Design and Analysis of Motor-Controller for Permanent Magnet Synchronous Motor using Three Level Inverter with FOC Control

Darshan Tagare[1], Shrusti Gadhe[2], Aarti Pawar[3]

[1-3]*Department of Electronics and Telecommunication, Pimpri Chinchwad College of Engineering, Pune, India*

Abstract - *In this paper we will see the design and analyze of motor controller for PMSM motor with three level invert using FOC control algorithm .The main aim of designing is to reduce the total harmonic distortions less than 15% .Electric motors are fastly becoming part of our daily life as it is used in various applications like Electric vehicles, Household appliances, pumps and compressors, robotics, aircraft, etc. an electric motor is controlled using a motor controller. Motor-controllers are responsible for the smooth speed and torque control of the motor and are also responsible for the output power efficiency of the system. The use of Permanent Magnet Synchronous motor is increasing but to drive the motor there are no efficient, stable and tunable Inverter/motor controller. These days controller and inverter that are used majorly are two level inverter which increases the size of the product and also the Total Harmonic Distortion is high which decrease the stability. The control algorithm previously used were Direct Torque control or scalar control method which have high torque, flux ripple and poor dynamic response at low speed So in this study we will be approaching towards Field Oriented Control algorithm.*

***Key Words*: Field oriented Control, Three level inverter, Neutral point clamp inverter, Permanent Magnet Synchronous Motor controller**

1.INTRODUCTION

An electric Vehicle runs on Electric motor and not a combustion engine. As in the past decade there has been a rise in carbon contamination and other environmental effects of fuel based vehicles the concept of electric vehicle has drawn a lot of interest and thus electric motors of medium and high powers have also received a lot of attention [1] .A scheme was introduced and which was in action from April 1 2019,the union Cabinet cleared the 10000-crore program. The objective of this scheme is to boost the growth of electric and hybrid vehicles by offering upfront incentive on purchase of electric vehicle and also establishing charging infrastructures. There are many different motors which are used for medium and high power applications like induction motor, Brushless DC motor, permanent magnet Synchronous motor. It is predicted in a report by Adamas intelligence that over 80 percent of EV's to use PMSM motor in upcoming year [2].Permanent magnet synchronous motor(PMS) is the most serious competitor to other motors as they have advantages like high power density, higher efficiency, high starting torque, and high torque density, Permanent magnet synchronous motor are 15% more efficient to their counterpart induction motor and are also the highest power dense motor commercially available. As there is an immense demand of Permanent magnet synchronous motors globally ultimately there is an equal need of motor controllers to control those motors. As batteries are DC source and motor required 3 phase AC, Inverter needs to be implemented to convert DC to 3 phase AC. Hence, motor controllers for 3 phase AC motors consist of Inverter stage and controller stage. Different Control algorithms are used to control a PMSM motor like direct torque control, Field Weakening control, Field Oriented control etc. In this paper Field oriented control with Three level inverter is studied. As At higher frequencies three level inverter decreases the total inverter losses whereas the losses are more in two level inverter. But the three level inverter requires more power switches compared to two level inverter. Having more power switches has an advantage as it reduces the voltage stress on individual switches. Phase conductor size associated losses and DC link current is reduced as three levels allow an increase in DC link voltage. The two level have higher thermal stresses as compared to three level at higher DC bus voltage.

1.1 Comparison Of inverter topology

The DC to AC power conversion technology is growing in the area of High power and medium voltage application [3].There are many different topologies used to convert DC to AC power each topology have their advantages and disadvantages. The DC to AC power conversion can be classified in two major topologies as shown in figure 1 i.e. Current Source and Voltage source. The Voltage source is again divided in two categories i.e. 2 level inverter and multi-level inverter. Multilevel inverters are preferred over two level inverter in medium and high power conversions as there are various advantages like the voltage stress on individual power switches is lower and also the total harmonic components in the line to line voltages applied to the load are less [4].It also has lower common mode voltage and lower dv/dt ratio to supply lower harmonic conversion in output current and voltage. Therefore Multilevel inverters are gaining more attention.as the technologies are improving different topologies in multilevel inverter, There are three major multilevel inverter topologies which have been used .

