Application of AFEC in Speed Regulation of Motor using PWM Switching

Sumit R. Patel[1]
Department of Electrical Engineering
MEC, Basna, Gujarat, India

Abstract— The research work is carried with the aim of developing an efficient closed loop speed regulation of Motor using PWM switching. SPWM technique has been used for providing triggering pulse to the AFEC and Inverter both in which IGBT is used as switch. It is very accurate method as it is concern with the modulation of the amplitude and frequency. Frequency modulation provides regulated control for varying the speed of the motor while amplitude modulation provides variable amplitude of output voltage and current. By changing Modulation index (ma) amplitude of the output voltage and current can be controlled. PWM is one of the best methods for the controlling the output voltage especially SPWM because it make it possible to control frequency and magnitude both in Induction motor. It is also used for the reduction of the harmonics from the system. The controlling or regulating the motor includes turn ON – desired speed for operation – turn OFF. AFEC has advantage of drawing balanced supply even in the unbalance supply form Utility. Using Matlab simulink this operation will be shown with the details like THD analysis, output voltage, output current, triggering signals for switching. Total circuitry controlling will also be developed in the Matlab. Applications of AFEC will be developed in Matlab simulink and the required triggering signals from PWM generator. The use of AFEC will enhance the speed regulation method for Induction motor. The comparative results of open loop and closed loop will conclude as the use of AFEC will make the controlling method more reliable and effective as the closed loop feedback goes through PI controller.

Keywords: AFEC (Active Front End Converter), PWM (Pulse Width Modulation), MATLAB, Induction Motor, PI Controller, Frequency Modulation, Speed Regulation of AC Motor, IGBT, Diode, Inverter, DC Link, triggering signal, open loop control, closed loop control.

I. INTRODUCTION

Electrical motor consumes a very large part of generated energy Worldwide; as its application is very diverse in industrial as well as domestic. Constant speed application consumes more energy as the machine works with the full rated input supply even if the required speed or working load is not full. Regulated speed drives became one of the most prime factors especially during Industrial Revolution around the world. Traditional method is to provide controlled input supply to the motor using a variac, this technique has many drawbacks; power electronics came with most efficient and versatile method of speed control of motor. This application leads to the power conversion i.e. AC/DC and DC/AC. AC/DC converting device, also know a rectifier is designed using diode or thyristor to provide uncontrolled and controlled dc power, also said as unidirectional and bidirectional devices. Other than Adjustable Speed Drive (ASD); Switch Mode Power Supply (SMPS), DC power supply (for measurement and testing), Uninterrupted Power Supply (UPS), Battery charging set, Grid interface of Solar PV module, and etc. employs AC/DC conversion. Controlled device is advantageous as the input harmonics is less and power factor is higher as compared to uncontrolled, because of which used of heavy and costly line filters can be eliminated. These controlled device uses power switches like MOSFET, IGBT, GTO, etc.

This days the regulated speed application of induction motor is most widely used with front end rectifier (AC/DC) and inverter (DC/AC) at load side. One of the best methods for this application is V/F control of induction motor, Pulse Width Modulation (PWM) or Sinusoidal Pulse Width Modulation (SPWM) can be use to provide the triggering pulse for both the converters with feedback control (in some applications) [1]-[3][8][14]. For more reliable operation and results filters can be used at the line side [7]. In some case the operation of speed control must be carried out even with unbalanced supply, Active Front End Converter can be employed for drawing balanced supply from available unbalanced supply [10]. PWM gate pulse is designed with suitable modulation index; it will also give the required Total Harmonic Distortion (THD). By varying the modulation index (m) current and voltage harmonics can be varied [8]. The variable speed also deals with the braking of motor; one of the braking methods is Regenerative type of braking in which torque-slip characteristics becomes negative. To use the regenerative energy, the power conversion devices must be bidirectional to employ dual way power transfer [9]. An advanced configuration of AFEC known as Neutral point clamped AFEC, it gives improved power quality, improved power factor and balanced dc output of rectifier [11]. For better operation of the speed control appropriate control technique should be applied with different topologies of front end rectifier. A Proportional-Integral controller is used to compare actual and desired values of dc link voltage or stator currents to get the error signal. The generated error signal is computed for the required pulse of triggering signal generator [3][5][6].

Regulated speed induction motor is widely used for more than 45 years, in industrial as well as domestic applications. Moreover it's used is increasing ever since because of the efficient operation, flexible speed control, ruggedness and low maintenance qualities. Induction motors are addressed as workhorse of the increasing automation demand in industries. Some other prior application areas are fans & elevators (in domestic area), conveyer belts, robotics, overhead cranes, paper mills, textile mills, etc. In general regulated speed AC induction motor is referred as AC Drives; it offers advantages like low cost, low maintenance, smaller size and reliable operation. The speed controlling have became more flexible after combining with power electronics; different kind of AC/ DC, DC/AC and AC/DC/AC configurations are used to provide desired speed operation of induction motor. The basic of variable speed operation is to apply variable voltage and variable frequency supply to the stator terminals of the induction motor.

