International Journal of Engineering Sciences & Emerging Technologies, Dec. 2017.
ISSN: 22316604 Volume 10, Issue 1, pp: 09-34 ©IJESET

PASSIVE FILTER SIZE REDUCTION IN FRONT END CONVERTER FED IM DRIVES

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ABSTRACT

Variable speed drives have become standard method of control of motor drives in most of the applications in industries as well as other appliances due to precise control and significant energy savings. Variable speed drives injects harmonic distortion to the AC power lines resulting in adverse effect on the sensitive equipments which shares the same AC power lines. For that passive filter are used at the input side in order to decrease the harmonics. This work aim to reduce the harmonic content in the converter by using Active Front end converter fed IM Drives without using Passive Filter. Modeling and simulation of AC/DC Diode Bridge Rectifier fed IM Drives is carried out without using passive filter. With this experiment very high harmonics contents injected in to the system. So in order to reduce the harmonic content we insert different passive filter at the input side and got the result in MATLAB. Because of Large size of passive filter used in AC/DC converter, Simulation Studies has been done with Active Front end Converter fed IM Drives with Hysteresis Current Control technique because of which the Input fundamental voltage and current comes in same phase which result in unity power factor at the input side and almost zero harmonic content without using passive filter.

KEYWORDS— *harmonics, Induction motor, inductors, optimization, variable speed drives (VSD), V/f control, Active Front End Converter, Passive Filter, hysteresis current control, hysteresis band*

I. INTRODUCTION

In the past years, various control methods has been employed to enhance the flexibility and consistency of manufacturing processes such as controlling the speed of the equipment, changing gear ratios or pulleys, and using hydraulic drives. In many cases, motors are controlled by means of a valve that regulates the flow of fuel or a vane that controls the airflow while the speed of the motor itself remains unchanged. Variable speed drives (VSD) are widely used to control the speed of induction machines. VSDs use the concept of constant flux or constant volts per hertz operation to control the speed of the machine. These drives are widely used in various industrial areas and introduce flexible starting and operating features such as variable speed operation.

Most motors are designed to operate at a constant speed and provide a constant output; however, modern technology requires different speeds in many applications where electric motors are used. A variable speed drive (VSD) is a device that regulates the speed and rotational force, or output torque of mechanical equipment. Variable speed motor drives have become standard method of speed control in number of utilities in industries as well as commercial applications due to its precise control and energy saving aspects. Variable speed drives are used in number of applications in industries such as fans, pump, cranes, conveyers, rolling mills, machine tools and robotics, heat pumps and air conditioners, locomotive applications etc.

The main function of the variable speed drive (VSD) is to control the flow of energy from the mains to load to achieve the require load torque characteristics [2]. Variable speed drives finds wide range of applications such as railways, chemical, mining, textile, fertilizer, cement, paper, food processing, steel plants, automotive etc.

The main features of the VSDs are:

- VSD allows to shape the steady-state and transient characteristics of the electrical drive to satisfy the load requirement for wide range of torque, speed and power ratings.
- Soft start characteristics resulting in reduced voltage dips and reduced starting impact shock on motor winding, coupling, shafts, gear and other driven equipment's.
- Using programmed drives the actual required speed-torque characteristics can be obtained for particular application, resulting in increased life and energy savings.
- Compared to other prime movers they have longer life, less noise, low maintenance, and cleaner operations and there is no need to refuel or warm up, they can be started instantly and can be immediately be fully loaded.
- Use of VSD results in energy savings resulting in increased system efficiency, energy savings translate into cost savings and reduction in GHG emissions for a given level of production.

The main disadvantage with VSD is that, VSDs injects harmonics to the power line [22- 26]. Current harmonics in the AC supply are created by VSD (as a nonlinear load) connected on the power distribution system. Harmonics pollute the electric plant, which cause problems if harmonic level increases beyond a certain level. Harmonic currents provide useless power. The effects of harmonics are overheating of transformers, cables, motors, generators, and capacitors. Large harmonics lead to increase factory downtime and operating costs. There are significant changes in waveform distortion at different speeds and torque levels in the operation of VSDs.

In order to overcome this disadvantage several method has been implemented such as attaching passive filter in source side to reduce the THD up to desired level which increases the overall size of the VSD. So a new concept is introduced known as active front end Converter (AFE) fed induction motor drives. This work aims to reduce the size of passive filter in front-end converter fed induction motor drives. The Technique used to control the source current is known as hysteresis current control technique.

VARIABLE SPEED DRIVES

Nowadays, technology requires different speeds in many applications where electric motors are used. Electric motors using traditional control methods have mainly two states; stop and operate at maximum speed. In most motor installation, motors are sized to provide the maximum power output required. If the rotational speed is constant at its maximum value to provide the maximum designed load, the power input to the motor remains constant at the maximum value. However, if the load decreases, significant energy savings can be achieved when the rotational speed of the motor is decreased to match with the load requirement. Nevertheless, the majority of motors operate only at 100% speed for short periods of time. This often results in many systems operating inefficiently during long periods of time. Consequently, there are significant energy losses during the operation time [1].

System loss reduction can be achievable by installing VSD systems to match the speed of the motor with the related load. VSD has become very popular because of their advantages over traditional control methods. By using VSD, the speed of a motor or generator can be controlled and adjusted to any desired speed. Besides adjusting the speed of an electric motor, VSD can also keep an electric motor speed at a constant level where the load is variable. There are different reasons for using VSDs. Some applications, such as paper making machines, cannot run without them while others, such as centrifugal pumps, can benefit from energy savings. In general, VSDs are used to match the speed or torque of a drive to the process requirements as well as save energy and improve efficiency.

VSDs are an efficient and economical retrofit option that should be considered for all variable speed systems. VSDs allow the motor speed to vary depending on actual operating conditions, rather than operating continuously at full speed. Varying speed allows it to match changing load requirements more closely, and because the power draw is proportional to the cube of its speed, reducing Potential savings from variable speed drives for fans and pumps. speed can save a lot of energy. Modern electrical VSDs can be used to accurately maintain the speed of a driven machine within ±0.1%, independent of load, compared to the speed regulation possible with a conventional fixed speed squirrel cage induction motor, where the speed can vary by as much as 3% from no load to full load. Most adjustable frequency drives today use pulse width modulation (PWM) to create a variable output voltage, current and frequency [2].

II. CLASSIFICATION OF VARIABLE SPEED DRIVES

The variable speed drives can be broadly classified in two categories based on the type of the motor [3, 4],

They are AC motor drive and DC motor drive.

2.1 DC Motor Drives

DC motors extensively use VSDs and position control systems where good dynamic response and steady state performance are required. DC motors are commonly used in industrial applications because the speed–torque relationship can be varied to almost any useful form for both DC motor and regeneration applications. DC motors are often applied where momentarily deliver of three or more times of rated torque is required. DC motors feature a speed, which can be controlled smoothly down to zero, immediately followed by acceleration in the opposite direction without power circuit switching. They respond quickly to changes in control signals due to the DC motor's high ratio of torque to inertia. The speed of DC motor can simply be set by applying the proper voltage. Speed variation from no-load to full load (rated) can be quite small. It depends on the armature resistance.

In all applications of DC motors a mechanical switch or commutator is employed to turn the terminal current, which is constant or DC into alternating current in the armature of the machine. DC motors have usually been applied in two broad types of application. One of these categories is when the power source is DC such as automobile motors. These motors drive fans for engine cooling and passenger compartment ventilation to the engine starter motor Another reason for using DC motors is that torque-speed characteristic is easier to tailor than all of the AC motor categories. Therefore, most traction and servo motors are using DC machines. For example, motors for driving rail vehicles are exclusively DC machines. DC motors are widely used in various applications due to simplicity of construction and ease of controlling motor performance. Nowadays, although the AC machines are the preferred choice, the DC machines are still valued for their wide speed and torque range as well as high overall efficiency. There are several advantages for using DC motors including simplicity of design, high starting torque, near-linear performance, ease of controlling speed and low cost drives. On the other hand DC motors are bulky and expensive and require high maintenance. They are not suitable to be used in explosive or very clean environment or high-speed operations due to commutator and brushes.

2.2.2 AC Motor Drives

AC motors work by setting up a magnetic field pattern that rotates with respect to the stator and then employing electromagnetic forces to entrain the rotor in the rotating magnetic field pattern. In the past Induction motors and synchronous motors were employed mainly in constant speed drives. AC motors are simple, low cost, reliable and easily replaceable with variety of mounting styles and many different environmental enclosures. With the development in the area of semiconductor converters employing thyristor, power BJT, MOSFETs, IGBTs and GTOs AC motors are now used in variable speed drives.

2.2.2.1 Induction Motor Drives

Induction motors are robust, cheaper, smaller, lighter, reliable, efficient, and require less maintenance as compared to DC motors. Even though induction motor drives are expensive than the dc motor drives, advantages of induction motor suits variable speed ac drives in number of applications in industries Such as fans, pump, cranes, conveyers, rolling mills, machine Tools and robotics, heat pumps and air conditioners, locomotive applications.

The control methods can be divided into scalar and vector control. According to in scalar control, which based on a relation valid for steady states, only the magnitude and frequency (angular speed) of voltage, currents, and flux linkage space vectors are controlled. Thus, the control system does not act on space vector position during transient. Therefore, this control is dedicated for application, where high dynamics is not demanded. Contrary, in vector control, which is based on relation valid for dynamics states, not just magnitude and frequency (angular speed), but also instantaneous position of voltage, current and flux space vectors are controlled. Thus, the control system adjusts the position of the space vectors and guarantees their correct orientation for both steady states and transients. The scalar control methods are simple to implement. The most popular in industry is constant Voltage/Frequency (V/Hz=const.) control. This is the simplest, which does not provide a high-performance. The vector control group allows not only control of the voltage amplitude and frequency, like in the scalar control methods, but also the instantaneous position of the voltage, current and flux vectors. This improves significantly the dynamic behavior of the drive.