1)Cascade Bridge with separate DC sources

2)Diode clamped(neutral clamped)

3) Capacitor clamped (Flying capacitor)

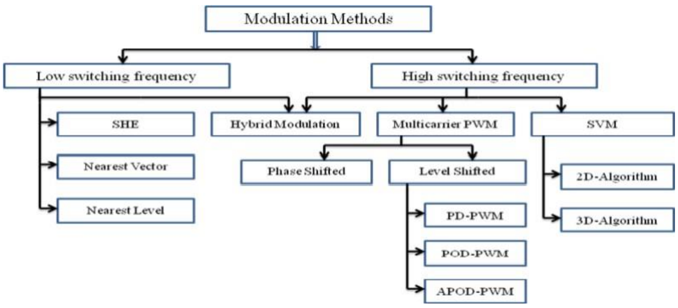

Fig -1: Classification of different inverter topologies

1.1.1 Cascade bridge multilevel inverter

Due to the modular structure of cascade H-bridge which solves voltage imbalance found in Neutral clamp and capacitor clamp it is very extensively used [5].A power conversion cell with individual isolated dc source on dc side which are generally obtained from fuel cells, batteries or else ultra-capacitors are present in a cascade H-bridge inverter. Reduced voltage imbalance can be considered as the main advantage of this topology but The main disadvantage of this topology is that isolated dc Source are required for each cell in each phase. The voltage which appears in common at both input terminals of a device with respect to the output is called as common mode voltage this voltage produces common mode current which generates losses in the system and grid current distortion. Common mode voltage can be eliminated if appropriate modulation scheme is used for this topology. Cascade bridge inverter produces very good sinusoidal output so only a smaller filter or in some cases no filter is required. The no of devices required are higher in NCP and FC inverter topologies as compared to Cascade bridge topology .The switches in this topology are not over stressed or overloaded as their load power is distributed properly, it also does not require clamping diodes or flying capacitors as required in different topologies. The only problem with cascade bridge is that it requires many isolated DC sources and link voltage controllers.

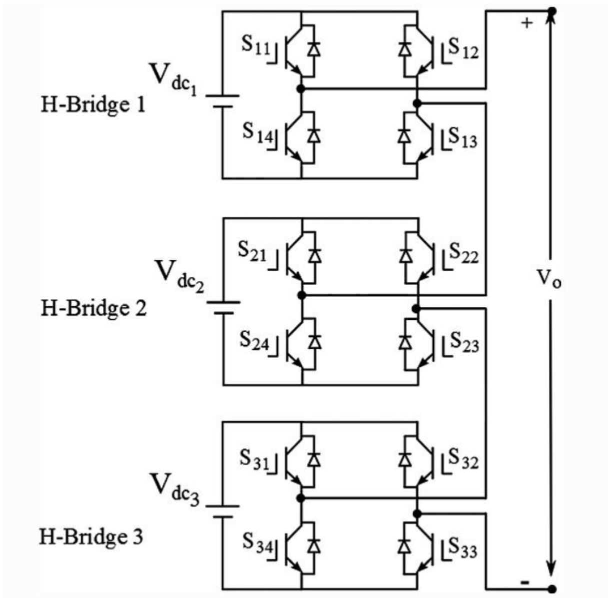

Fig -2: Cascade bridge multilevel inverter

1.1.2 Diode clamped (neutral point clamped) multilevel inverter

In diode clamped inverter the voltage is dividing in two equals of the supply voltage this is ensured by the two clamping diodes which clamps the switch voltage to the half of Supply voltage this is held at these points with neutral point between them. The voltage at midpoint is called as neutral point hence the name neutral point clamped. Capacitors are placed in series. Diodes are used to generate multiple voltage levels from the different phase of this capacitor bank. The capacitors are used to stiffen the DC bus voltage and to provide low impedance path for high frequency currents, they can also be precharged as a group. This topology provides higher efficiency the frequency used for switching devices is the fundamental frequency and so the method of back to back power transfer system is simple. Following equation is used to find out the number of devices required for any level of diode clampe inverter. Consider (n) as the number of levels and (k) as the capacitor used at the DC.The number of freewheeling diode(f) per phase can be calculated by using equation number 2 and the number of clamped diodes(d) also can be calculate by using equation number 3.[9]