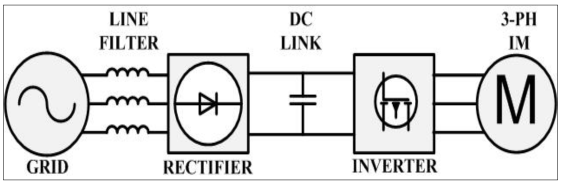

Fig. 1: Basic Block diagram of Speed Regulation

Because of the growing energy crisis, the ways of saving the energy is always an prior issue as it is concern with the economic operation of the system. It is calculated that about a half of the generated electricity of the world is used in motors in various industrial and domestic applications. Mostly those motors are driven without a frequency converter. Without a frequency converter a motor can only be driven full speed or not driven at all. A frequency converter gives the ability of control to motor input energy. A frequency converter has a user interface that allows the modification of the driving input frequency of the motor terminals. It means that the motor can be driven with almost unlimited variety of frequencies providing a wide range of speed control. A frequency converter use can save up to thirty percents of energy. The total energy savings could thus be gigawatt hours per year around the world.

A frequency converter contains four main parts that can be seen in figure 1.3 the first part from the grid is a line filter; it filters the current of the converter so that it does not interfere the grid too much. The second part is a converter; it converts the alternative current into a direct current form. The converter can be passive or active. A diode rectifier is a passive converter. After implementing the passive converter, nothing can be changed unless the bridge itself is changed. On the other hand an active converter or in other words an AFE is controllable. An IGBT bridge is one example of active converters; it allows active changing of the switching times. That way the power factor can be optimized to one and the DC-voltage can be controlled. An AFE also enables the possibility of returning power toward the grid, a diode rectifier only allows power to pass in one direction. A diode rectifier (uncontrolled) can be seen on the left side of figure 1.3 and an IGBT inverter (controlled) on the right side of the same figure.

II. INDUCTION MOTOR

Both stator and rotor are laminated and consists of an insulated winding to carry current and magnetic flux. The stator provides path for the magnetic field and the housing for the stator windings. The stator and rotor are laminated to reduce eddy current losses. When single phase alternating supply is fed to the stator of induction motor, the ac current circulates in the stator winding. This flowing current produces a flux having alternating nature known as stator flux. The generated flux links with the rotor windings and hence rotor conductor cuts the stator flux as a result emf induces in the rotor winding. Current will flow in the rotor as the rotor windings are short circuited, this current is said as rotor current. Flow of rotor current in the rotor winding will produce rotor flux. These two fluxes will produce the desired torque which is required by the rotor to rotate.

A. *Working principle*

The working principle of three phase induction motor is a bit different than single phase. As its stator houses three phase winding which are displaced in space by 120 degree, when three phase supply is fed to the stator windings, a rotating magnetic flux (rotating at synchronous speed) is established in the stator.

Synchronous Speed, $N_s = 120f / P$

Where, f = supply frequency

P = number of pole

This flux passes through the air gap and cuts the stationary rotor conductors as a result of relative speed (motion) emf are induced in the rotor winding. Since the rotor conductors are short circuited, rotor current will produce whose direction will be same as of the rotating magnetic field according to Lenz's Law.

The operation of induction motor can be better understood by the equivalent circuit as the calculative part becomes simple. The figure below represents AC equivalent circuit.

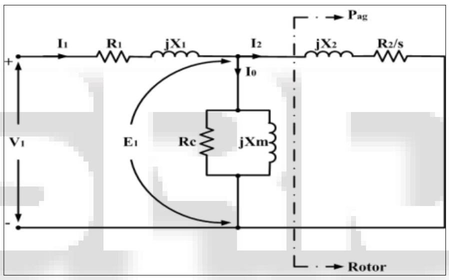

Fig.2.1: Equivalent circuit of Induction motor

Where,

V_1 = Stator terminal voltage per phase
I_1 = Stator current
I_2 = Rotor current
R_1 = Stator winding resistance
R_2 = Rotor winding resistance
X_1 = Stator leakage reactance
X_2 = Rotor leakage reactance
Xm = Magnetizing inductance
Rc = Core losses
Pag = Air gap power

Selection of motor for a certain application or load, the primary factors that are to be considered are with respect to torque and speed of the motor.

B. *Operating modes of Induction Motor*

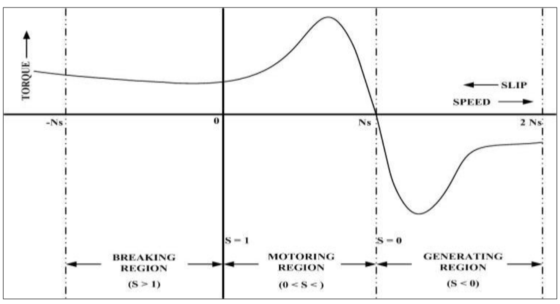

Fig.2.2: Operating characteristics of Induction motor

1) *Braking*

A simple technique is used to stop the rotating induction motor, by simply interchanging any two phases at the stator terminals. This method is also known a Plugging of an Induction Motor. What actually happens is the reversal (opposite direction) of the rotating magnetic field in the stator winding, thus it acts as applying brake on the motor.

2) *Motoring*

This is the natural operational mode of the induction motor. When stator windings are energized with a balanced three phase supply (120 degree apart from each other), a rotating magnetic field is produced rotating at a speed equal to the synchronous speed of the motor. The stationary conductors of the rotor get cut by the rotating field and an emf is established as a result of which current will flow in the rotor winding. By Lenz's law the rotor will rotate in the same direction of the rotating magnetic field of the stator. The electrical energy is converted o mechanical energy; this is said as motor action.

3) *Regenerative*

Referring figure (2.2), an induction motor can be operated as a Generator by operating it with a speed higher than synchronous speed. It converts the receiving mechanical energy into the electrical energy released by the stator. When motor exceed its synchronous speed, it begins delivering active power (P) to the three phase supply lines. However it absorbs reactive power (Q) from the same line for producing its magnetic field. It means the direction of the active power & reactive power will be opposite to each other. The generated power is directly propositional to the slip above the synchronous speed (Ns).