However, induction motor has a nonlinear structure and a coupling exists in the motor, between flux and the produced electromagnetic torque. Therefore, several methods for decoupling torque and flux have been proposed. These algorithms are proposed by various researchers based on different ideas and

analysis over a period of time. General classification of induction motor control methods are as shown in Fig. 1.

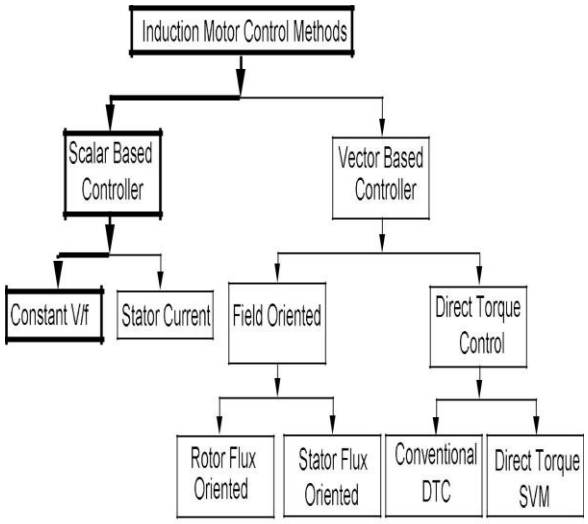

Fig. 1 General classification of induction motor control methods

The first vector control method of induction motor was Field Oriented Control (FOC) [5] presented in early of 70s. Those methods were investigated and discussed by many researchers and have now become an industry standard. In this method the motor equations are transformed into a coordinate system that rotates in synchronism with the rotor flux vector. The FOC method guarantees flux and torque decoupling. However, the induction motor equations are still nonlinear fully decoupled only for constant flux operation. In the middle of 80s new strategies for the torque control of induction motor was presented as Direct Torque Control (DTC) [6, 7]. Those methods thanks to the other approach to control of IM have become alternatives for the classical vector control – FOC. The authors of the new control strategies proposed to replace motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers, which corresponds very well to on-off.

Operation of the inverter semiconductor power devices. These methods are referred to as classical DTC. Simple structure and very good dynamic behavior are main features of DTC. However, classical DTC has several disadvantages, from which most important is variable switching frequency. Recently, from the classical DTC methods a new control technique called Direct Torque Control – Space Vector Modulated (DTC-SVM) has been developed. In this new method disadvantages of the classical DTC are eliminated. The DTC-SVM structures are based on the same fundamentals and analysis of the drive as classical DTC.

2.2.2.2 Synchronous and Permanent Magnet AC Motor Drives

Synchronous motors were mainly used in constant speed applications. The development of semiconductor variable frequency sources, such as inverters and cycloconverters, has allowed their use in variable speed applications such as high power and high speed compressors, blowers, induced and forced draft fans etc. The power of offered synchronous motors is in the range several kW to MW.

Generally, the permanent magnet AC machines can be classified into two types trapezoidal type called "brushless DC machine" (BLDCM) and sinusoidal type called permanent magnet synchronous machine (PMSM) [4]. The BLDC machines operate with trapezoidal back electromagnetic force (EMF) and require rectangular stator phase current. The PMSMs generate sinusoidal EMF and operate with sinusoidal stator phase current. The PMSM can be further divided into two main groups in respect how the magnet bars have mounted in the rotor. In the first group magnets are mounted in the rotor and this type is called interior permanent magnet synchronous motors (IPMSM). The second group is represented by surface permanent magnet synchronous motors (SPMSM). In the SPMSM magnet bars are mounted on the rotor surface. The main advantages of Permanent Magnet machines are,

- high air gap flux density
- higher power/weight ratio
- large torque/inertia ratio
- small torque ripples

- high speed operation
- high torque capability (quick acceleration and deceleration)
- high efficiency low maintenance
- high power factor (low expense for the power supply),
- Compact design.

The PMSM's are usually used in high performance servo drives, in special applications as computer peripheral equipment, robotics etc. However, recently the PMSM are also used as adjustable speed drives in variety of application such as fans, pumps, compressors, blowers. Another area is automotive application as an alternative drive in hybrid mode with classical engine.

2.3 COMPONENTS OF VARIABLE SPEED AC DRIVE [2]

General block diagram of the variable speed drive is shown in Fig. 2.3. Typical VSD system consists of three basic components: rectifier, DC link, inverter and motor. The electric motor is connected directly or indirectly (through gears) to the load. The rectifier controls the power flow from an AC supply (often via a supply transformer), to the motor by appropriate control of power semiconductor switches of the inverter. The DC link capacitor id used to filter out the ripples in the rectified DC.

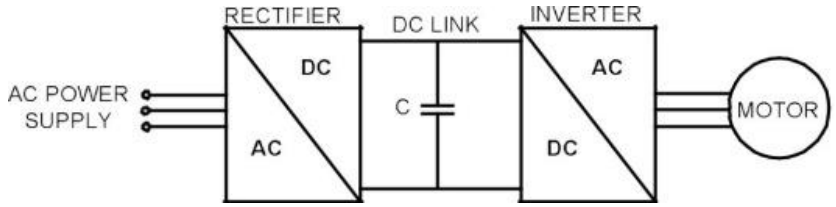

Fig. 2 General block diagram of variable speed drive

2.3.1 Rectifier

Rectifiers are used to convert alternative current (AC) to direct current (DC). There are two main topologies for medium power rectifier units: the diode and the IGBT rectifiers. The diode rectifier (also known as the six-pulse uncontrolled rectifier) is the most commonly used AC-to-DC power converter to produce a fixed DC voltage. The power circuit of the rectifier consists of six power diodes in a three-phase bridge configuration. This means the DC link voltage is fully depending on the AC supply voltage. Diode rectifiers are non-linear loads and a non-sinusoidal current is taken from the feeding line.

2.3.2 DC Link

DC link is the connection between the output of the rectifier and the inverter with a capacitor connected across the rectifier output terminals. The function of the capacitor is the filter out the voltage ripple in the rectified DC so that it will be pure DC without any fluctuations. Generally two capacitors of same capacitance value are connected series to form DC link.

2.3.3 Inverter

Inverters generate an AC by sequentially switching a DC in alternate directions through the load. Nowadays, all inverters are equipped with MOSFET or IGBT components. MOSFET inverters are used for low power application and IGBT inverters are used for medium power applications. The structure of IGBT results in a lack of parasitic body diode. Therefore, the IGBT required a freewheeling diode often placed across it. PWM control is widely used for control of the switches. PWM control consists of rapidly switching on and off the switches, in such a way that pulses with variable width constitutes a variable waveform.

Inverters can be broadly classified into two categories [8] such as Voltage Source Inverter (VSI) and Current Source Inverter (CSI).

2.3.3.1 Voltage Source Inverter (VSI)

A VSI should have stiff voltage source at the input that is, its thevenin's impedance should ideally be zero. A voltage source is called, if the source voltage magnitude does not depend on load connected to it. The large capacitor is connected at the input if the source is not stiff. The VSI circuit has direct control over output voltage (AC) and the output wave forms are not affected by the load conditions. VSI power circuit configuration is shown in Fig. 2.4.

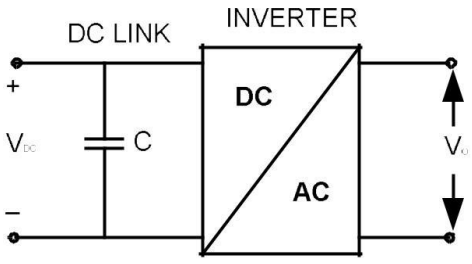

Fig. 4 Voltage source inverter (VSI)

The common circuit of VSI for variable speed drives is shown in Fig. 2.5

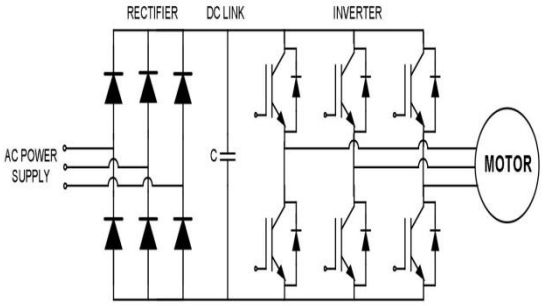

Fig. 5 VSI fed motor drive

Applications of VSI are as follows,

- AC motor drives
- AC uninterrupted power supply (UPS)
- Induction heating
- Active harmonic filter
- Static VAR generator and compensator

2.3.3.2 Current Source Inverter (CSI)

A CSI should have stiff current source at the input that is, it's Thevenin's impedance should ideally be infinite. A variable voltage source can be converted to variable current source by connecting a large inductance in series and controlling the voltage within a feedback current control loop. With a stiff dc current source the output ac current waves are not affected by the load conditions. VSI power circuit configuration is shown in Fig. 2.6.

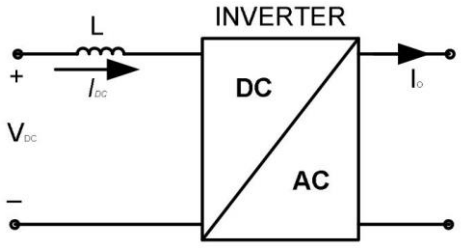

Fig. 6 Current source inverter (VSI)

Applications of CSI are as follows,

- Speed control of large power induction and synchronous motor
- High frequency induction heating
- Super conducting magnet energy storage
- Static VAR compensator

In VSI, the power devices always remain forward biased due to DC supply voltage and therefore, self-controlled forward or asymmetric blocking devices such as GTOs, BJTs, Power MOSFETS, IGBTs are suitable. CSI inverter must withstand reverse voltage and therefore the standard asymmetric devices should not be used. In symmetric voltage blocking GTOs and thyristor devices should be used.

