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Volts per Hertz Speed Control of 63-Level Multilevel Inverter Fed Induction Motor Using PID Controller

[1]M. R. L. Manaswini, [2]G. V. Siva Krishna Rao

[1]Student of Master of Technology, [2]Professor
[1]Department of Electrical Engineering,
[1]Andhra University, Visakhapatnam, India

Abstract : Induction motors are playing a vital role in many of the industrial and domestic applications because of their inherent superior characteristics. For induction motor's variable speed applications, variable voltage and variable frequency(V/f) speed control is generally used because of the smooth and wide-range of speed control it provides. In conventional speed control, a two- or three-level VSI is used which produces voltage with high harmonic distortion and hence, a pulsating torque is produced and life of motor decreases. The recent advances in Power Electronics field led to the development of Multilevel Inverters (MLI) which have the capability of producing voltages with reduced harmonics and with increased efficiency and power handling capability. This work is aimed at employing a Sixty-three level Multilevel Inverter in the closed loop Volts/Hertz speed control thereby overcoming the disadvantages encountered with conventional method. A closed-loop induction motor speed control model using Volts/Hertz method and PID controller as speed controller is presented in this work. The main objective is to enumerate the advantages of PID controller which are: economical, wider range of operating conditions, easier to adapt etc., thereby investigating its suitability as a speed controller for induction motor. The performance of the PID controller is observed by developing the model in MATLAB/SIMULINK.

***Index Terms* – Multilevel Inverter, PID Controller, Induction Motor, Volts per Hertz Control**

I. INTRODUCTION

The use of induction motors has increased tremendously since the day of their invention. They are being used as actuators in various industrial processes, robotics, house appliances and other similar applications. The reason for their day by day increasing popularity can be primarily attributed to their robust construction, simplicity in design and cost effectiveness. These have also proved to be more reliable than DC motors. Apart from these advantages, they have some unfavorable features like their time varying nature and non-linear dynamics.

Speed control is one of the various application-imposed constraints for the choice of a motor. Hence, in the last few years it has been studied by many, and various methods for the same have been developed. Out of all the speed control mechanisms, the Volts/Hertz control scheme is very popular because it provides a wide range of speed control with good running and transient performance and also it maintains the air-gap flux constant. This control mechanism is referred to as scalar control mode. Here both the input and output commands are speed.

The field of power electronics has contributed immensely in the form of voltage-frequency converters which has made it possible to vary the speed over a wide range. The power electronic converters that are used for the speed control of induction motor are voltage source inverters, current source inverters and cyclo-converters.

Voltage source inverters are the most used converters because the voltage sources are widely available in practice like batteries or a rectified AC. This voltage source inverters provide a two or three level voltage output but it suffers from the following drawbacks:

- The output voltage contains greater amount-of harmonics.
- The presence of these harmonics causes the stator current to be distorted due to which the stator gets heated up.
- The torque ripples will be more due to which the motor provides a jerky motion.
- More stress will be developed on the switching devices.
- A considerable amount of power loss occurs while converting the DC voltage to AC.
- Due to the presence of higher amount-of harmonics in the output voltage, pulsating torque is produced which reduces the life of the motor.

The aforementioned problems show the necessity of better converter which provide voltage with reduced harmonics, increased power handling capability and increased efficiency.

A multilevel inverter provides a solution for the above problems. It is a type of voltage source inverter which provides high-voltage waveforms from lower-voltage components. The output voltage from a multilevel inverter is a stepped waveform which nearly resembles a sinusoidal waveform. Hence its output voltage has lower harmonic distortion hence the power loss will also be low. The voltage stress on the switches will be less because the change from one level to another is small. The output voltage waveform produced by multilevel inverters will be almost similar to a sinusoidal waveform.

The highly non-linear nature of the induction motor control dynamics demands strenuous control algorithms for the control of speed. The controller types that are being regularly used are: Proportional(P), Integral(I), Proportional Integral (PI), Proportional Derivative (PD), Proportional Integral Derivative (PID) or a blend of them.

The PID controller offers a very efficient solution to numerous control problems in the real world. If PID controllers are tuned properly, they can provide a robust and reliable control. This very feature has made PID controllers exceedingly popular in industrial applications.

Some of the disadvantages of PI and PD controllers are:

- They have long response time.
- They have longer period of oscillation.
- They do not improve the steady state error.
- They amplify the noise signals produced in the system.

To overcome the disadvantages of the PI and PD Controllers, PID Controllers are being used. Certain advantages of the PID Controller are mentioned below. Some of the advantages of PID Controller are:

- It provides fast and stable responses.
- It eliminates steady-state error.
- It minimizes overshoot and oscillations.

To reduce the torque ripple which is produced in the Volts/Hertz speed control of induction motor, PID Controller is used as speed controller.

II. LITERATURE REVIEW :

Multilevel inverter topologies (MLIs) are increasingly being used in medium and high- power applications due to their many advantages such as low power dissipation on power switches, low harmonic contents and low electromagnetic interference (EMI) outputs.

The basic types of multilevel inverter topologies are: Diode clamped MLI, Flying capacitor MLI and Cascaded H-bridge MLI [1],[2]. Out of all the studies, the cascaded H-bridge is proved to be more efficient adopting lesser number of devices, providing better isolation between different voltage sources employed, modular nature etc. The sinusoidal pulse-width modulation provides better control.

The cascaded H-bridge multilevel inverters have a number of advantages like modular structure, lower THD, lower dv/dt, high voltage operation without switching devices in series[3]. There are two types of CHB-MLI. The first one having equal magnitude of DC sources in all the H-bridges known as symmetric type CHB-MLI. The second one having unequal magnitude DC sources in each H-bridge known as asymmetrical type CHB-MLI. For the same number of devices used in asymmetrical type CHB-MLI produces greater number of levels when compared to symmetrical type CHB-MLI.

A number of topologies of asymmetrical multilevel inverters are developed nowadays with reduced number of switching devices. All these topologies are developed with an aim to have lower THD while producing greater number of levels[4]. In a multilevel inverter, whichever topology it might be, there is a criterion with which the magnitude of the DC sources is to be selected. The output voltage which is produced by the multilevel inverter is the sum of small DC components and hence it represents the peak value of the output voltage. Hence, the magnitude of the DC sources is to be selected in such a way that the resultant peak output voltage generated by the multilevel inverter gives the required rms voltage[5].

Multicarrier pulse width modulation techniques based on different combinations of carrier and modulating signals are used: PD, POD, APOD and CO- PWM and other is phase-shifted PWM. Different types of modulating signals used are: sine wave, third-harmonic injected sine wave, modified sine wave and the trapezoidal wave of which sinusoidal PWM technique with POD scheme provides better performance[6].

