are peak dv/dt, parasitic earth currents, eddy current loss in motor, bearing currents, acoustic motor noise. The conventional EMI filter is improved with the combination of dv/dt and sine wave filter. In this approach, dv/dt filter is connected at incoming side of VFD to reduce rise of current, harmonics and high dv/dt. Also, sine wave filter is connected at output side of inverter to control common mode noise, high edge voltage waveform, harmonics, overvoltage transients. The proposed filter provides an effective compensation performance for EMI. The performance of the proposed filter is verified with the theoretical and the experimental results by comparing with the conventional filter.

6.2 Future scope

The proposed filter is implemented using hardware implementation. The avilable rating for the filter can be increased to minimise the radio frequency noise also.Radio frequency interference is the conduction or radiation of radio frequency energy that causes an electronic or electrical device to produce noise that typically interferes with the function of an adjacent device. So for the future scope, the proposed filter can be implemented with some modifications in inductance, capacitance and attenuation of filter.

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