C. *Speed control technique for induction Motor*

1) *V / f control speed control technique (frequency control).*

This is one of the most widely used methods especially for the Adjustable Speed Drive (ASD) or Variable Frequency Drive (VFD) which is basically used for controlling the speed of the motor. When three phase supply is fed, the stator rotating magnetic field rotates with the synchronous speed given by:

Ns = 120*f / P

The induced emf of induction motor is given by:

E or V = 4.44*Φ*k*T*f

Where, K = winding constant
T = number of turns / phase
f = supply frequency

From above equation we can observe that change in frequency will directly affect the induced emf (E). But with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor. That means it is important to maintain flux (Φ) constant and it is only possible by changing voltage too as it is the only other variable term. If the frequency is reduced than voltage must be increased to make the flux constant. Hence we are keeping the ratio of V / f constant.

D. *Total Harmonic Distortion (THD) effect in Induction Motor*

The advancement in the controlled operation and other applications of controlled output voltages leads to the increasing use of power electronics. This power switches are one of the major reasons for the production of harmonics with different orders in the system. It is nothing but the sine component of the periodic waveform having a frequency in the integral multiples of the fundamental frequency. First order harmonic is addressed as Fundamental frequency (f), second order harmonic can be described as 2f followed by third harmonic as 3f and likewise. Even harmonics are eliminated naturally as the overall distortion gets cancelled, positive cycle = negative cycle.

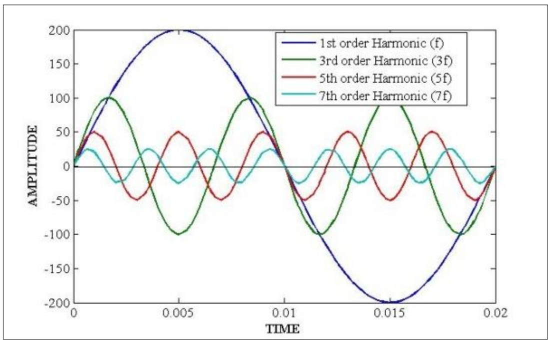

Fig.2.3: Waveform of different harmonic order

As name suggest THD is the combined effect of the orders of the harmonics present in a single system. Total Harmonic Distortion (THD), is the ratio of the summation of all the harmonic components (3^{rd}, 5^{th},… orders) of the current or voltage waveform compared to the fundamental component (f).

$$\text{THD} = \frac{\sqrt{I22+I32+I32+I42+\cdots+In2}}{I1} * 100\ \%$$

Where I1 is the fundamental current (mention all variables)

The equation above shows the calculation for the THD components of the currents. The calculated value is a percentage comparing the harmonic component to the fundamental component of the current. For THD analysis, MATLAB have a ready to use tool in powergui block i.e. FFT Analysis.

III. POWER CONVERSION

Our technology is developing with a variety of power conversion techniques, in quest of better efficiency and reliable operation of the electrical and electronic device. Almost every device we use in day to day life need a power conversion except simple battery powered devices. Mostly devices these days have an operating range for desired function other than conventional turn ON & OFF. This controllability is done using electronic circuitry, operates on DC voltage source while power we receive is AC in nature hence power conversion is must. This conversion also varies the voltage level as required, as it is the task of power electronics to convert and control the flow of electrical energy required by the load.

A. Types of Power Conversions

Different types of conversion are used for various applications. This conversion and control of electrical power depends on the switching characteristics of the power devices (switches) like BJT, MOSFET, GTO, or for this particular paper IGBT. For switching ON – OFF, PWM generator is used. The power conversion can be mainly classified as under:

(1) AC to DC conversion (controlled or uncontrolled Rectifiers).
(2) AC to AC conversion (AC voltage controllers).
(3) DC to AC conversion (Inverters).
(4) DC to DC conversion (DC choppers).

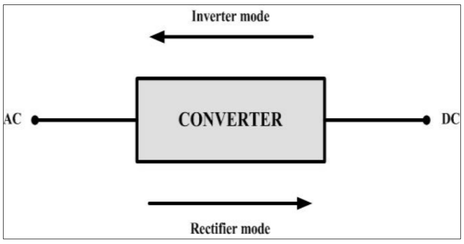

Fig.3.1: Basic block diagram of Power conversion

1) AC to DC

This conversion technique can be used with two different topologies i.e. Uncontrolled and Controlled. Uncontrolled rectifier also known as diode rectifiers, converts fixed AC input voltage (single phase or three phase) to fixed DC output voltage. Controlled rectifiers have natural commutated thyristors instead of diodes, this makes the output controllable. With fixed AC input (single phase or three phase) the average output voltage can be controlled by changing the turn ON time (conduction time) of thyristor or firing angle delay.

2) AC to AC

This type of converters is also known as AC voltage controllers. It converts fixed AC input into variable AC output by controlling conduction time of a TRIAC

3) DC to AC

This type of converters is also known as Inverters. In which thyristors are used to obtain variable output voltage by controlling thyristor conduction time from a fixed DC input.

4) DC to DC

This type of converter is also known as DC coppers. It converts fixed DC input into variable DC output by controlling the conduction time of thyristors.