There are various methods to control the speed of induction motor and each methodology has different problems associated with it such as speed variations, current and voltage ripple or harmonics. Out of all the speed control methods, Volts/Hertz control is found to be efficient[7].

To reduce the torque ripple which is produced in the Volts/Hertz speed control of induction motor when a PI controller is used. Generally, PI controller is used as a speed controller in Volts/Hertz speed control method. Due to the PI controller, the overshoot produced will be more and the system requires greater settling time and also the torque ripples produced will be more. To overcome all these, a PID controller is employed and it is found that the torque ripples are reduced[8].

III. MULTILEVEL INVERTER TOPOLOGY USED :

The circuit includes twenty switches wherein all the switches are in the 5 cascaded H- bridges. S_1, S_2, S_3, S_4 form the first H-bridge, S_5, S_6, S_7, S_8 form the second H-bridge. S_9, S_{10}, S_{11}, S_{12} form the third H-bridge, S_{13}, S_{14}, S_{15}, S_{16} form the fourth H-bridge and S_{17}, S_{18}, S_{19}, S_{20} form the fifth H-bridge. Hence these switches should have a minimum voltage rating as the MLI's operating voltage. The proposed sixty-three level MLI includes five DC sources which are in binary configuration. In the fig.1 shown below, the circuit diagram consists of only two bridges for convenience. There are three more bridges similar to the two bridges shown in the fig. 1. The magnitudes of the DC sources are unequal and taken as V_{dc}, $2V_{dc}$, $4V_{dc}$ and $8V_{dc}$,$16V_{dc}$.

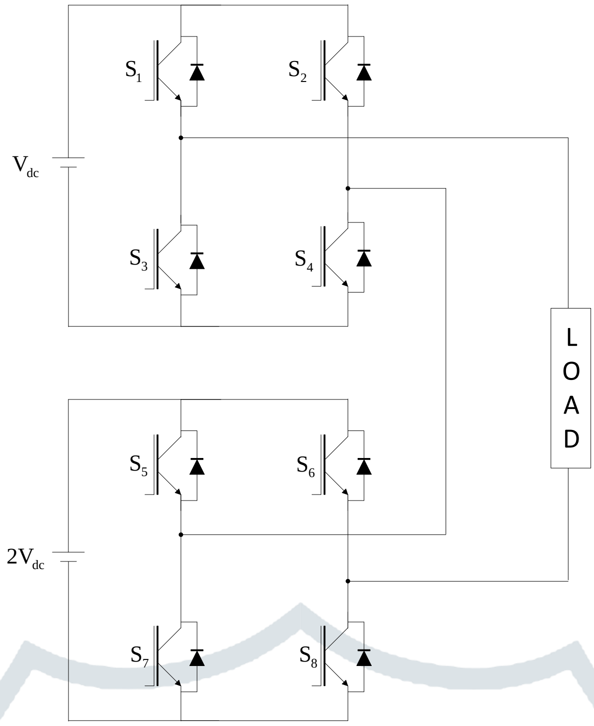

Fig. 1 Sixty-three Level MLI with Power Switches

3.1 Operation :

Multilevel Sinusoidal pulse width modulation (SPWM) is used due to its simplicity and better results suited for motors. Triangular carrier waves and sinusoidal reference wave are used. Number of carrier waves used for ‘n’ level inverter is ‘n-1’. Hence, 62 carrier waves are used for 63-level inverter. The reference wave and the carrier waves are given to the comparator and reference wave is compared with the multiple carrier waves generating required gating signals. SPWM-POD is used in which carrier wave compared with positive and negative half cycles of reference wave are in phase opposition with each other.

3.2 Switching Sequence :

The switching sequence in which the switches are turned on is as follows. Some of the operating states are explained as follows:

- State 0: Switches S_1, S_2, S_5, S_6, S_9, S_{10}, S_{13}, S_{14}, S_{17}, S_{18} are in ON state and hence load current flows through the path S_1-load-S_{18}-S_{17}-S_{14}-S_{13}-S_{10}-S_9-S_6-S_5-S_2-S_1. Hence the load voltage V_L=0.
- State 15: Switches S_{13}, S_{12}, S_9, S_8, S_5, S_4, S_1, S_8, S_{17} and S_{16} switches are in ON state and the load current flows through the path V_4(+)-S_{13}-S_{12}-V_3(-)-V_3(+)-S_9-S_8-V_2(-)-V_2(+)-S_5-S_4-V_1(-)-V_1(+)-S_1-load-S_{18}-S_{17}-S_{16}-V_4(-). Therefore, the load voltage, $V_L=V_1+V_2+V_3+V_4=15V_{dc}$.
- State 31: Switches S_{17}, S_{16}, S_{13}, S_{12}, S_9, S_8, S_5, S_4, $S_1$and S_{20} switches are in ON state and the load current flows through the path V_5(+)-S_{17}-S_{16}-V_4(-)-V_4(+)-S_{13}-S_{12}-V_3(-)-V_3(+)-S_9-S_8-V_2(-)-V_2(+)-S_5-S_4-V_1(-)-V_1(+)-S_1-load-S_{20}-V_5(-). Therefore, the load voltage, $V_L= V_1+V_2+V_3+V_4+V_5 =31V_{dc}$
- The circuit operates similarly in the negative half cycle.

Table 1 Switching sequence of Sixty-three MLI

O/P Voltage	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}
31 V_{dc}	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
30 V_{dc}	1	1	0	0	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
29 V_{dc}	1	0	0	1	1	1	0	0	1	0	0	1	1	0	0	1	1	0	0	1
28 V_{dc}	1	1	0	0	1	1	0	0	1	0	0	1	1	0	0	1	1	0	0	1
27 V_{dc}	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	1	1	0	0	1
26 V_{dc}	1	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1	1	0	0	1
25 V_{dc}	1	0	0	1	1	1	0	0	1	1	0	0	1	0	0	1	1	0	0	1
24 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	1	0	0	1	1	0	0	1
23 V_{dc}	1	0	0	1	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	1
22 V_{dc}	1	1	0	0	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	1
21 V_{dc}	1	0	0	1	1	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1
20 V_{dc}	1	1	0	0	1	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1
19 V_{dc}	1	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0	1	0	0	1
18 V_{dc}	1	1	0	0	1	0	0	1	1	1	0	0	1	1	0	0	1	0	0	1
17 V_{dc}	1	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0	1	0	0	1
16 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	0	0	1