2.4 PULSE WIDTH MODULATION (PWM) TECHNIQUE

In the voltage source inverter conversion of dc power to three-phase ac power is performed in the switched mode shown in Fig. 2.5. This mode consists in power semiconductors switches are controlled in an on-off fashion. The actual power flow in each motor phase is controlled by the duty cycle of the

respective switches. To obtain a suitable duty cycle for each switches technique pulse width modulation [8] is used. Many different modulation methods were proposed and development of it is still in progress. The modulation method is an important part of the control structure. It should provide features like:

- wide range of linear operation,
- low content of higher harmonics in voltage and current,
- low frequency harmonics,
- operation in over modulation,
- reduction of common mode voltage,
- Minimal number of switching to decrease switching losses in the power components.

All PWM methods have specific features. However, there is not just one PWM method which satisfies all requirements in the whole operating region. Therefore, in the literature are proposed modulators, which contain from several modulation methods. For example, adaptive space vector modulation, which provides the following, features:

- full control range including over modulation and six-step mode, achieved by the use of three different modulation algorithms,
- reduction of switching losses thanks to an instantaneous tracking peak value of the phase current.

The content of the higher harmonics voltage (current) and electromagnetic interference generated in the inverter fed drive depends on the modulation technique. Therefore, PWM methods are investigated from this point of view. To reduce these disadvantages several methods have been proposed. One of these methods is random modulation. The classical carrier based method or space vector modulation method are named deterministic, because these methods work with constant switching frequency. In opposite to the deterministic methods, the random modulation methods work with variable frequency, or with randomly changed switching sequence.

2.4.1 Carrier Based PWM

The most widely used method of pulse width modulations are carrier based. This method is also known as the sinusoidal (SPWM), triangulation, sub harmonic, or sub oscillation method. Sinusoidal modulation is based on triangular carrier signal as shown in Fig. 2.7. In this method three reference signals Va, Vb, Vc are compared with triangular carrier signal Vt, which is common to all three phases. In this way the logical signals SA, SB, SC are generated, which define the switching instants of the power switches as is shown in Fig. 2.8.

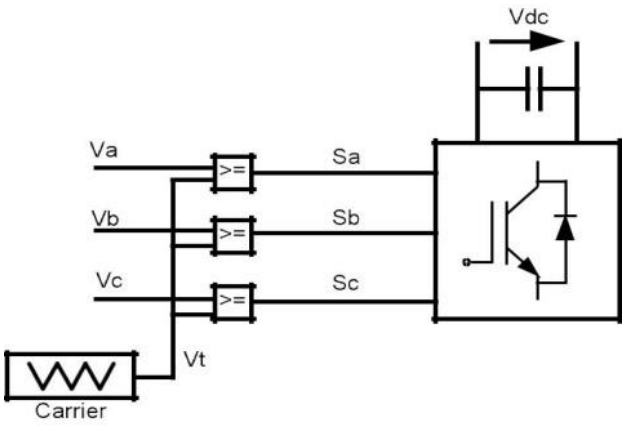

Fig. 7 Block diagram of carrier based sinusoidal PWM

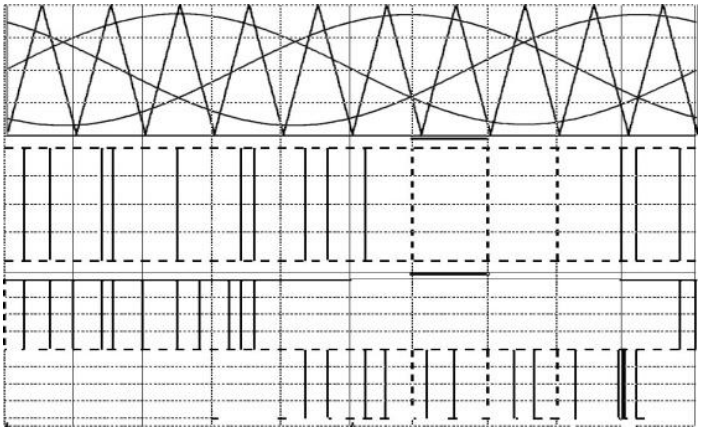

Fig. 8 Basic waveforms of carrier based sinusoidal PWM

The modulation index m can be varied between 0 and 1 to give a linear relation between the reference and output wave. At m=1, the maximum value of fundamental peak voltage is Vdc/2, which is 78.55% of the peak voltage of the square wave. The maximum value in the linear range can be increased to 90.7% of that of the square wave by inserting the appropriate value of a triple harmonics to the modulating wave. It is shown in Fig. 2.9, which presents the whole range characteristic of the modulation methods [10]. This characteristic include also the over modulation (OM) region.

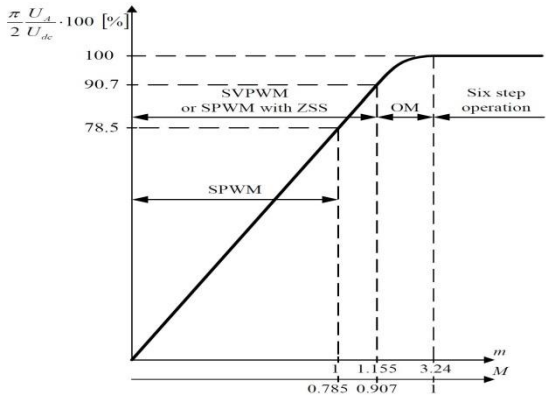

Fig. 9 Output voltage of VSI versus modulation index for different PWM techniques

III. MODELING AND SIMULATION OF AC/DC CONVERTER FED IM DRIVE

3.1 INTROCUDTION

AC to DC power conversion is very essential for almost all power electronic application such as variable speed drives, uninterrupted power supplies, batter chargers etc. Conventional uncontrolled diode rectifier or controlled rectifier using thyristor suffers from the main drawback of high current harmonics and low power factor for the source current. In order to overcome this problem we use passive filter across the source side and DC link inductor in between the rectifier and inverter. In this chapter we basically deal with the AC to DC converter which converts the AC power to fixed DC power. After that V/f controlled inverter are used to control the speed of the Induction Motor smoothly. Simulation is done to show the input current waveform and FFT analysis is done to find the Total Harmonic Distortion (THD) without filter as well as with filter.

Induction motors are robust, cheaper, smaller, lighter, reliable, efficient, and require less maintenance as compared to dc motors. Even though induction motor drives are expensive than the dc motor drives, advantages of induction motor suits variable speed ac drives in number of applications in industries such as fans, pump, cranes, conveyers, rolling mills, machine tools and robotics, heat pumps and air conditioners, locomotive applications etc. [3]. The motor has to be controlled to obtain required speed or torque requirement for specific loads. Control of induction motor is broadly divided into two categories such as,

1. Scalar Control

2. Vector Control

In scalar control, only the magnitudes of the control variables such as voltage or frequency or both are controlled. But in vector control, both the magnitude and the phase alignment of vector variables are controlled. Most popular and widely used scalar control for induction motor drive is the constant V/f control method, because it is less expensive and easy to implement [8]. In this work, study concentrates on the V/f controlled induction motor drive [11, 12].

3.2 V/f CONTROL METHOD

The scalar control of induction motor is based on the steady-state model of the induction motor. The steady-state model of induction motor is shown in Fig.3.1

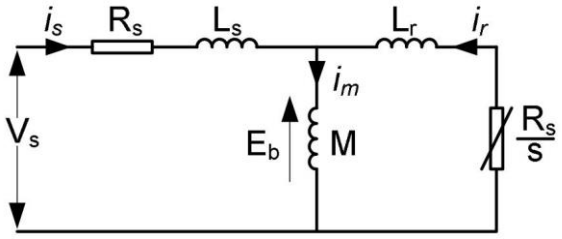

Fig. 10 Steady state model of induction motor drive

Where,

Rs : stator resistance
Ls : stator leakage inductance
Rr : rotor resistance
Lr : rotor leakage inductance
M : mutual inductance
S : slip
im : magnetizing current
Eb : back emf
Vs : terminal voltage

The magnetizing current is responsible for the air-gap flux, then back emf is given by,

Eb = mMim –(1)

Difficulty of measuring back emf as equivalent mutual inductance is fictitious and not accessible, terminal voltage (Vs) is considered instead of back emf. By maintaining V/f ratio, flux in the core is maintained constant which allows a wide speed range operation without losing torque generation capabilities of induction motor drive. Below base frequency motor develops constant maximum torque as V/f ratio is maintained constant. At low frequencies the terminal voltage is comparable to the stator resistance drop in order to compensate this drop and to maintain the maximum torque, V/f ratio is increased at low frequencies. Above the base frequency, terminal voltage reaches rated value; therefore frequency is varied with constant voltage leading to operate in field weakened region resulting in decreased maximum torque [8].

f: frequency below boost voltage is applied

Let the ‘k’ be the V/f ratio,

$$K = \frac{Vs}{f} \qquad (3)$$

4) A boost voltage of 23V is applied at low frequencies below 5Hz. The characteristic of the V/f controller is shown in Fig. 3.2.

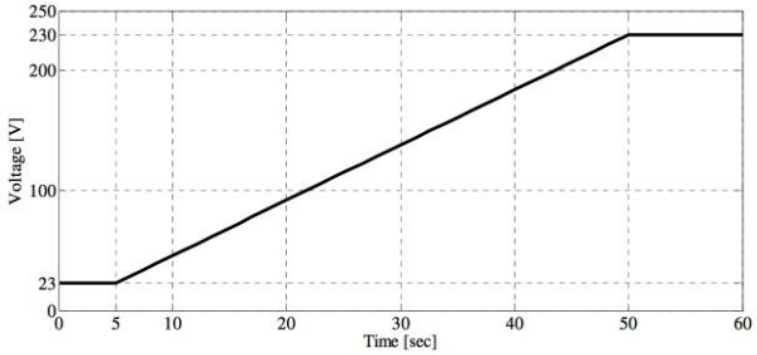

Fig. 11 V/f controller characteristics

3.2.1 V/f CONTROL IN OPEN-LOOP

In open-loop control, no feedback signals are used for the controlling purpose. Block diagram of open loop control configuration is shown in Fig.3.3.Three phase ac supply is rectified, filtered and supplied to the PWM-inverter as shown. The control variable is the reference speed command (ωref). Reference speed is integrated to generate the angle signal (θ*) and voltage reference (V*) is directly generated from the V/f controller [3, 8]. Angle signal(θ*) and voltage reference (V*) is fed to PWM pulse generation, which ultimately controls the inverter operation and thereby achieving the desired speed.