B. Pulse width modulation technique

In conventional method fixed gate signal are given to switch from a pulse generator, the switch will operate likewise. While PWM technique enables the user to change the duty cycle by changing frequency and amplitude of the modulation

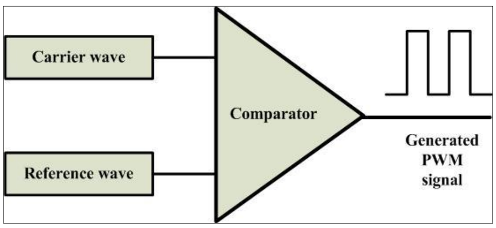

Fig.3.2: Basic block diagram of PWM

The above figure shows basic working of PWM (Pulse Width Modulation).Two different signals i.e. Reference signal & Carrier signal are compared together through a Relational Operator (Matlab). It will compare both the waveforms and gives result with the condition provided. It will consider one reference signal & other as carrier signal. Here in example 1 (below) reference signal in Fixed DC while Triangle wave is carrier signal. Now the condition <= (less than or equal to) works when the reference signal is less than the carrier signal means when Fixed DC is less than Triangle wave than we will get output otherwise the output will be zero (0). By changing modulation index we can vary the output directly. Modulation index is given as m = Am / Ac where Am is Amplitude of sine and AC is Amplitude of carrier triangular.

Three phase induction motors are most widely used for any industrial control and concern automation. It is often required to control the output voltage of inverter for the constant voltage/frequency (V/f) control of an induction motor. PWM (Pulse Width Modulation) based firing of inverter switches provides the best constant V/F control of an induction motor. Amongst the various PWM techniques, the Sinusoidal PWM (SPWM) is good enough and most popular that provides smooth changeover of V/f, four quadrant operation, harmonic elimination, etc in both closed and open loop applications. When three phase inverter is feeding a three phase induction motor it requires six pulse control (at least).

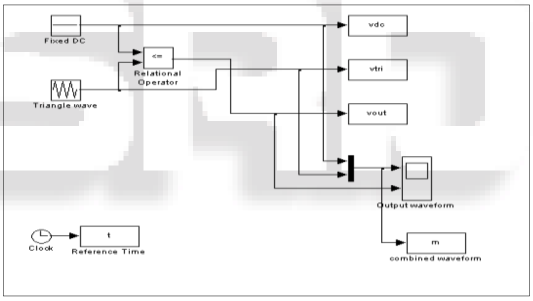

Fig. 3.3: Simulation of simple PWM Generator

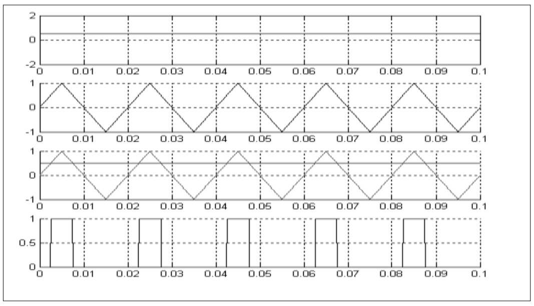

Fig.3.4: Waveforms – Simulation of simple PWM Generator

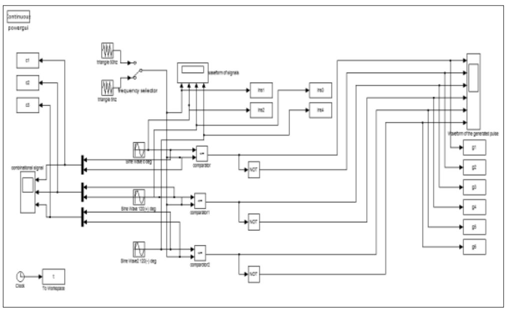

Fig.3.5: Simulation of 6 pulse PWM Generator

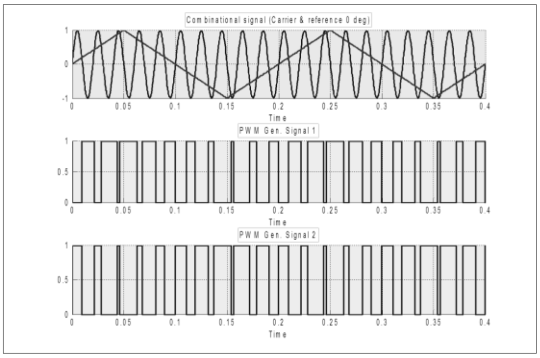

Fig.3.5(a): waveform–Simulation of 6 pulse PWM Generator

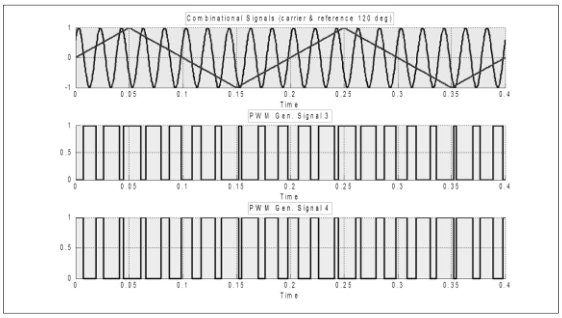

Fig.3.5 (b): waveform – Simulation of 6 pulse PWM Generator

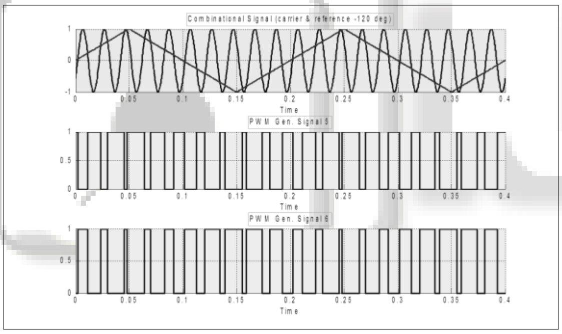

Fig.3.5 (c): waveform – Simulation of 6 pulse PWM Generator

C. Concept of Active Front End Converter (AFEC)

The Active Front End Converter is same as the controllable inverter or rectifier. It can allow bidirectional power flow as it can work in both the ways i.e. rectifier or inverter. The basic arrangement of AFEC is shown in the figure below,