15 V_{dc}	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	1	0	0
14 V_{dc}	1	1	0	0	1	0	1	1	1	0	0	1	1	0	0	1	1	1	0	0
13 V_{dc}	1	0	0	1	1	1	0	0	1	0	0	1	1	0	0	1	1	1	0	0
12 V_{dc}	1	1	0	0	1	1	0	0	1	0	0	1	1	0	0	1	1	1	0	0
11 V_{dc}	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	1	1	1	0	0
10 V_{dc}	1	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1	1	1	0	0
9 V_{dc}	1	0	0	1	1	1	0	0	1	1	0	0	1	0	0	1	1	1	0	0
8 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	1	0	0	1	1	1	0	0
7 V_{dc}	1	0	0	1	1	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0
6 V_{dc}	1	1	0	0	1	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0
5 V_{dc}	1	0	0	1	1	1	0	0	1	0	0	1	1	1	0	0	1	1	0	0
4 V_{dc}	1	1	0	0	1	1	0	0	1	0	0	1	1	1	0	0	1	1	0	0
3 V_{dc}	1	0	0	1	1	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0
2 V_{dc}	1	1	0	0	1	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0
1 V_{dc}	1	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
0 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
-1 V_{dc}	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
-2 V_{dc}	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	0
-3 V_{dc}	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	0
-4 V_{dc}	1	1	0	0	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0
-5 V_{dc}	0	1	1	0	1	1	0	0	1	1	1	0	1	1	0	0	1	1	0	0
-6 V_{dc}	1	1	0	0	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0
-7 V_{dc}	0	1	1	0	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0
-8 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	0	1	1	0	1	1	0	0
-9 V_{dc}	0	1	1	0	1	1	0	0	1	1	0	0	0	1	1	0	1	1	0	0
-10 V_{dc}	1	1	0	0	0	1	1	0	1	1	0	0	0	1	1	0	1	1	0	0
-11 V_{dc}	0	1	1	0	0	1	1	0	1	1	0	0	0	1	1	0	1	1	0	0
-12 V_{dc}	1	1	0	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	0	0
-13 V_{dc}	0	1	1	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	0	0
-14 V_{dc}	1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	1	1	0	0
-15 V_{dc}	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	1	1	0	0
-16 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	0	1	1	0
-17 V_{dc}	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	0	0	1	1	0
-18 V_{dc}	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	1	1	0
-19 V_{dc}	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0	0	1	1	0
-20 V_{dc}	1	1	0	0	1	1	0	0	1	1	1	0	1	1	0	0	0	1	1	0
-21 V_{dc}	0	1	1	0	1	1	0	0	0	1	1	0	1	1	0	0	0	1	1	0
-22 V_{dc}	1	1	0	0	0	1	1	0	0	1	1	0	1	1	0	0	0	1	1	0
-23 V_{dc}	0	1	1	0	0	1	1	0	0	1	1	0	1	1	0	0	0	1	1	0
-24 V_{dc}	1	1	0	0	1	1	0	0	1	1	0	0	0	1	1	0	0	1	1	0
-25 V_{dc}	0	1	1	0	1	1	0	0	1	1	0	0	0	1	1	0	0	1	1	0
-26 V_{dc}	1	1	0	0	0	1	1	0	1	1	0	0	0	1	1	0	0	1	1	0
-27 V_{dc}	0	1	1	0	0	1	1	0	1	1	0	0	0	1	1	0	0	1	1	0
-28 V_{dc}	1	1	0	0	1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0
-29 V_{dc}	0	1	1	0	1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0
-30 V_{dc}	1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
-31 V_{dc}	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0

IV. VOLTS/HERTZ SPEED CONTROL OF MULTILEVEL INVERTER FED INDUCTION MOTOR USING PID CONTROLLER :

From the discussions in the literature review, it is seen that variable voltage and variable frequency speed control is the best method of speed control, in which the induction motor is fed from a VSI which suffers from a lot of drawbacks. Here an idea of employing an MLI in place of VSI to obtain reduced harmonic content in the supply to the induction motor and thereby investigating the performance of the closed loop speed control drive.

4.1 Speed Control Model :

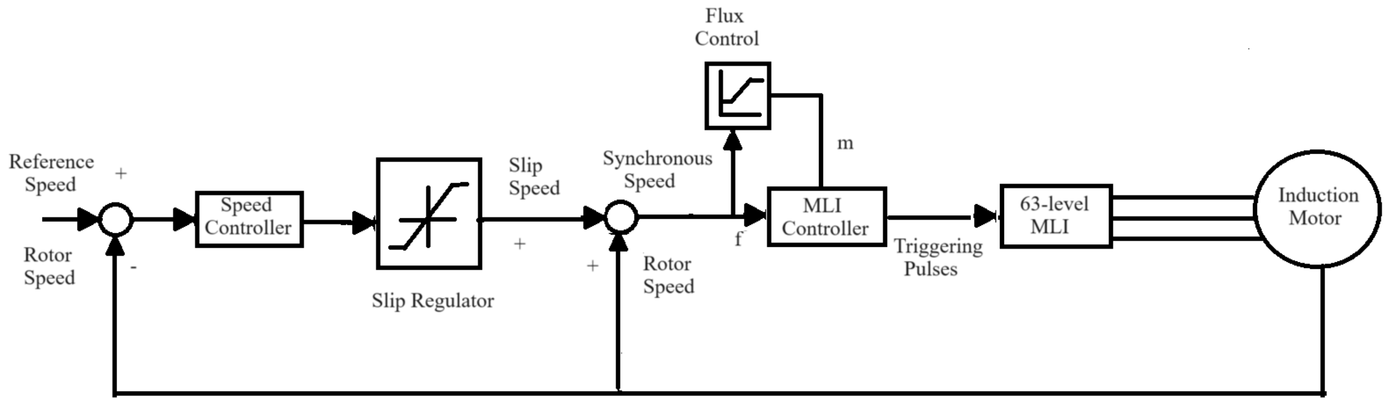

Fig. 2 Block Diagram of the Speed Control Model

As shown in the block diagram fig.2 , the actual speed of the rotor is compared with the reference speed in a comparator and a speed error is generated which is the slip-speed. This mechanism is the feedback mechanism which provide quality of automation to the control system. The speed error is fed to the speed controller which processes the speed error and generates a controlled output i.e., the slip-speed with reduced noise and good steady-state accuracy. In the proposed model, conventional PID controller is used. This controller performs proportional, integral and derivative operations on the speed error and finally generates the controlled output.