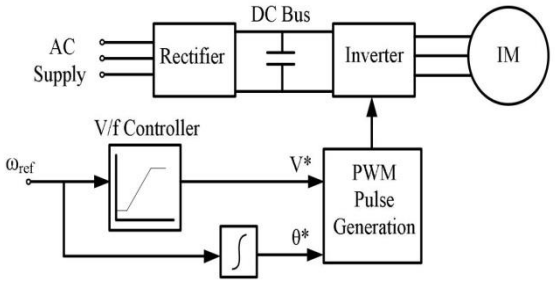

Fig. 12 Open-loop V/f control configuration

Angle signal (θ*) and scaled voltage reference (V*) is used to generate three-phase sinusoidal signals using the equations (3), (4) and (5).

$$Va = V^* \sin(\theta^*) \quad (5)$$

$$Vb = V^* \sin(\theta^* - 2\pi/3) \quad (6)$$

$$Vc = V^* \sin(\theta^* + 2\pi/3) \quad (9)$$

These three-phase sinusoidal signals are then compared with reference triangular waveform of required switching frequency to generate PWM pulses for the voltage source inverter feeding induction motor. The simulink model of the open-loop V/f controlled induction motor drive is shown in Appendix I.

3.2.2 V/f CONTROL IN CLOSED-LOOP

Closed-loop control configuration is shown in Fig.3.4. In closed-loop control, actual rotor speed (ω*m*) is measured and fed back after conditioning. The actual speed (ω*m*) is compared with the reference speed (ω*ref*). The error is processed by a controller to generate slip frequency (ω*sl*). Slip frequency (ω*sl*) is added to actual speed (ω*m*) to get the synchronous speed (ω*m**) [8]. The saturation is placed to limit synchronous speed to make the motor model valid. By placing saturation a limit has been set for both torque and current indirectly [15]. The angle signal (θ*) and voltage reference (*V**) for PWM pulse for inverter are generated from the value of synchronous speed (ω*m**) as in the open-loop control. The controller performs a crucial role in the performance of the closed loop control. The controller used is a PI controller as the PID controller results in noise production by switching of inverter switches [15]. The simulink model of the closed-loop V/f controlled induction motor drive is shown in Appendix I.

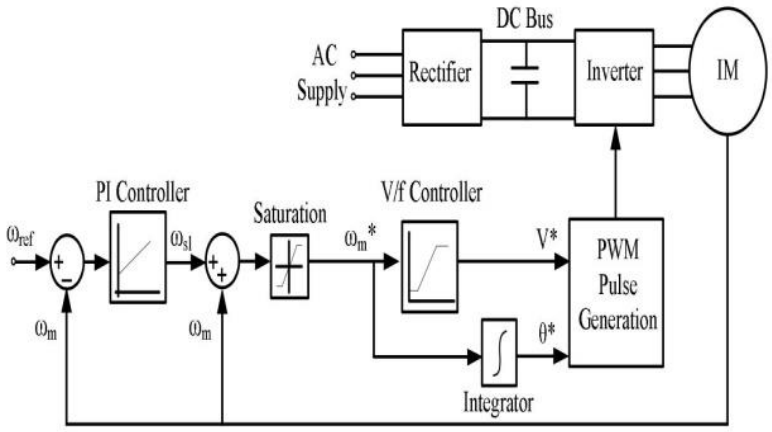

Fig. 13 Closed-loop V/f control configuration

Reference speed specified in rpm is converted into radians per second (ω*ref*) and compared with actual speed (ω*m*) in radians per second. The error is processed and slip speed (ω*sl*) is generated, which is added to actual speed (ω*m*) to generate the synchronous speed (ω*m**), which is converted to electrical radians per second (ω*e**). The remaining operation remains same as that of open-loop control discussed in the previous section.In this chapter we are using open loop V/f control for Induction Motor Drives to see the speed response as well as the input current THD and to improve that we use passive filter in front side of the AC to DC converter.

3.2.3SPEED RESPONSE V/f INDUCTION MOTOR UNDER NO LOAD

Built-in induction motor model in MATLAB/ Simulink [19] of 10HP (7.5kW) has been used for the simulation of the open-loop and closed-loop configurations parameters of the induction motor model is shown in Appendix I. The speed response for a set speed of 1440rpm of the open-loop control is shown in Fig.3.5 and closed-loop is shown in Fig. 3.6.

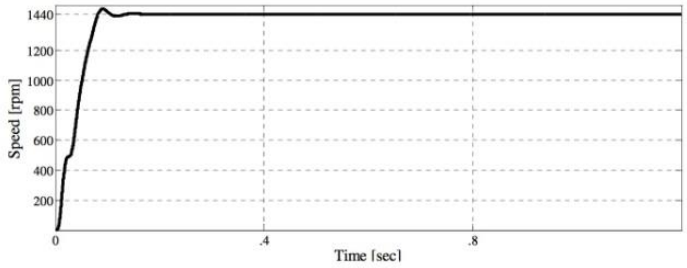

Fig. 14 Speed response of open-loop under no-load for a set speed of 1440rpm

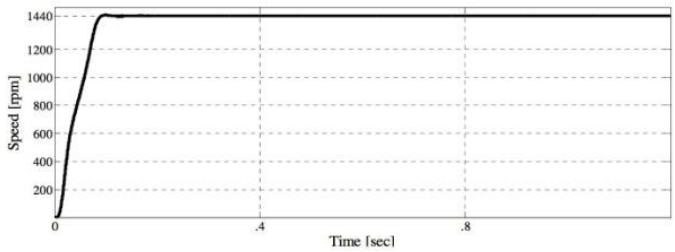

Fig. 15 Speed response of closed-loop under no-load for a set speed of 1440rpm

The speed response of closed-loop is superior to the open-loop control in terms of smooth start-up rise, reduced overshoot and faster settling, the steady state error in the open-loop and closed-loop model is comparable and very less.

The speed responses for step variation of speed command (in rpm) from 1420 to 1460 and 1460 to 1440 of the open-loop control are respectively shown with zoomed-in views in Fig. 3.7 and Fig. 3.9 and closed-loop is shown in Fig. 3.8 and Fig. 3.10

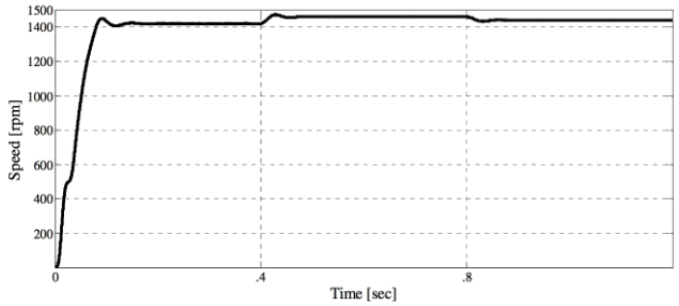

Fig. 16 Speed response of open-loop under no-load with step change in speed

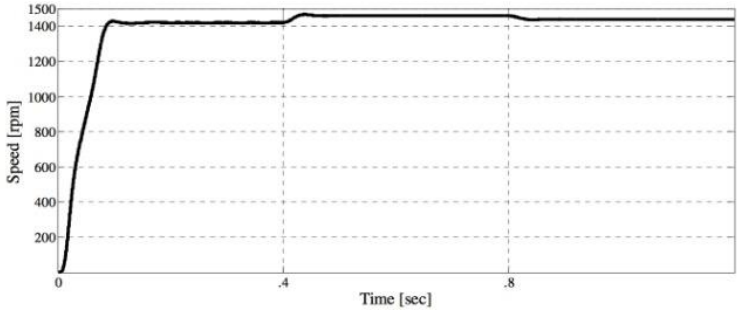

Fig. 17 Speed response of closed-loop under no-load with step change in speed

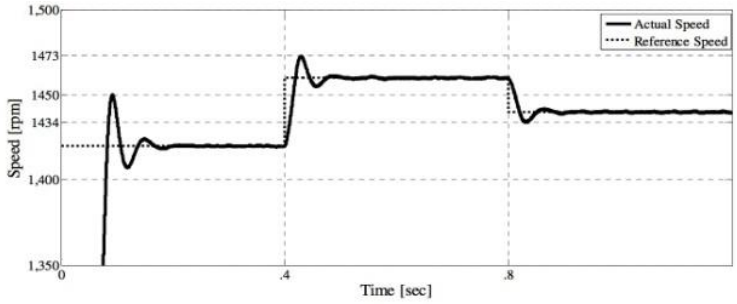

Fig. 18 Zoomed-in view of speed response of open-loop control under no load with step change in reference speed

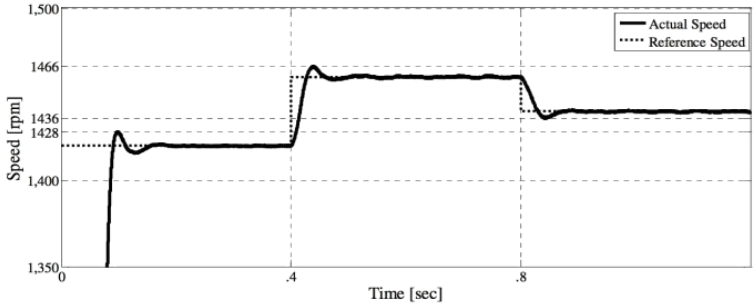

Fig.19 Zoomed-in view of speed response of closed-loop control under no load with step change in reference speed

The first overshoot during the start-up in speed response of closed-loop configuration is reduced by 44% as compared to that of the open-loop configuration, along with smooth rise from the zero speed. The settling time in the closed-loop configuration is lesser than that in the open- loop configuration. The over shoot during step increment in reference speed and under shoot during step decrement in reference speed for closed-loop is also reduced as compared to those in the open-loop control.