$k=n-1$…………(1)

$f=2(n-1)$..........(2)

$d=(n-1).(n-2)$....(3)

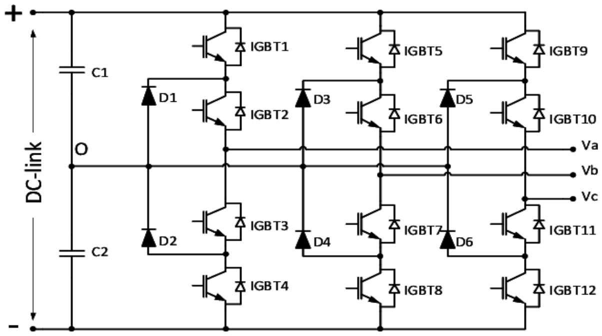

Fig -3: Diode clamped (neutral point clamped) multilevel inverter

1.1.3 Capacitor clamped (Flying capacitor)

The problem of static and dynamic sharing of voltage across the switches which is seen in Neutral point clamped topology is removed in the Flying capacitor topology. Instead of clamping Diodes used in NPC Flying capacitor topology uses capacitors. The working ,structure and switching pattern is similar to NPC topology .The capacitors which are used instead of the clamping diode are independent of the other capacitors in the circuit. The topology is called flying capacitor as the flying capacitor used only transfer a limited voltage to electrical device, with independent capacitors clamping the device voltage to one capacitor voltage level. Some of the Major Drawbacks of this topology is that the numbers of required capacitors are more in the circuit. If the operating voltage is high then the capacitor required should also be that of the same rating for high voltage steps which is a major issue for high voltage system, Also precharging all the capacitors is difficult and complex in this topology. Due to the switching redundancy in this topology the efficiency is poor for real power transmission. The other Problem with this inverter same as NCP inverter is that the maximum output AC voltage is half of the input voltage DC voltage.[8].As the Voltage source can only be used as a single dc source so The cascade H bridge is avoided and due to the different disadvantages mentioned of Flying capacitor over NPC topology, NPC topology is further studied and different control strategies are studied for the same.

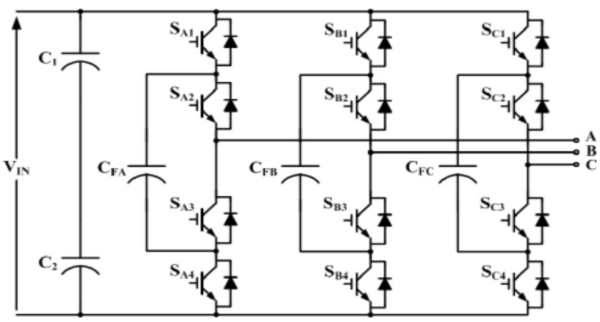

Fig -4: Capacitor clamped inverter

1.2 Control Strategies for Three level inverter for PMSM

The Factor which determines the Performance of a multilevel inverter is the control or modulation technique used. Majorly in Synchronous motors the control schemes are divided in two types 1) Scalar control 2) vector Control. Scalar Control as name suggests, is based on varying two parameters simultaneously. The speed is varied by increasing or decreasing the supply frequency, but these results in change of impedances eventuates the increase or decrease in current. It is necessary to vary the frequency and the voltage at the same time.[10]The vector Control methods are of different types like Field oriented control and Direct torque control. In PMSM a decoupled control of the Torque and flux magnitudes are done. d-q transformation is used to for that, in this the d and q components are separated of the stator current responsible for flux and torque production respectively. As there is flux of the permanent magnet there is no need to generate flux using is d current. This current can be kept to zero increasing the efficiency of the driver. The field control ensures good and robust control in case of transients**[10][11]**.A a basic block diagram of FOC control is show in the below diagram