This controlled output obtained from the PID controller is fed to a slip regulator which controls the slip thereby limiting the operation of the motor in the stable region of torque-speed characteristics i.e., from the synchronous speed to the speed corresponding to the maximum torque. Also, the stator currents and the torque produced are limited within safe value by controlling the slip otherwise the stator windings get heated up. This controlled and regulated slip-speed is added with the rotor speed to obtain the synchronous speed. The synchronous speed in mechanical rad/sec is given by,

$$\omega_s = 4\pi f/P \quad (1)$$

$$\omega_s \; \alpha \; f \quad (2)$$

Hence, the synchronous speed obtained above is an indirect information about how the inverter frequency should change. In order to maintain the air-gap flux constant, the magnitude of the supply voltage should be changed along with the frequency. This is done in this flux control block. It generates the three-phase reference signal of desired frequency and modulation index for the Sinusoidal Pulse Width Modulation control of multilevel inverter that feeds the induction motor. Hence, the magnitude and frequency of supply voltage to the induction motor is changed, and therefore the speed of the induction motor is changed accordingly.

V. SIMULATION AND RESULTS :

5.1 Simulation of MLI :

To verify the effectiveness of the used topology a simulation model is developed with MATLAB/SIMULINK tool. Five input DC sources with V_1=10.5V, V_2=21V, V_3=42V, V_4=84V, V_5= 168V are used. A carrier frequency of 400Hz is taken. The Simulink model is shown in Fig.3

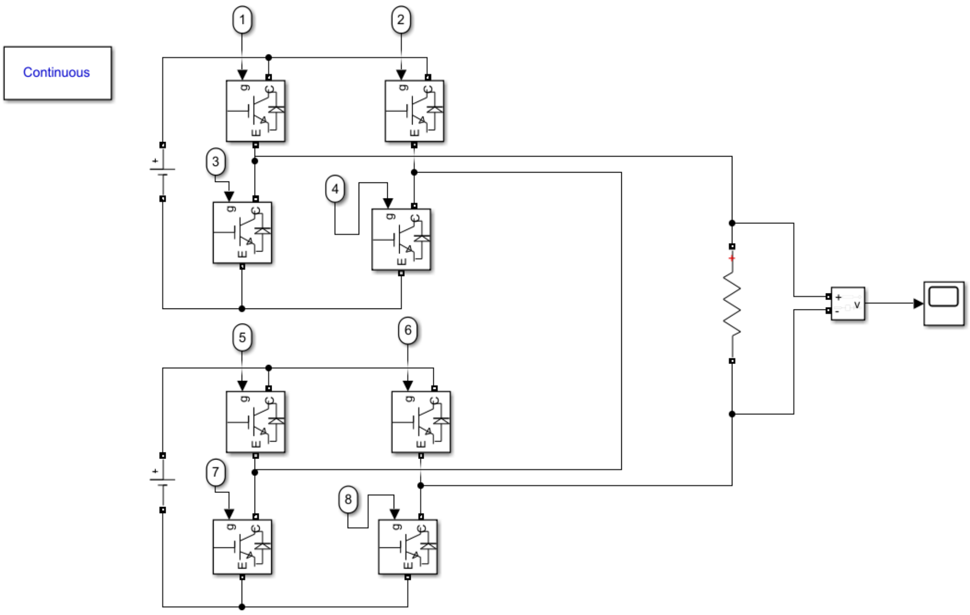

Fig. 3 Simulation model of the multilevel inverter

5.2 Simulation of Speed Control Model :

The proposed speed control model is simulated using MATLAB/SIMULINK tool as shown in Fig. 4. A three-phase squirrel-cage induction motor of rated voltage 400V and speed 1500rpm is chosen. From the motor parameters the slip-speed value corresponding to the maximum speed is found to be 55.8rps. Hence, this value is chosen a limiting value in slip regulator. In the design of the PID controller, the proportional, integral and derivative gains are selected to be 1.2, 1, 0.005 respectively.

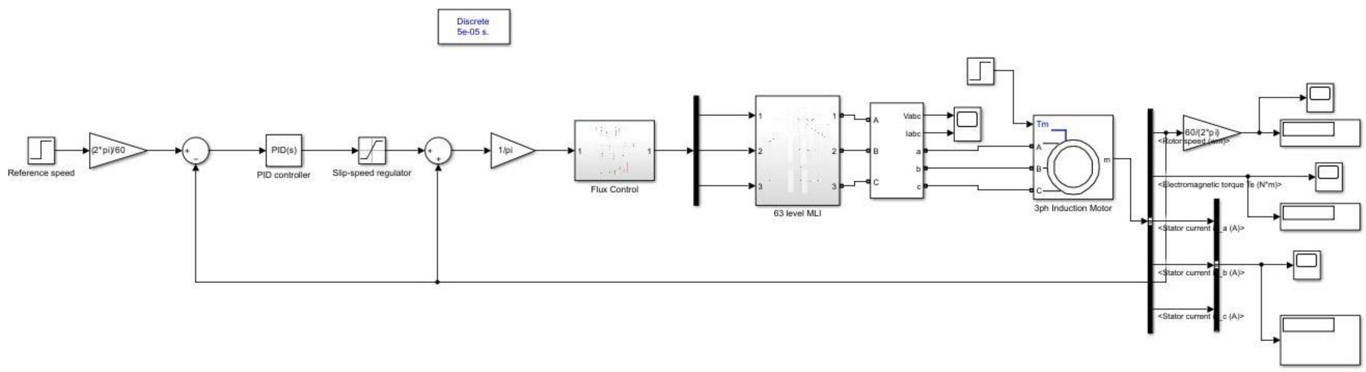

Fig. 4 Simulation model of the speed control model

Fig. 5 shows the simulation model of the flux control block which limits the frequency to 50Hz which is the rated frequency and produces the three-phase modulating signal of required frequency. The voltage is boosted to a slightly higher value at low frequencies to overcome the stator resistance drops.