3.3 BLOCK DIAGRAM TO AC/DC CONVERTER FED IM DRIVES

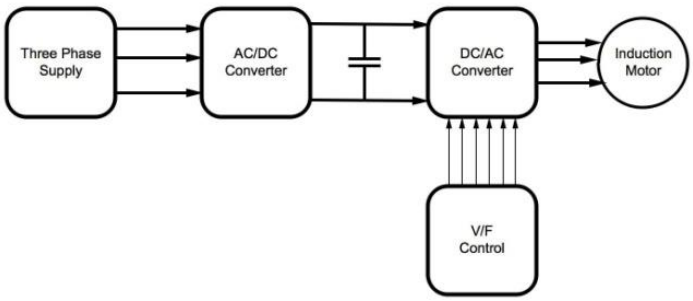

Fig. 20 Block Diagram of AC/DC Converter fed IM Drives

The block diagram of AC/DC converter fed induction motor drive is shown in Fig. 3.11 above. In this, a three-phase supply is given to the input of three phase diode bridge rectifier which converts ac power in dc power. DC voltage is passed through dc link capacitor to make smooth dc and further it is fed to input side of V/f controlled inverter which converter dc to ac. This ac voltage is fed to the 7.5kW,400V induction motor in order to run the motor at desired speed. The reference speed is set to 1400RPM.

3.4 EFFECT OF POWER LINE DISTORTION

The effect of current distortion on power distribution systems can be serious, primarily because of the increased current flowing in the system. In other words, because the harmonic current doesn't deliver any power, its presence simply uses up system capacity and reduces the number of loads that can be powered. Harmonic current occur in a facility's electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, tripping of circuit breakers, and solid-state component breakdown. The cost of these problems can be enormous. Harmonic currents also increase heat losses in transformers and wiring. Since transformer impedance is frequency dependent, increasing with harmonic number, the impedance at the 5th harmonic is five times that of the fundamental frequency. So each ampere of 5th harmonic current causes five times as much heating as an ampere of fundamental current. More specifically, the effects of the harmonics can be observed in many sections of electrical equipment and a lot machines and motors. These effects can be described in more details as follows:

3.4.1 Effects of Harmonics on Rotating Machines

For both the synchronous and the induction machines, the main problems of the harmonics are increasing on the iron and copper losses, and heating by result of the high current caused by harmonics as a result reducing the efficiency. The harmonics can be a one reason as an introduction of oscillating motor torque. Also, the high current can cause high noise level in these machines.

3.4.2 Effects of Harmonics on Transformers

Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Harmonic distortion of the current, in particular, as well as the voltage will contribute significantly to additional heating. There are three effects that result in increased transformer heating when the load current includes harmonic components:

a. RMS current.

If the transformer is sized only for the KVA requirements of the load, harmonic currents may result in the transformer rms current being higher than its capacity. The increased total rms current results increase conductor losses.

b. Eddy-current losses.

These are induced currents in the transformer caused by the magnetic fluxes. These induced currents flow in the windings, in the core, and in the other connecting bodies subjected to the magnetic field of the transformer and cause additional heating. This component of the transformer losses increases with the square of the frequency of the current causing the eddy current. Therefore, this becomes a very important component of transformer losses for harmonic heating.

c. Core losses.

The increase in core losses in the presence of the harmonics will be dependent on the effect of the harmonics on the applied voltage and the design of the transformer core. Increasing the voltage

distortion may increase the eddy currents in the core laminations. The net impact that this will have depends on the thickness of the core laminations and the quality of the core steel. The increase in these losses due to harmonics is generally not as critical as the previous two.

3.4.3 Effects of Harmonics on Lines and Cables

The main problems associated with harmonics are: increased losses and heating, serious damages in the dielectric for capacitor banks and cables, appearance of the corona (the amount of the ionization of the air around the conductor or the transmission line) due to higher peak voltages and corrosion in aluminum cables due to DC current.

3.4.4 Effects of Harmonics on Converter Equipment's

These equipments can be expressed as switches or On-Off equipment because of the switching the current and voltage by some devices such as diodes and thyristors. These converters can switch the current so, creating notches in voltage waveforms, which may affect the synchronizing of the other converter equipment. These voltage notches cause misfiring of the thyristors and creating unarranged other firing instances of the other thyristors in the equipment.

3.4.5 Effects of Harmonics on Protective Relays

The protective devices such as circuit breakers and fuses are designed to trip out in specific current and voltage and through very specific short time. The presence of the harmonics causes the difference on the voltage and current. So, this can cause failing tripping of these protective equipment. Also, the harmonics can let the relays to operate slower and/or at higher pickup values. Over current and over voltage can cause improper operation for relays. However, this cause the unsuitable tripping time so, causing some serious damages as far as fire occurs.

3.5 CONTROLLING HARMONIC DISTORTION [29, 30]

When adjustable frequency drives are applied to AC systems, it is important to limit the harmonic voltage distortion that they can cause. When an industrial adjustable frequency drive is used in an AC application, this important caution is too frequently overlooked. As a result, the Entire building's electrical system may suffer. The key to controlling harmonic distortion is limiting the current pulses. Several techniques can be used to mitigate harmonics. The most commons are

1. Inductor Placement

There are two fundamental locations where harmonic reducing reactors are added to a variable speed drive. Inductor can be placed either on the DC link side (After the rectifier) or on the AC link side (Before the rectifier). Details of the inductor placement are discussed in the next chapter.

2. Active Filters/ Front End Converter

Most passive techniques aim to cure the harmonic problems once they have been created. Active filters, or active front ends, use dynamic switches like IGBTs and other power components to stop harmonics from occurring in the first place. Current flow through a switch is manipulated to recreate a waveform that linearly follows the applied voltage waveform. Apart from the active front ends, there also exist active shunt filters that introduce a current waveform into the distribution network that when combined with the harmonic current.

3.6 FILTER DESIGN

In AC/DC converter fed IM Drives, although the speed and torque is controlled by the drives but it inject harmonics in to the system which results in poor power quality and distorted source current waveform. So in order to reduce the total harmonic distortion (THD) we place filter at the front side of converter. This is generally accomplished through the use of inductor coils, which may also be called reactors or chokes. The inductance of a coil creates a back electromotive force (emf), or voltage, as the current pulse passes through it. This reduces the rate of the current pulse. There are two places where inductor can be attached

(a) DC Link Inductor Placement
(b) AC Line Reactor Placement
(c) LCL Filter

3.6.1 Design of DC Link Inductor

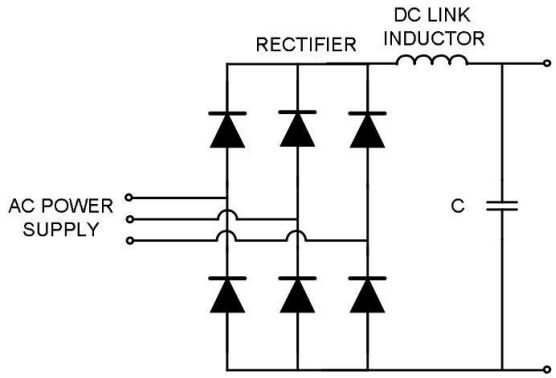

Fig. 21 Placement of DC Link Inductor

Inductor of adequate value placed in between the ac source and the dc bus capacitor of the VSD will help in improving the current waveform as shown in Fig. 3.12.The resonant frequency fo of the filter circuit must be less than the minimum operating frequency of the inverter. In the case of the six-step inverter, fo < 6fI min

(13) Hence these two equations are rewritten as given by (14) and

(15) .For the six-step inverter,

$$L = \frac{0.0176}{C\ f_l^2}$$

For the PWM inverter,

$$L = \frac{0.158}{C\ N^2\ f_l^2}$$

3.6.2 Design of AC Line Reactor

Three phase line reactors added in series with VFD will reduce harmonics [27] as shown in Fig. 3.12 .This placement can lower harmonics by 50% depending on the amount of impedance added to the line. The most common value of AC line reactor are 3% and 5% [30].

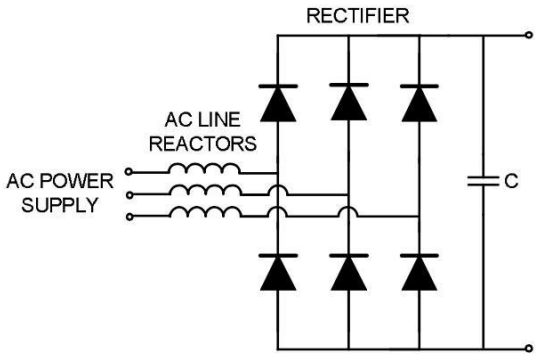

Fig. 22 Placement of AC Line reactor

One can show that the effective impedance offered by DC link choke is about 50% of its equivalent ac inductance [34]. In other words, a 3% ac line reactor is equivalent to 6% DC link inductor. This can be mathematically derived equating ac power flow to dc side power flow [35]. After deriving we can easily conclude that the impedance offered at dc side is double than the impedance offered at dc side

3.6.3 Design of LCL Filter

LCL filter design is taken from the Crompton Greaves Drives Manual. The circuit diagram is given below in Fig. 3.13

L1 is the converter side inductor per choke

L2 is the grid side inductor per choke

Transfer function between converter output voltage and line current in frequency domain form is given as:

$$G^{\alpha\beta}(jh\omega_1) = \frac{\frac{1}{L_1L_2C}}{h\,\omega_1\,|-h^2\omega_1^2+\frac{L_1+L_2}{L_1L_2C}}$$

Here h is the frequency index i.e. switching frequency divided by the fundamental frequency. Several combination of filter parameters L1,L2 and C can be used to fulfill the harmonic requirements. Following combination are found sufficient

L1=2*L2 (18)

C=0.05*Cbase (19)

Solving equation (17) for L_2 and using the assumption in (18) & (19) gives the design expression for LCL filter as:

$$L_2 = max_h\,(\frac{3}{4Ch^2\omega_1^2} + \sqrt{(\frac{3}{4Ch^2\omega_1^2})^2 + \frac{U_{phase,h}}{(h\,\omega_1)^3 I_{h\,max}\,.2C}}) \quad (20)$$

So by choosing the proper value of L1 , L2 and C simulation is done according to the data given in Crompton Greaves Manual.