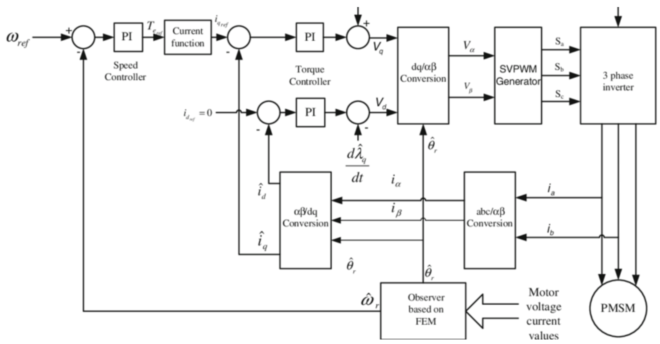

Fig -5: Basic block diagram of Field oriented control

In Direct torque control the torque control is done by changing the angle between the stator flux and the Permanent magnet flux .The angle between them can be changed by changing the Stator voltage. The conventional DTC has problems such as large torque ripple and variable switching frequency. [11][12] As the FOC provides high performance response behavior response with steady state behavior, FOC using PWM control method can be better for PMSM in electric vehicle applications and more.

1.3 DC link imbalance

The DC link voltage imbalance is considered a major concern and drawback in NCP topology inverter. Many studies are done recently worldwide to remove this problem this problem should be solved correctly while designing NCP inverter. There are different methods to avoid this problem. First is to select a capacitor of higher capacitance this can increase the overall cost and volume of the system.

Depending on the application requirement there exist different topologies to balance the DC link voltage. The known two types of DC link capacitor voltage balancing scheme are; Hardware and PWM based control techniques. Two separate rectifiers are used to keep the two capacitors balanced in hardware scheme [14], The total system cost is increased as it requires two transformers with isolated secondary windings. Hence they are not efficient and have larger volume and are costly. A back to back NPC converter can replace this type of transformer. Again, PWM based control strategies for 3-level inverters can be divided into three categories: 1. Selective-harmonic-elimination (SHE), 2. Carrier-based PWM (CB PWM), 3. Space vector PWM (SV-PWM). [13].

2. PROPESED DESIGN

As Studied above Field oriented control has various advantages over scalar control for medium and high power systems required in applications like electric vehicles. The FOC with PWM which can increase controllability and tenability. Neutral point clamped topology for three levels is opted as it has different advantages as studied above. The design is done with three levels as above three levels the complexity, cost and Space volume also increase which is not suitable for the application such as electric vehicle. The Selection of the DC link capacitor is a crucial part as DC link imbalance is seen in NPC topology .Film capacitor are selected over Al-electrolytic capacitors as Film capacitors have very low ESR(Equivalent Series Resistance) which gives them much better ripple current ratings. They are also more tolerant of voltage over stress and significantly increase system reliability and lifetime. To avoid Dc imbalance in the capacitor the values of the capacitors are selected using MATLAB simulations. The components which are to be used are mentioned in Table 1.

Table -1:

Sr.no	Components	Product name
1	DC link capacitor	B32678G3107 (polypropylene film capacitor)
2	Switch	IGBT module (SEMiX405MLI07E4)
3	Gate Driver	SKYPER 42 LJ R
4	Motor controller	C2000 Delfino MCU F28379D LaunchPad™ development kit

The basic System block diagram is as shown below in figure 6

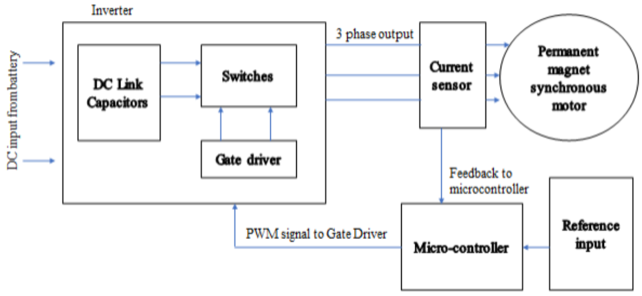

Fig -6: System block diagram

3. SIMULATIONS

The simulations parameters of the proposed system are given in Table 2

Table -2:

Sr.no	Parameters	Specification
1	Output power	80kW
2	DC link voltage	480V
3	Capacitor capacitance	480uF
4	ESR of capacitor	0.9mOhms
5	Switching frequency	10kHz
6	Max current	150A

A 3 level inverter model is developed by using seascape N-channel IGBT blocks. The sinusoidal pulse width modulation technique is used. The switchin frequency is set at 10kHz. Switching frequency can be iterated to optimum values based on THD, power losses etc.