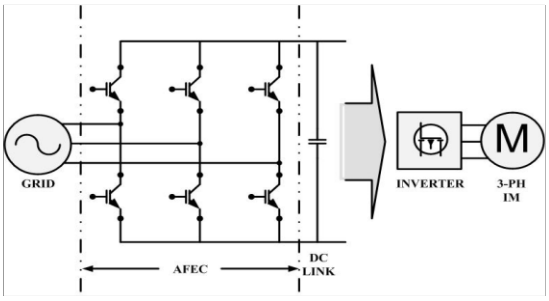

Fig.3.6: Block diagram of basic AFEC setup.

In rectifier mode, the switches will work together with the grid (line) side inductance as a boost converter. To ensure the controllability of output voltage, it has to stay above √2 VLL otherwise the diodes will start to act as a standard rectifier (uncontrollable). AFEC has fully controllable over the current that is drawn from the grid; this is the main advantage for which it is employed. It means the input current can be made very close to sinusoidal and input side harmonic distortion can be eliminated which in case of traditional rectifier is not possible. Moreover if any kind of harmonic is present in the DC link than it will not be fed back into the grid when bidirectional power flow is considered. The control technique i.e. PWM will however inject some switching harmonics.

D. Open loop speed control

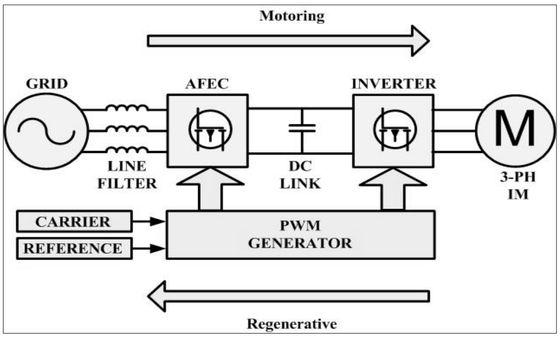

Fig.3.7: Block diagram of Open loop speed control.

Figure (3.7) above shows the circuit diagram of the open loop speed control of AC motor using PWM switching. Three phase supply is connected the AFEC. The AFEC operates and gives the DC output; this output is pulsating, so in order to remove that pulsation the DC link (capacitor) is connected in parallel with the output terminals of the rectifier. The DC link will make the output constant and this output will be given as the input of the Inverter (three-phase). This inverter is basically a six step bridge inverter; it consists of six IGBT Switches. Every arm has two switches i.e. S1 - S4; S3 - S6 and S5 - S2. Every switching device requires triggering pulse which is used to give the triggering (on-off) sequence. Here PWM generator is used to give the triggering pulse to the Inverter as well as AFEC too.

E. Closed loop speed control

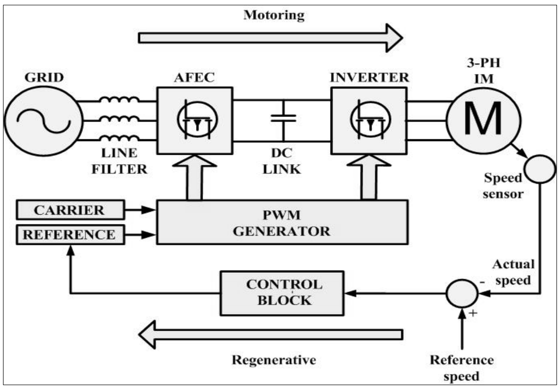

Fig.3.8: Block diagram of Closed loop speed control.

Unlike open loop control system closed loop control system has a feedback signal which controls the speed of the rotor as required. As shown in the figure (3.8) above speed sensor senses the actual speed of the motor and fed it to a comparator were the actual speed is compared with the required or desired speed. Further a control block having a PI controller will generate the required signal for the correction with respect to the required speed.

F. Control block

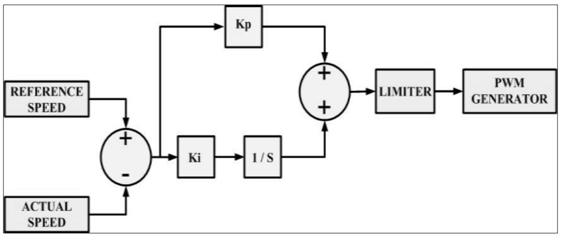

Fig.3.9: Block diagram of Control system for Closed loop speed control.

A three phase induction motor is connected to the output terminals of same phase inverter its rotor starts rotating at rated speed (actual speed). The speed is sensed by sensor and converted from angular speed (ωm) to rpm; this actual rpm speed is feedback to a comparator. The comparator generates an instantaneous error signal from actual speed in rpm and reference speed (required speed). The generated instantaneous error is fed to a Proportional – Integrator (PI) controller. As name suggests it contains two separate modes i.e. Proportional mode (P) and Integral mode (I). The proportional part calculates the reaction to reduce the current error while the Integral part determines the reaction to reduce offset based on recent error which also improves the tracking by reducing the instantaneous error between the reference and the actual speed. The output error is forced to remain in specified range by a limiter. The resulting error signal is multiplied with the reference sinusoidal waveform in PWM Generator. Basic block diagram of control system is shown in Figure (----) above.