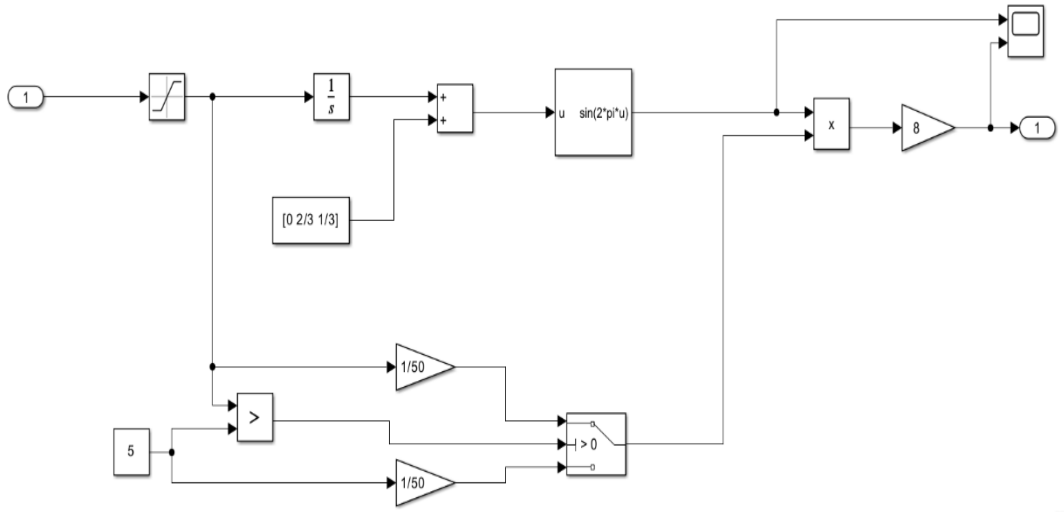

Fig. 5 Simulation model of the flux control block

5.3 Simulation Results :

The carrier waves compared with the reference sine wave for switching signals generation is shown in fig. 6. The output voltage V_L and its harmonic order are shown in Fig. 7 and Fig. 8 respectively. The voltage waveform comprises of sixty-three levels. Peak value of output voltage obtained is $V_1+V_2+V_3+V_4+V_5$ = 325V and total harmonic distortion (THD) of 2.56% without filter is obtained.

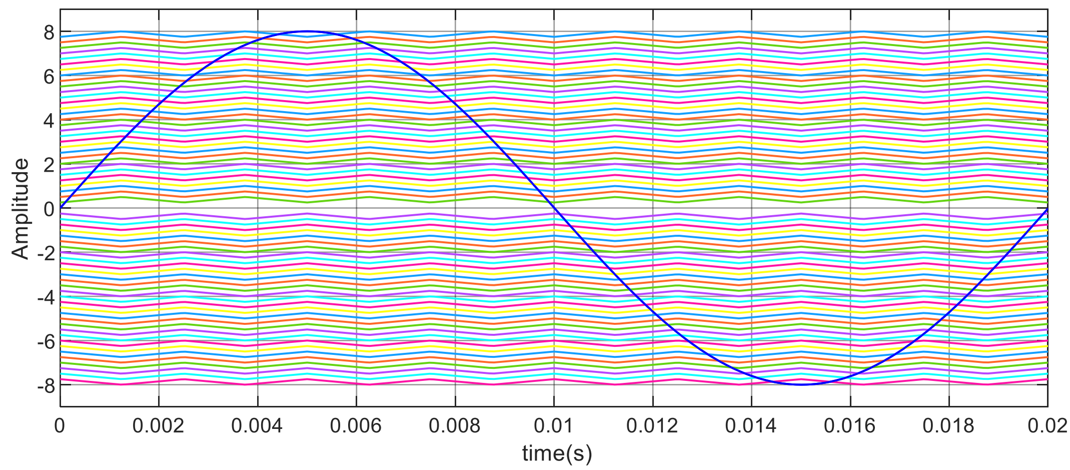

Fig. 6 Carrier waves compared with the reference wave

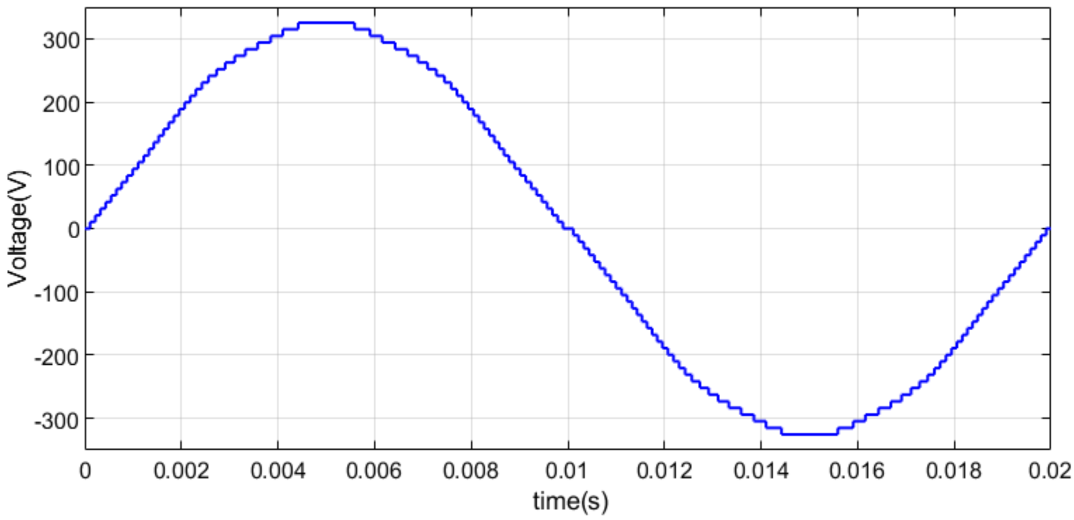

Fig. 7 Output Voltage Waveform of the Sixty-three Level MLI

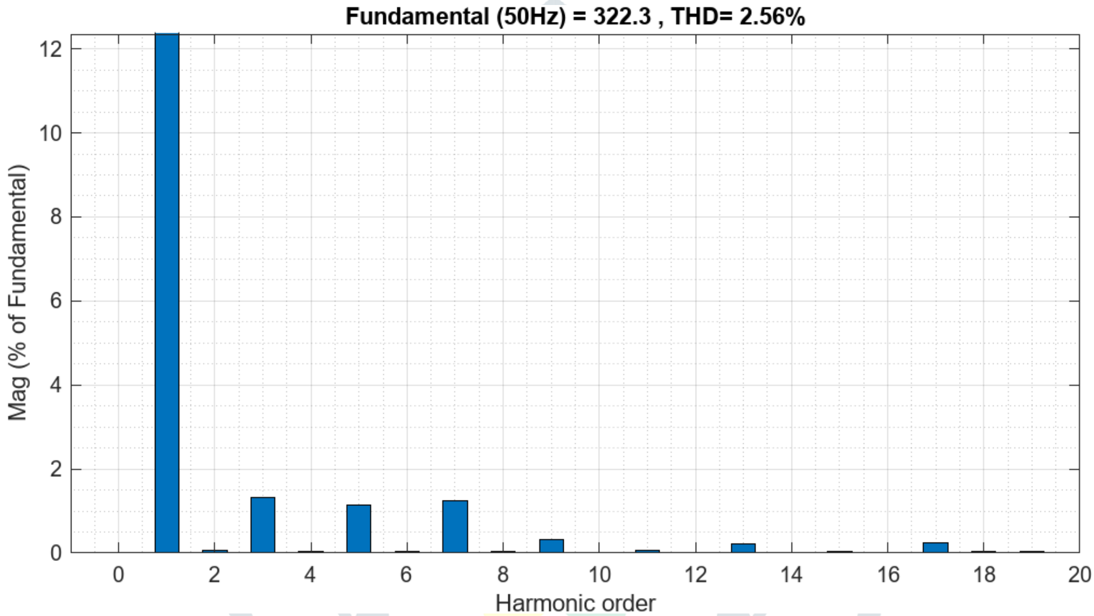

Fig. 8 Total harmonic distortion for the Sixty-three Level MLI

To test the viability of the proposed model it is tested under two conditions:
1)Variable speed and Constant load torque &
2)Constant speed and Variable load torque