3.7 SIMULATION STUDY

The simulation studies are carried out on open-loop V/f controlled 7.5KW induction motor drive in MATLAB/ Simulink. For the simulation the reference speed is set to 1400rpm and full load conditions with career frequency 1kHz. Fig. 3.14 shows the Input Voltage (line-line) (Vab), Input current (Ia) without any inductors. Fig. 3.15 shows the input current distortion and Fig. 3.16 shows the harmonic spectrum of the input current**.** After that simulation is done by placing ac line reactor, dc link inductor, and both and then simulation is done by placing LCL filter according to the data given by Crompton greaves manual.

3.7.4 Simulation Result With DC Link Inductor and AC Line Reactor

A simulation study is carried out with both DC link inductor and AC line reactor attached with AC/DC converter fed IM Drives, result is shown in Fig. 3.23 and Fig. 3.24. Also LCL filter is inserted in between source and rectifier and simulation result is shown in Fig. 3.25

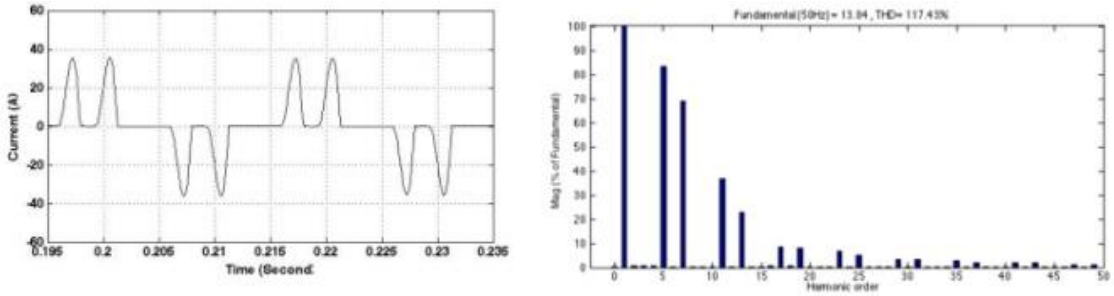

Fig. 23 DC Link Inductor=0.1mH AC Line Reactor=0.2mH

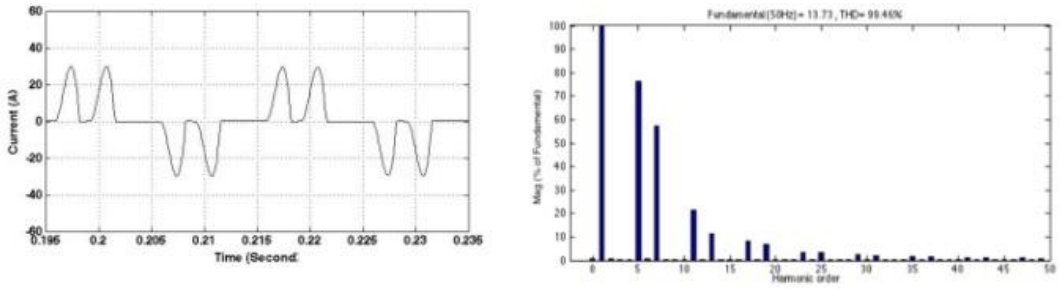

Fig. 24 DC Link Inductor=0.2mH AC Line Reactor=0.4mH

3.7.5 Simulation Result with LCL Filter

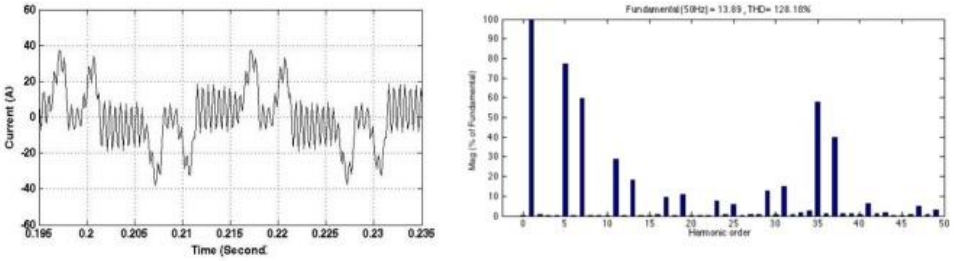

Fig. 25 LCL Filter with L1=0.2mH, L2=0.2mH, C=40uF

IV. ACTIVE FRONT END CONVERTER FED INDUCTION MOTOR DRIVE

4.1 INTRODUCTION

AC to DC power conversion is very essential for almost all power electronic application such as variable speed drives, uninterrupted power supplies, batter chargers etc. Conventional uncontrolled diode rectifier or controlled rectifier using thyristor suffers from the main drawback of high current harmonics and low power factor for the source current. Hence additional power conditioners are required to be installed to meet with the utility power standards. To improve the power quality we use Active Front End Converter [20].

Active Front End (AFE) converters use semiconductor switches (such as IGBTs) as rectifiers instead of the diode bridges, which are otherwise generally used. For the control of electric power or power conditioning, the conversion of electric power from one form to another is necessary. The static power converters perform these functions of power conversions. A diode bridge rectifier circuit converts AC voltage into a fixed DC voltage and is the most commonly used topology because of its simple construction, low cost and high reliability. The diode bridge rectifier forms a part of the power circuit in many applications. At lower power levels, the application is in the area of computers, telecommunications, air-conditioning, battery charging etc. At higher power levels, the application is in industries like for AC and DC drives. In case of AC drives, a diode bridge rectifier provides the necessary DC bus voltage, which acts as an input to the inverter. In all these applications, a large capacitor is normally used at the output stage of the bridge rectifier to reduce the DC output ripple. This diode bridge rectifier with a large output capacitor will have a highly distorted, non-sinusoidal input current with a lot of lower order harmonics and very poor power factor. In order the source current to follow the reference current, proper switching pulses have to be generated. For this any PWM technique such as Sinusoidal PWM (SPWM), Space Vector PWM (SVPWM), Hysteresis Current Control technique may be used. In this chapter we use hysteresis current control technique to control the switching frequency of AFE so that source current will follow the reference current to make the unity power factor and reduce the THD level below 5%, which follow the requirement of standard IEEE 519

4.2 BLOCK DIAGRAM OF ACTIVE FRONT END CONVERTER

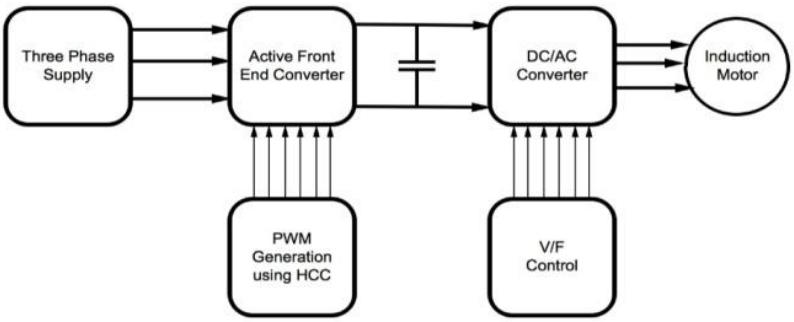

Fig. 26 Block Diagram of Active Front End Converter

The block diagram shown above depicts the active front end converter fed induction motor drives. Three phase supply is given to active front end converter consist of 6 fully controlled IGBT switches which

converter AC to DC by generating PWM using hysteresis current controller. The hysteresis current control technique makes the input current sinusoidal and in phase with the voltage in order to improve the power quality and reduces the THD to less than 5%. The detail explanation of Hysteresis Current Controller (HCC) is explained in 4.4. The DC taken from the active front end converter is fed to the v/f controlled inverter to run the induction motor at desired speed smoothly.

4.3 FEATEURES OF ACTIVE FRONT END CONVERTER

Following are the characteristics of active front-end converter:

- In active front end converter the power can be flow in both direction i.e. bidirectional power flow can be possible because of the use of MOSFET/IGBT switch which allows bidirectional current to flow and provide high efficiency operation for variable speed drives. So active and reactive power can be controlled in both the direction which is the biggest advantage over diode bridge rectifier
- We can make source current sinusoidal in case of active front-end converter that is not possible in case of diode bridge rectifier without filter. So overall the size of AFE is less as compared to diode bridge rectifier.
- We can remove the passive filter used in the source side and make current sinusoidal.
- We can control the DC link voltage by controlling the switching frequency of IGBT/MOSFET based active front-end converter.

4.4 HYSTERESIS CURRENT CONTROL TECHNIQUE

PWM rectifier can be of Voltage source or current source type depending on the load requirement. Again it may be current controlled or voltage controlled depending on the type of modulators used for the gate pulse generation. The gating pulses generated from such controller make the switches ON and OFF, according to the pre-defined reference. In order the source current to follow the reference current, proper switching pulses have to be generated. For this any PWM technique such as sinusoidal PWM (SPWM), space vector PWM (SVPWM), hysteresis current control technique may be used [20].

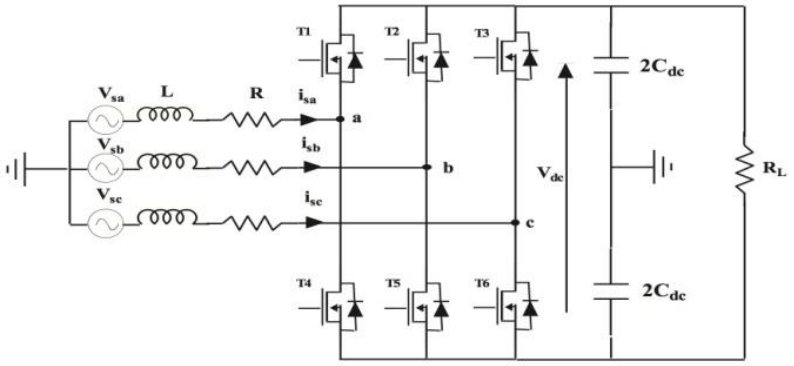

Fig. 27 Power Circuit Configuration

Hysteresis current controllers are simple to implement as it uses the comparators to switch between the specified hysteresis bandwidth. It offers excellent dynamic performance as it acts quickly [21].
Following are the types of hysteresis current controller which can be implemented to control the switch of AFE converter:

1. Constant Hysteresis Band Current Controller
2. Sinusoidal Hysteresis Band Controller
3. Adaptive Hysteresis Band Controller
4. Simplified Adaptive Hysteresis controller

All the four controlling scheme has been discussed briefly below.