IV. SIMULATION AND RESULTS

The simulation is done in MATLAB / Simulink. A three phase Induction motor is fed by AC / DC / AC controllable power circuit. As shown in the open loop as well as closed loop circuits. Three phase supply is given to the AFEC which works as a controllable rectifier and gives variable DC across DC link (bus). The DC is fed to Inverter which gives controllable three phase AC output for Induction motor. For controlling AFEC and Inverter a SPWM generator is used which has a reference signal with 50 Hz frequency and carrier
signal with 15 KHz frequency. A 4 pole, three phase squirrel cage induction motor, 220 V, 50 Hz
and 1500 rpm (rated) is fed through proposed controllable AC / DC / AC system. Simulation parameters includes a three phase supply block with 400 V (phase to phase), L – C – L source side filter, a front side 3 arm IGBT converter, a DC bus with capacitor across it, a 3 arm IGBT inverter at
the load end, SPWM generator and a 3 HP Asynchronous machine block. A constant load torque with nominal value of 11.9 Nm is given to shaft. Some noise is introduced in the rotor and stator currents due to the PWM switching which is also observed in Electromagnetic torque (Te). This noise doesn't appear in the speed because of the inertia of the motoritself.

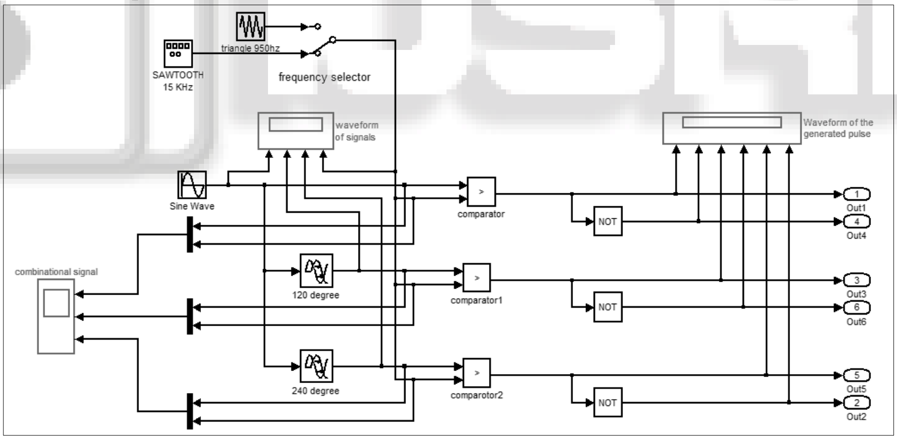

Figure 4.1: Simulation of Open Loop Speed Control.

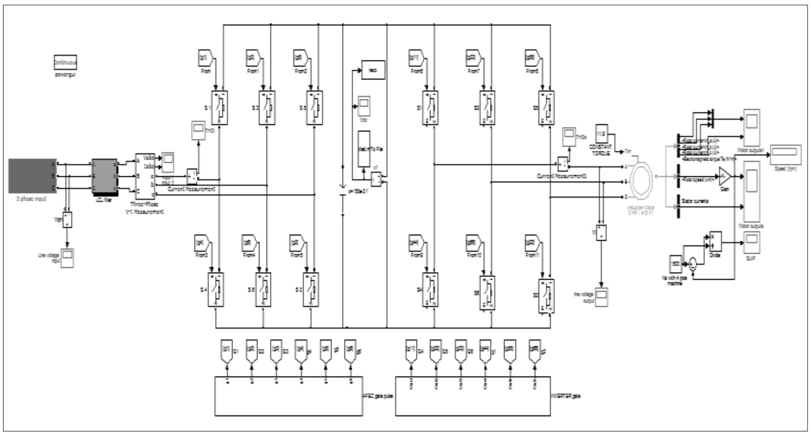

Figure 4.2: Simulation of SPWM Generator for Open Loop Speed Control

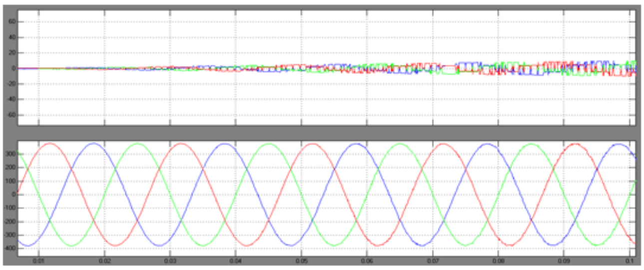

Figure 4.3: Waveform of input I & V for Open Loop Speed Control.

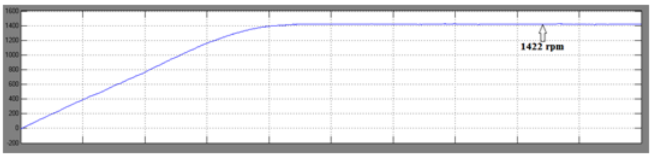

Figure 4.4: Waveform of Speed for Open Loop Speed Control.