Case 1: Variable speed and Constant load torque:

The motor torque is kept constant at 20N-m and the speed is given a step change from 1000rpm to 1400rpm at t=2s and again to 700rpm at t=4s. The speed, torque, stator current responses and MLI output obtained using each controller are as follows.

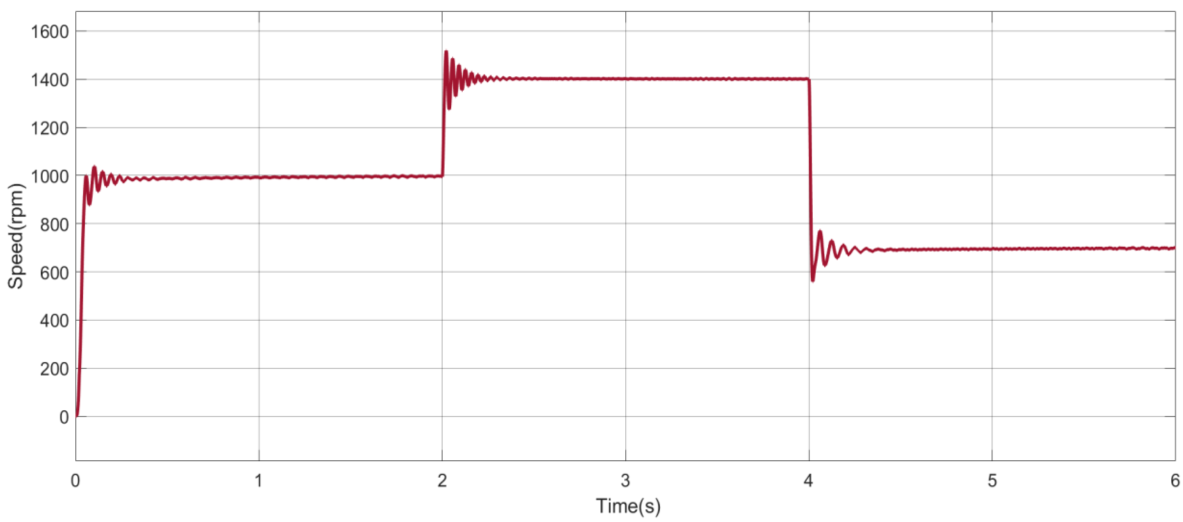

Fig. 9 Variations in speed response using PID controller

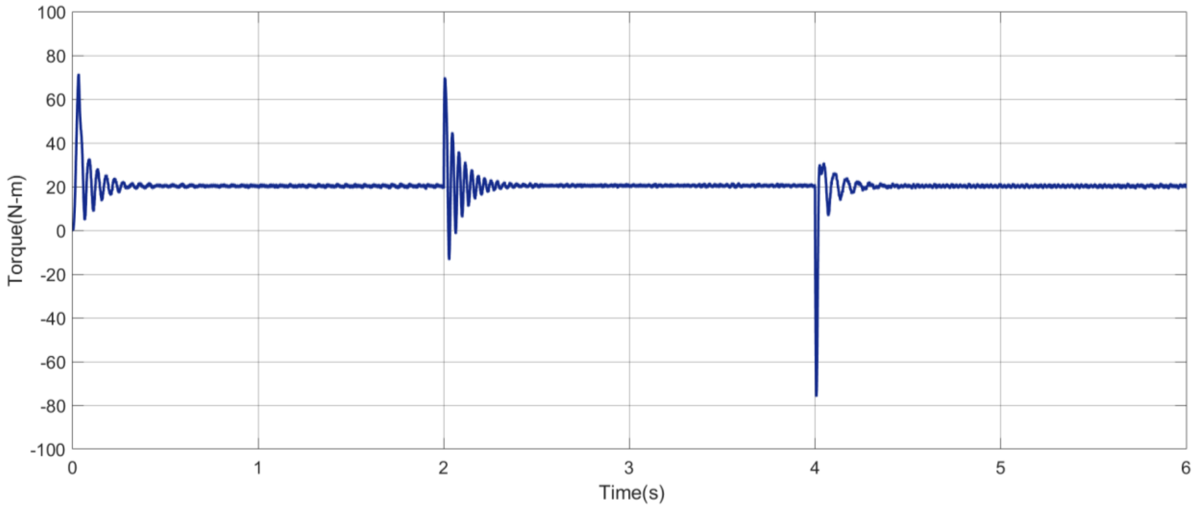

Fig. 10 Variations in torque response using PID controller

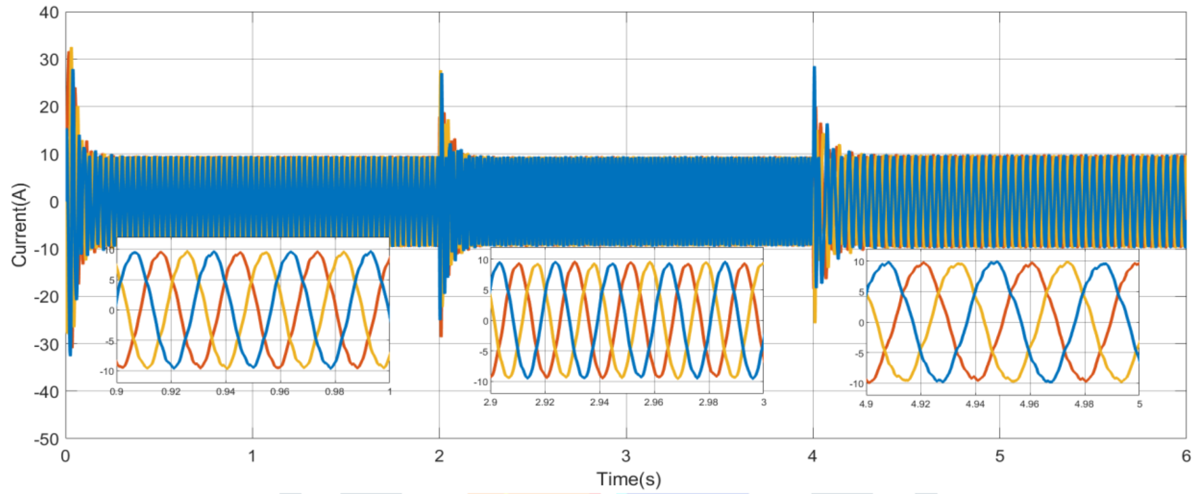

Fig. 11 Variations in stator currents using PID controller

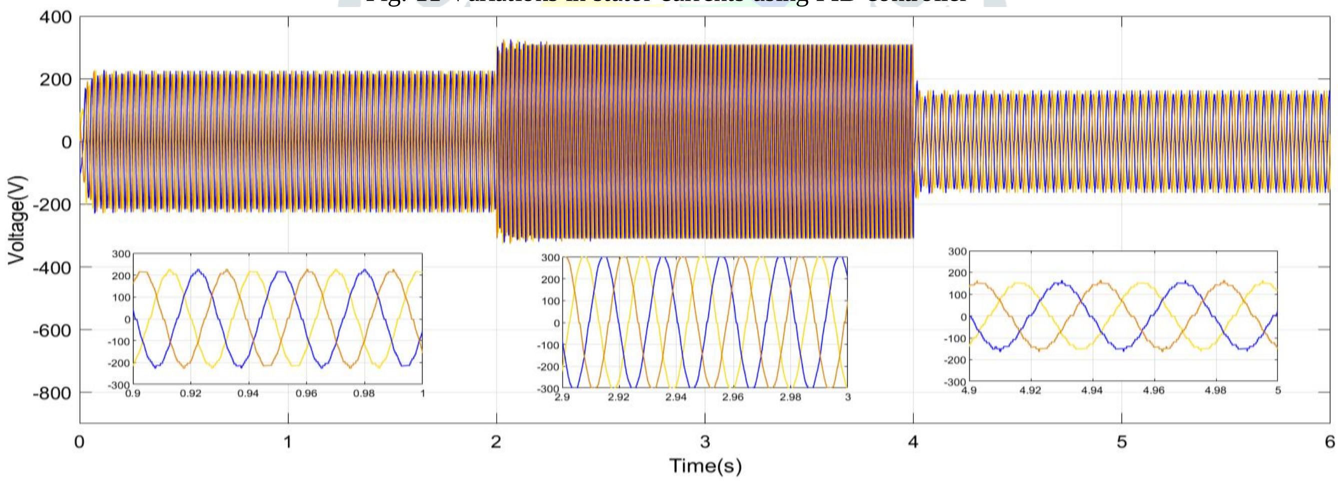

Fig. 12 Variations in MLI output using PID controller

It is observed that the motor tracks the reference speed precisely. The magnitude and frequency of the MLI is observed to be changing with the reference speed as anticipated. The torque ripples are observed to be low. Overshoots in torque response as well as in the stator currents are observed for every speed change. The development of this higher amount of torque is to drive the motor to the required reference speed. Overshoots are also observed in the speed response which required less than 1sec to get settled down.

Case 2: Constant speed and variable load torque:

The motor speed is kept constant at 1200rpm and the load torque is given a step change from 5N-m to 30N-m at t=2s. The speed, torque, stator current responses and MLI output obtained using each controller are as follows.