4.4.1 Constant Hysteresis Band Current Controller [21]

The purpose of hysteresis controller is to force the actual current (i_a) to follow the predefined reference current (i_a*). In conventional hysteresis controller, the comparators switch between the fixed bandwidth and the voltage of point 'a' (Fig. 4.2) with respect to neutral (V_{aN}) are shown in fig 4.3. The bandwidth is fixed irrespective of the dynamic nature of current. The hysteresis bandwidth (HB) along with the current dynamics decides the switching instants and hence the switching frequency.

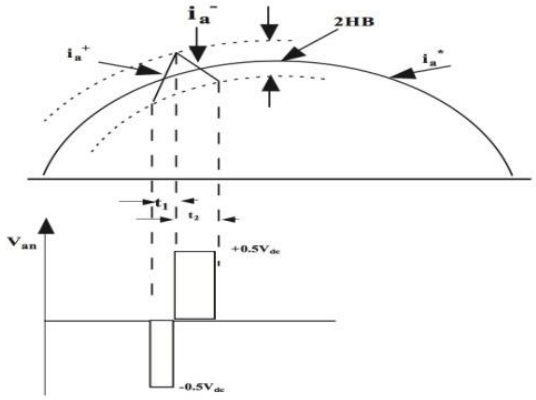

Fig. 28 Current and voltage wave with constant bandwidth

The switching strategy is as follows:

If $i_a > i_a^* + HB$, then upper switch is turned ON and If $i_a < i_a^* - HB$, then lower switch is turned ON

Advantage

This method is very simple, provides fast dynamic response reduces steady state error, minimum hardware and software required for implementation, and no need of information about system parameters.

Drawback:

It suffers from the drawback of variable switching frequency i.e. the frequency changes with respect to time depending on the operating point in a power cycle. This variable frequency causes increased switching loss, acoustic noise and complicated input filter design. Magnitude of hysteresis bandwidth is a critical factor in this case, as a smaller bandwidth reduces ripple and harmonic content in the current wave, at the same time increases the magnitude of switching frequency and the range of variation of switching frequency.

4.4.2 Sinusoidal Hysteresis Band Controller [21]

In this type of controller hysteresis bandwidth is varied sinusoidally over a fundamental period for each phase. The switching strategy can be given below:

If $i_a > i_a^* + HB \sin(\omega t)$, then upper switch is turned ON

If $I_a < i_a^* - HB \sin(\omega t)$, then lower switch is turned ON

As the magnitude of hysteresis bandwidth also varies at the same frequency of reference current, the switching speed is very high so that the actual current is able to exactly follow the reference current. This scheme reduces the harmonic content in source current to a greater extent, but the switching frequency is very high and wide in range. The switching frequency cannot be predicted and controlled as it depends on the dynamic nature of current relative to the fixed value of sinusoidal bandwidth.

4.4.3 Adaptive Hysteresis Band Controller

In order to overcome the problems of variable switching frequency, the hysteresis bandwidth is made variable as a function of system parameters like source voltage magnitude, inductance value, dc bus voltage etc. and the switching frequency is kept at fixed value. The adaptive hysteresis bandwidth can be calculated from the system steady state performance equations and assuming constant switching period.

Here the hysteresis bandwidth varies depending on the instantaneous system parameter as given by (8) so that the switching frequency is maintained constant. According to the design requirement the switching frequency can be made fixed and operated with minimum range of variation from the selected frequency.

4.4.4 Simplified adaptive hysteresis controller

In this method also the hysteresis bandwidth is varied with system parameters as in (8) above, where the slope of the reference current is considered to be zero as the switching time period is very small as compared with the time period of the reference current. Hence the reference current during a single switching interval is treated as constant and hence the complexity of the measurement of slope is now reduced. In this way we studied the types of hysteresis current controller. In this chapter we are using constant hysteresis band current controller to generate the PWM pulse for AFE converter.

4.5 Control Scheme of AFE Converter

As we discussed earlier that AC to DC power conversion is very essential for almost all power electronic application such as variable speed drives, uninterrupted power supplies, batter chargers etc. The biggest disadvantage of using this converter is power line harmonics, which we discussed in chapter 3. So in order to improve the power quality we use AFE with hysteresis current control [20]. The circuit diagram is given below.

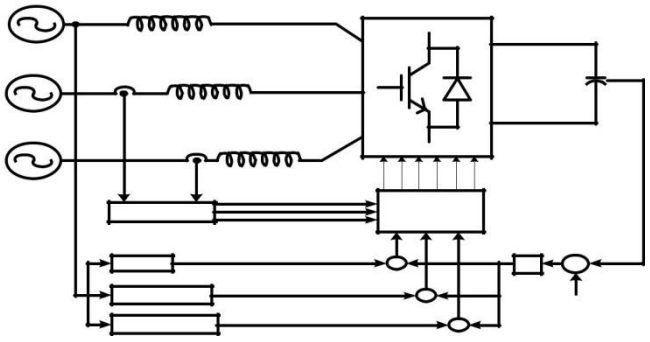

Fig. 4.4 Control scheme of AFE converter using HCC

The Fig. 29 depicts a three phase two level active front end converter using the hysteresis current control (HCC) technique. As shown in the Fig. 4.4, a current waveform template for each phase is generated. Each input current is measured and compared with its respective current template. By using negative feedback switching of power devices in the rectifier the line currents are forced to follow the desired current template thus resulting in sinusoidal line currents with unity power factor.

4.6 SPEED RESPONSE:

Built-in induction motor model in MATLAB/ Simulink [19] of 10HP (7.5kW) has been used for the simulation of the open-loop configurations parameters of the induction motor model. The Transient response in speed for a set speed of 1400rpm of the open-loop control is shown in Fig.4.5.It is observed that initially the speed increases linearly reaches approximately to 1500RPM which is above the reference speed and after 0.12 second it settles down to 1400RPM which is the required speed. Initially the peak overshoot is observed in speed response. However at steady the motor achieved its reference speed and continue to run at 1400RPM.

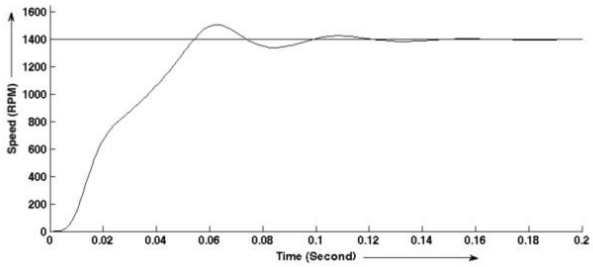

Fig. 30 Transient Response in speed

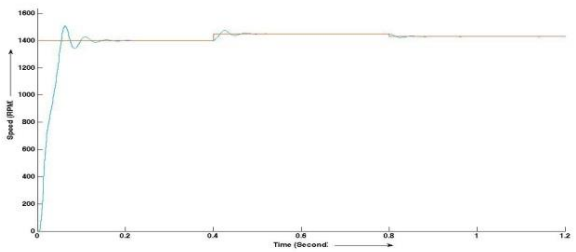

Fig. 31 Speed Response with step change in speed

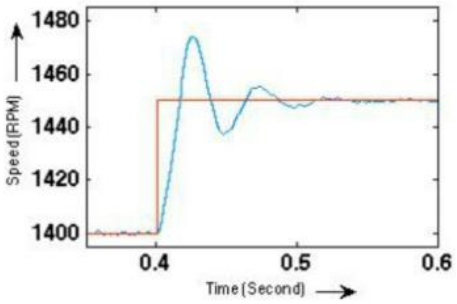

Fig. 32 Step change in speed with 50RPM

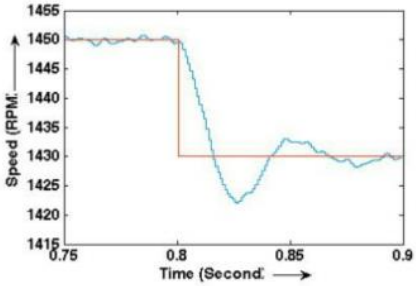

Fig. 33 Step change in speed with20 RPM

4.7 SIMULATION RESULT:

The simulation studies are carried out on open-loop V/f controlled 7.5KW induction motor drive in MATLAB/ Simulink with active front end converter. For the simulation the reference speed is set to 1400rpm and full load conditions with career frequency 1kHz. Fig. 4.10 shows the Input Voltage (line-line) (Vab), Input current (Ia) Fig. 4.11 shows the harmonic spectrum of the input current. From the voltage and current waveform it has been seen that the voltage and current are in same phase means the converter is working at unity power factor and THD in source current is found to be 1.78% which is less than 5%, following the IEEE 519 standards. The supply peak voltage is taken as 150V with 10HP (7.5kW) induction motor. The control scheme is used in MATLAB is hysteresis current control which is explained in detail in section 4.6.

4.7.1 Simulation Model

The simulation model drawn in MATLAB [19] as shown in Fig. 4.9. The AFE converter subsystem block denotes the bidirectional IGBT AC to DC converter which is controlled by generating pulses using hysteresis current controller. V/f controlled Inverted subsystem denotes the IGBT based DC to AC converter which controlled by V/f method. A 10 HP (7.5kW) motor are used for simulation and source current as well as source voltage waveform are shown in Fig. 4.10 and Fig. 4.11 respectively.