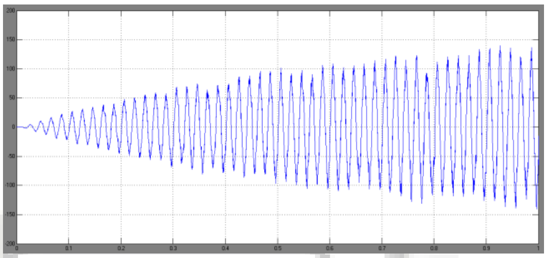

Figure 4.5: Waveform of load I for Open Loop Speed Control.

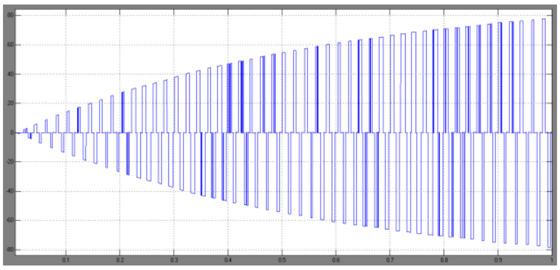

Figure 4.6: Waveform of load V for Open Loop Speed Control.

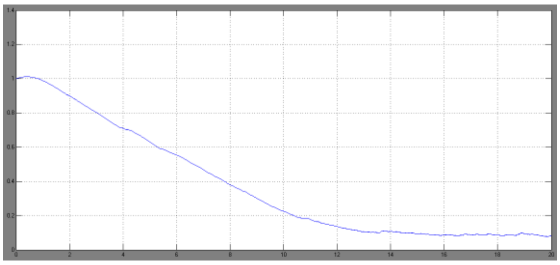

Fig.4.7: Waveform of Slip for Open Loop Speed Control.

Modulation Index (ma)	Current THD %		Voltage THD %	
	Input	Output	Input	Output
1	4.96	2.11	32.24	20.47
0.8	3.31	2.28	30.02	17.45
0.6	1.78	1.99	26.39	19.99
0.4	0.93	2.48	29.13	23.71

Table 4.1: THD analysis for Open Loop Speed Control.

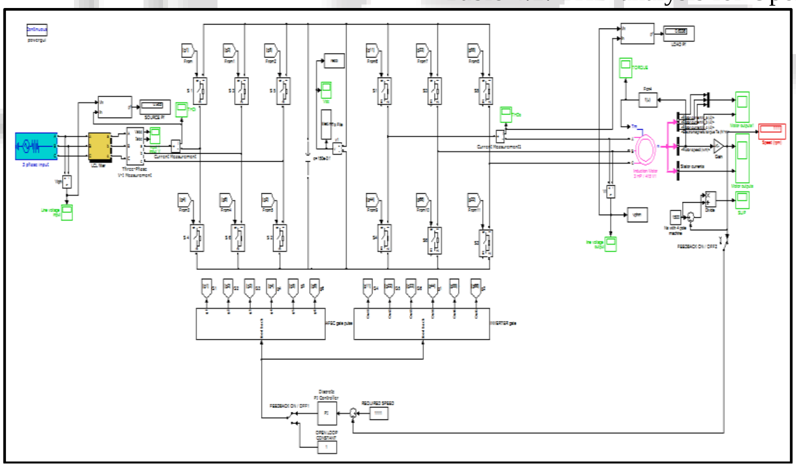

Fig.4.8: Simulation of Closed Loop Speed Control.

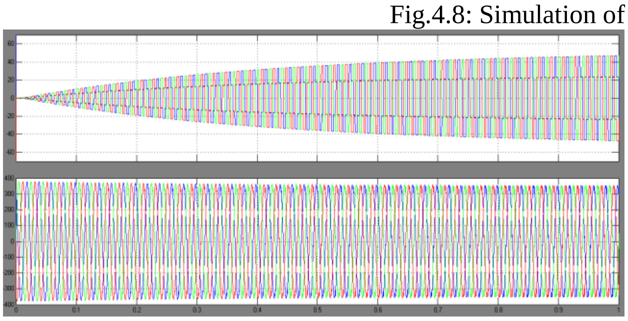

Fig.4.9: Waveform of input I & V of Closed Loop Speed Control

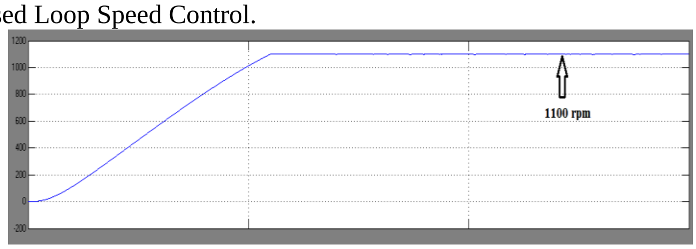

Fig.4.10: Waveform of Speed for Closed Loop Speed Control.

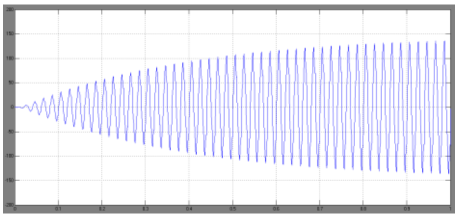

Fig.4.11: Waveform of load I for Closed Loop Speed Control.

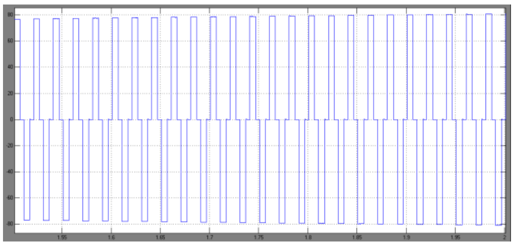

Fig.4.12: Waveform of load V for Closed Loop Speed Control.