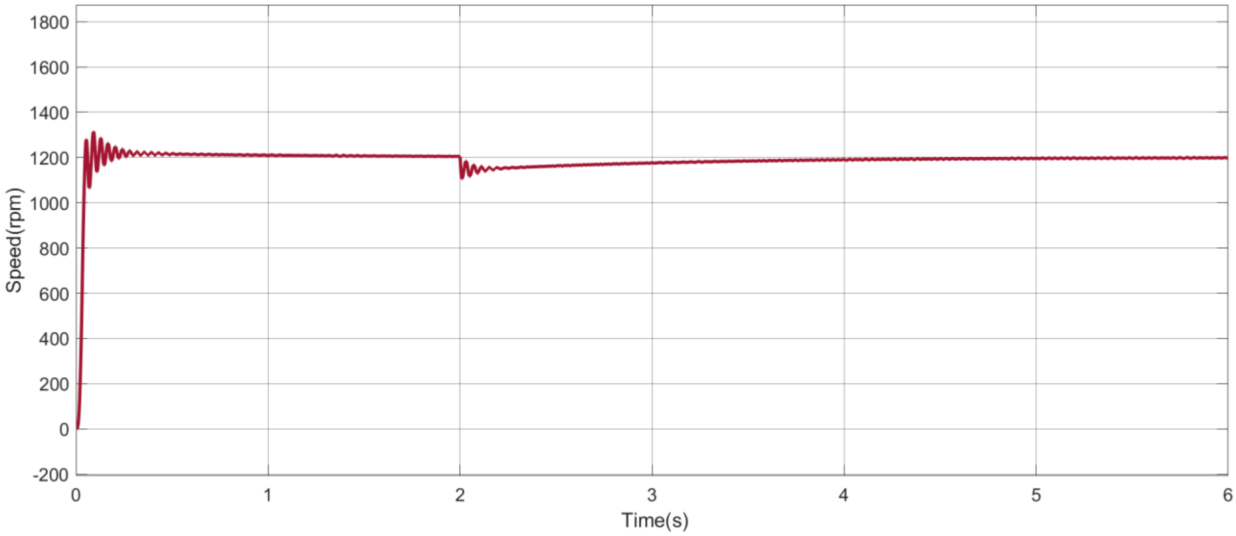

Fig. 13 Variations in speed response using PID controller

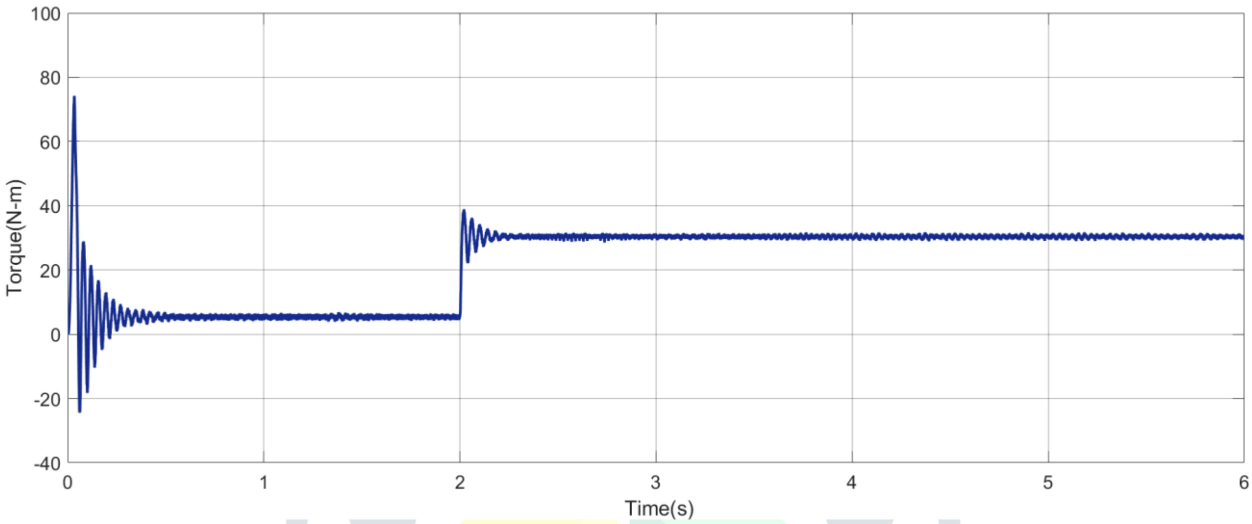

Fig. 14 Variations in torque response using PID controller

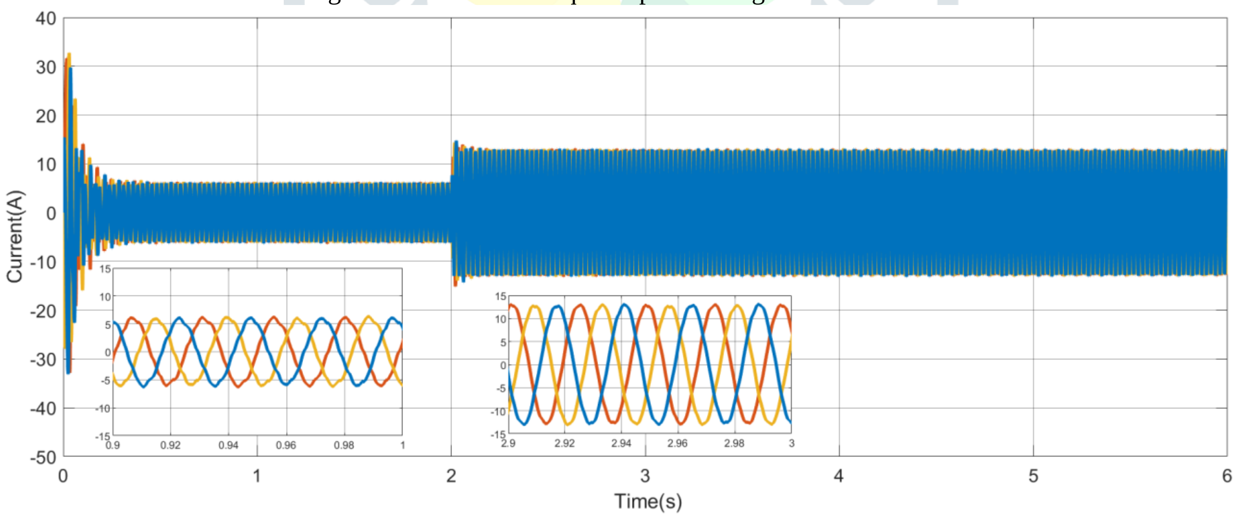

Fig. 15 Variations in stator currents using PID controller

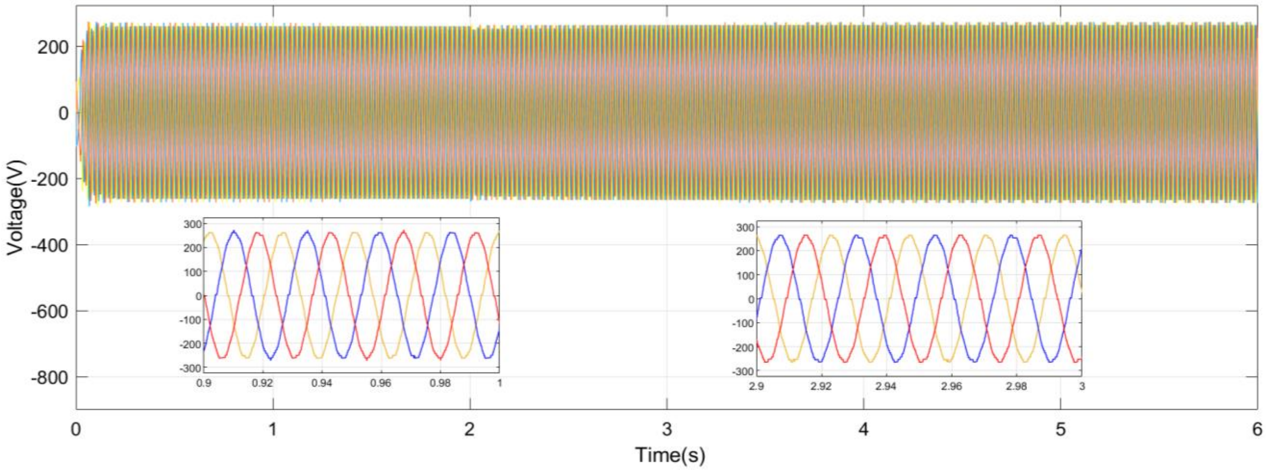

Fig. 16 Variations in MLI output using PID controller

It is observed that the motor tracks the reference speed precisely even when the load torque on the motor is changed. Approximately after 2sec after the load change, the motor was able to run at the reference speed. The motor developed the required electromagnetic torque to drive the load. The magnitude and frequency of the stator currents and also the MLI output is also varied in order to develop the required torque.

VI. Conclusion :

The volts/hertz closed loop control scheme for Multilevel inverter fed induction motor is developed in MATLAB/SIMULINK. 63-level Multilevel inverter is employed. The model is simulated using conventional PID Controller in two cases i.e., reference speed change and load torque change.

From the results it is evident that the torque and current ripples are reduced to a great extent, harmonic distortion in input supply voltage to induction motor i.e., multilevel inverter output and in stator current are also reduced, power loss is reduced and hence efficiency is increased as compared to two-level inverter employing open loop control. The controller provided good response.

Hence, this model of volts/hertz control of Multilevel inverter fed induction motor can be employed in small, medium and high-power applications with optimum use of input power using PID Controller depending on the application.

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