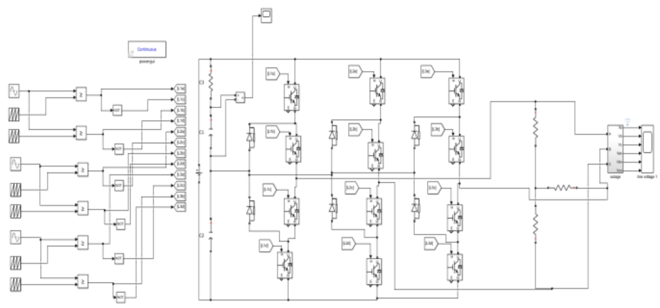

Fig -7: Three level three phase NPC inverter MATLAB model

As mentioned above the value of the DC link capacitor was selected using MATLAB model. When the Dc link capacitor value is kept 100uF the Voltage deviation (Vdel) is seen upto

300V.So the output voltage is also distorted as seen in figure 8 and 9.

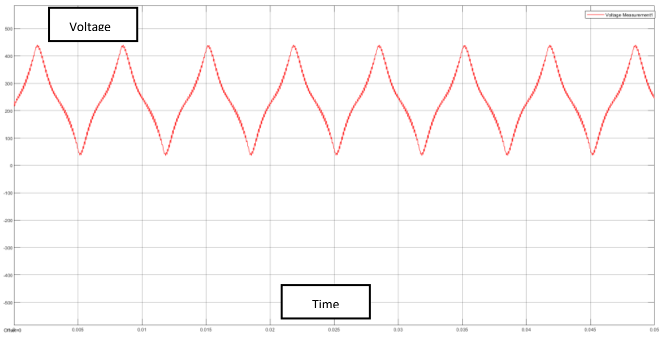

Fig -8: DC imbalance when capacitor value is 100uF

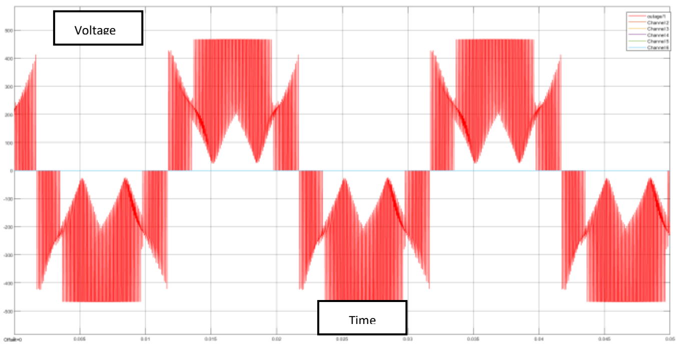

Fig -9: Output voltage when DC link capacitor is 100uF

When the capacitor value is changed to 1000uF then the voltage deviation is reduced very drastically to 10V.The output seen also has very less distortion .So the Capacitor used are of 480uF which are placed in 2s4p configuration.

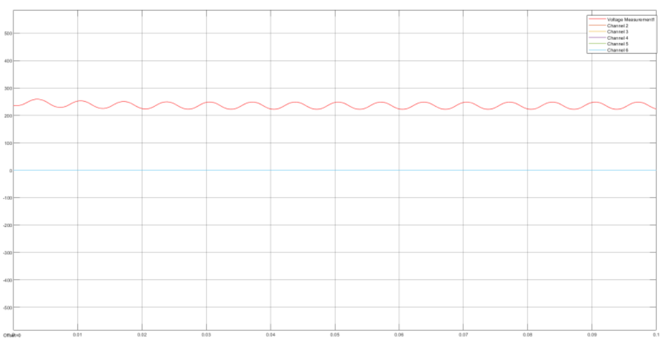

Fig -10: DC imbalance when capacitor value is 1000uF

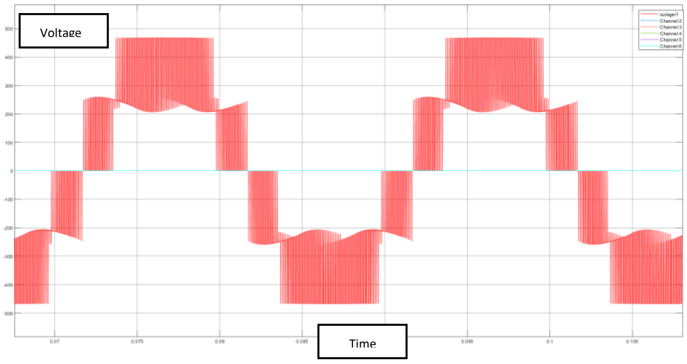

Fig -11: Output voltage when DC link capacitor is 1000uF

The below figures 12 shows gate voltages of IGBT1, IGBT2, IGBT3, IGBT4 respectively.