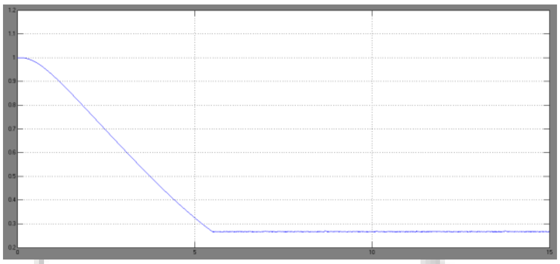

Fig.4.13: Waveform of Slip for Open Loop Speed Control.

Modulation Index (ma)	Current THD %		Voltage THD %	
	Input	Output	Input	Output
1	6.79	5.46	30.61	34.91
0.8				
0.6				
0.4				

Table 4.1: THD analysis for Closed Loop Speed Control.

V. CONCLUSION

The speed control of three phase Induction motor is done successfully in open loop as well as closed loop circuits. The THD analysis is done with different modulation index from 0.4 to 1.0; this variation also affects the speed of the motor. The speed waveforms are almost smooth irrespective of load currents. The application of AFEC at the line side gives the smooth operation and reduced THD even with lower Modulation index. The THD of open loop system is affected by variations in modulation index while in closed loop circuit it does not.

REFERENCES

[1] C. S. Sharma & Tali Nagwani *"Simulation and Analysis of PWM Inverter Fed Induction Motor Drive"* International Journal of Science, Engineering and Technology Research (IJSETR) Volume 2, Issue 2, February 2013.

[2] Aswathi G, S Nalini & R. Sudeep Kumar *"Simulation of Active Front End Converter Based VFD for Induction Motors"* International Journal of Scientific & Engineering Research, Volume 4, Issue 6, June-2013.

[3] José R. Rodríguez, Juan W. Dixon, José R. Espinoza, Jorge Pontt, & Pablo Lezana *"PWM regenerative rectifiers state of the art"* IEEE Transactions on Industrial Electronics, vol 52, No. 1, Feb 2005.

[4] José R. Rodríguez, Jorge Pontt, César Silva, Eduardo P. Wiechmann, Peter W. Hammond, Frank W. Santucci, Rodrigo Álvarez, Rodrigo Musalem, Samir Kouro, & Pablo Lezana *"Large current rectifiers State of the art and future trends"* IEEE Transactions on Industrial Electronics, vol 52, No. 3, Feb 2005.

[5] C. Attaianese, V. Nardi & G. Tomasso *"A Novel Approach To Modelling and Control of Active Front-end Inverter Feeding Induction Motors"* 0-7803-71 56-9102 IEEE 2002, P.P. 1322 – 1327.

[6] Atif Iqbal1, R.K. Behera, Ahmad Anad, Haitham Abu-Rub *"Analysis of A Field Oriented Controlled Five- Phase Motor Drive with Active Front End Converter"* 978-1-4673-5019-8/12 IEEE 2012, P.P. 396 – 401.

[7] Anirudh Acharya, Shankar Murthy, Vinod John & T.*Saboo "Filters for Active Front End Motor Drives"* ISRO-IISc Space Technology Cell project No. ISTC244.

[8] Amit Kumar Sharma, Tushar Deep Saxena, Shirazul Islam & Arun kumar Yadav *"Performance Analysis of Three Phase PWM Voltage Source Inverter Fed Three Phase Induction Motor Drive"* ISSN (Print) : 2278-8948, Volume-2, Issue-2, 2013.

[9] Mikko Purhonen *"Applying Active Front End to Multilevel Inverter"* Lappeenranta University of Technology, April 2008.

[10] Samir Kouro, Mariusz Malinowski, K. Gopakumar, Josep Pou, Leopoldo G. Franquelo, Bin Wu, Jose Rodriguez, Marcelo A. Pérez & Jose I. Leon *"Recent Advances and Industrial Applications of multilevel Converters"* IEEE Trans., VOL. 57, NO. 8, AUGUST 2010.

[11] Amit Ojha, P. K. Chaturvedi, Arvind Mittal & S. Jain *"Performance of 3-Phase Neutral Point Clamped Active Front End Multilevel Converter"* IJSETR Volume No.2, Issue No.7, P.P. 619-625, (ISSN : 2277-1581) July 2013.

[12] Luis Morán, José Espinoza, Mauricio Ortíz, José Rodríguez & Juan Dixon *"Practical Problems Associated with the Operation of ASDC based on Active Front End Converters in Power Distribution Systems"* The Chilean Research Council project No. 1020460.

[13] P. Lezana, J. Rodrıguez, D. Rojas & J. Pontt *"Novel Cell based on Reduced Single – phase Active Front End for Multicell Converters"* IEEE 2005.

[14] Michał KNAPCZYKFF & Krzysztof PIEŃKOWSKIF *"Analysis of Pulse Width Modulation Techniques for AC/DC Line – side Converters"* Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Politechniki Wrocławskiej Nr 59, Nr 29, 2006.

[15] Muhammad H. Rashid, *"Power Electronics Circuits, Devices, and Applications"*, Second Edition, Prentic

Hall of India Private Limited. New Delhi – 2000. P.P. 370 to 387
[16] Dr. P. S. Bimbhra, *"Power Electronics"*, Khanna Publishers. Delhi. Chapter 8 – Inverters, P.P. 454 to 456.