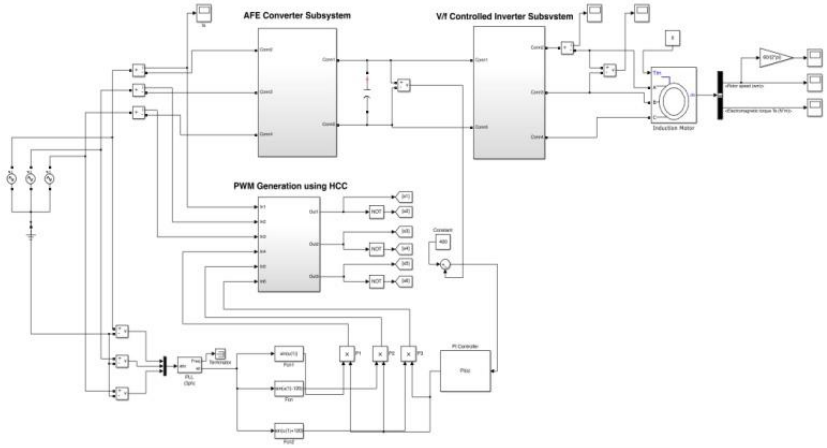

Fig. 34 Simulink Model of AFE converter fed induction motor drives

For the simulation the reference speed is set to 1400rpm and full load conditions with career frequency 1kHz. Fig. 4.10 shows the Input Voltage (line-line) (Vab), Input current (Ia) Fig. 4.11 shows the harmonic spectrum of the input current and Fig. 4.12 shows the output voltage of V/f controlled inverter which is the input voltage given to induction motor.

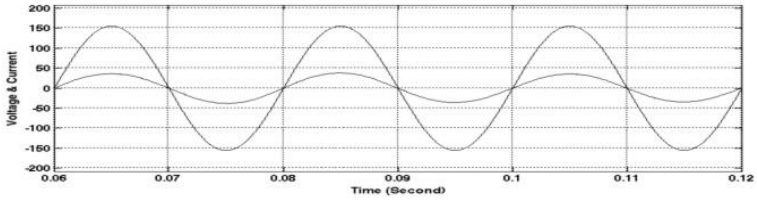

Fig. 35 Waveform of Voltage and Current in AFE converter fed IM Drives

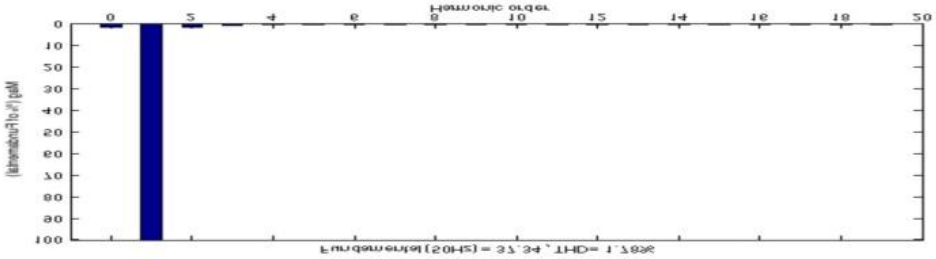

Fig. 36 Harmonic Spectrum of Source Current in AFE Converter Fed IM Drives

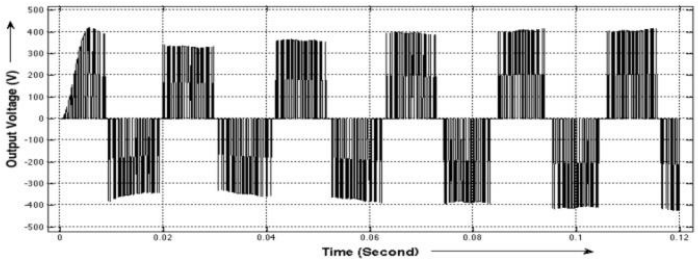

Fig. 36 Output Voltage of V/f controlled inverter

V. CONCLUSION AND FUTURE SCOPE

This work aimed to reduce the size of passive filter in active front end converter fed induction motor drives and to address the line harmonic distortion generated by the variable speed drives by proper placement of filter. For this, first of all a brief study of variable speed drives have been carried out with classification based on motor selection, major components of VSDs. Carrier based PWM modulation techniques were used in this thesis and basics of 2-level PWM were covered.

Further, studies focused on V/f controlled induction motor drive. In which open-loop and closed-loop control methods are discussed in detail.

A simulation study shows the closed loop control is superior to open-loop control by means of transient and steady-state characteristics.

Further, the line harmonic distortion has been shown in AC to DC converter fed induction motor drives by placing the AC line Reactor, DC Link inductor, both and LCL filter according to the data given by Crompton greaves. The simulation results of inductor placement with DC link inductor, AC line reactor and both DC link inductor and AC line reactor and LC filter is shown in Table 5.1, Table 5.2,Table 5.3 and Table 5.4

Table 1 Effect of both DC link inductor and AC line reactor placement
In a variable speed drive

DC Link Inductor(mH)	AC Link reactor(mH)	Input Current Ia THD(%)	Peak value of Input current
0.1	0.2	117	38.1
0.2	0.4	99.46	36.4

Table 2 Effect of LCL Filter in variable speed drives

L1(mH)	C(uF)	L2(mH)	Ia Input current THD %	Ia(Peak)
0.2	40	0.1	128.18	39.1

So by inserting the filter we reduce the THD up to desired level but as we increase the value of L and C further then the size of filter will increase which is not desirable. So further study and simulation is carried out with active front-end converter fed induction motor drives by using hysteresis current control technique in chapter 4. The maximum source voltage is taken as 150V and peak current is observed equal to 45A. AFE converter using HCC force the input current to remain sinusoidal and in phase with the voltage which reduces the THD to 1.76% which is under 5% according to IEEE519 without filter. So no filter is required with the hysteresis current control technique.

Table 3 Source Voltage, Source Current & THD in source current inAFE fed Induction Motor Drives.

Vs(V)Peak	Isa(Peak)A	THD in Isa(%)
150	**45**	**1.78**

5.2 FUTURE SCOPE

- Only scalar control method of inductions motor is discussed in this thesis, further studies are possible with vector control of induction motor.
- In this thesis only two-level carrier based

Table 4 Effect of AC line reactor in variable speed drives

DC Link Inductor (mH)	Input Current (Ia) THD (%)	Peak Value of Input Current Ia(peak)
0	219.31	45.8
0.1	157.7	42.9
0.3	125.15	38.8
0.5	111.53	36.2

Table 5. Effect of DC link inductor placement in a variable speed drive

DC Link Inductor (mH)	Input Current (Ia) THD (%)	Peak Value of Input Current Ia(peak)
0	219.31	45.8
0.1	136.56	40.4
0.3	106.89	36.2
0.5	93.81	35.7

- PWM modulation techniques are used, further studies can be done based on multilevel inverter fed induction motor drive with reduced harmonic contents.
- Input current harmonic reduction is done by using passive filter in two level converter. Further studies can be carried out in multi level inverter.
- Hysteresis current control technique are in used two level AFE converter fed IM drives. Further studies can be done with multi level inverter.
- Study of AFE converter is done with open loop V/f control fed IM drives. Further study can be done with closed loop V/f control induction motor drives.

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APPENDIX I – SIMULINK FIGURES

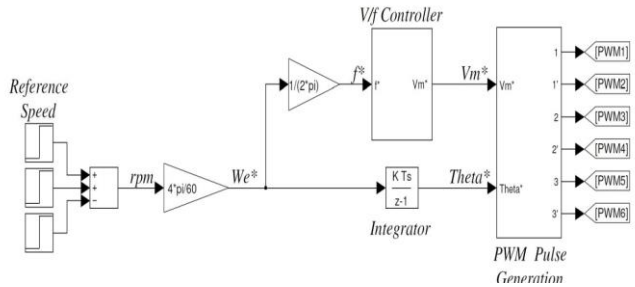

Fig.A.1 Simulink model of Open loop V/f control

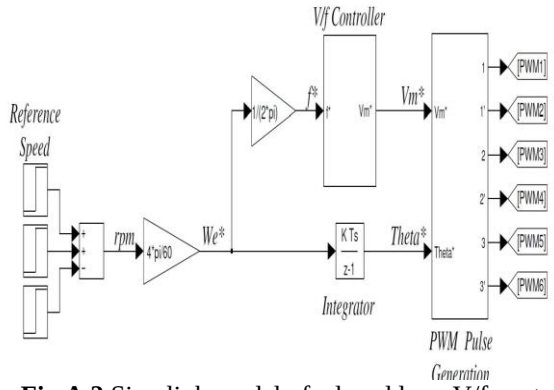

Fig.A.2 Simulink model of closed loop V/f control

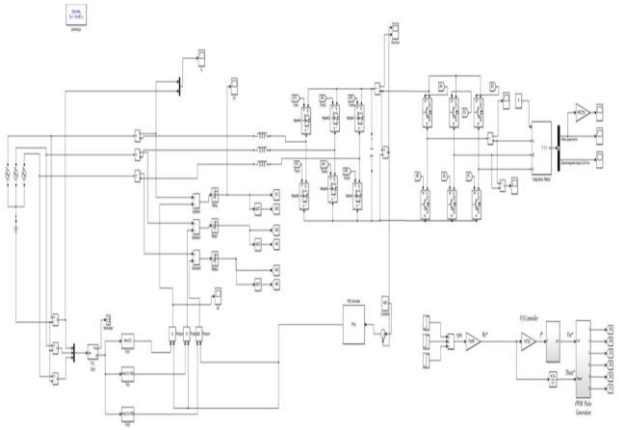

Fig.A.3 Simulink model of AFE fed IM drive

APPENDIX 2: INDUCTION MOTOR PARAMETERS

Parameters	Value
Nominal Power	7.5kW
Voltage (Line-Line)	400V
Frequency	50Hz
Stator Resistance (Rs)	0.7384 Ohm
Stator Inductance (Ls)	0.003045H
Rotor Resistance (Rr)	0.7402Ohm
Rotor Inductance (Lr)	0.003045H
Mutual Inductance (M)	0.1241H
Inertia (J)	0.0343kg.m^2
Friction Factor (F)	0.000503N.m.s
Number of Poles (P)	4