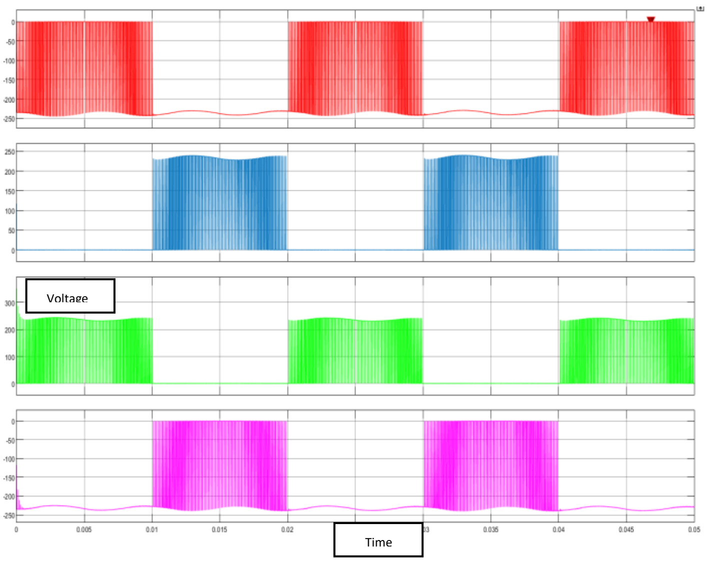

Fig -12: Gate voltages

As we can see that all the IGBTs are not conducting at the same time preventing short circuit.

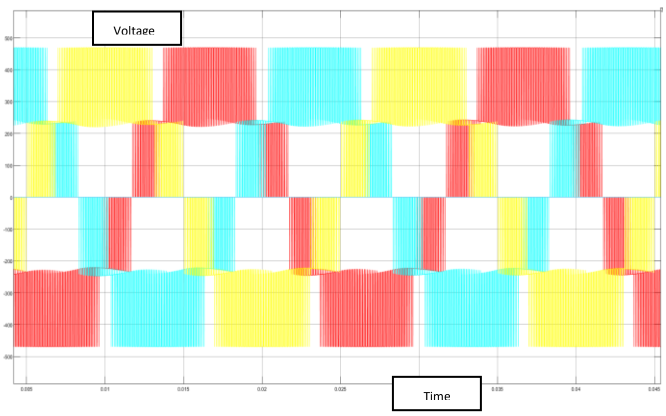

Fig -13: Three phase output voltage staircase waveform

The above figure shows the output three phase voltage staircase waveform. Each wave is 120 degree phase shifted.

The switching frequency is 10kHz. Switching frequency can be iterated to optimum values based on THD, power losses etc.

Motor controller model consist of 7 major blocks i.e. Battery pack, Motor, FOC controller, Resolver, Load, current measurement and inverter. The Permanent magnet synchronous motor model is used. The motor is parameterized according to Emrax 208 which is a PMAC motor. The simulation is focused on selection of appropriate gate driver parameters. The sinusoidal PWM is used to decrease complexity. Carrier frequency selection is being done by model to reduce THD to required value. The model is shown below in figure 14.

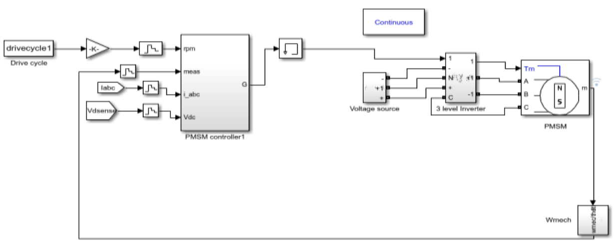

Fig -14: Motor controller MATLAB model

Two PI controller are used for current control ,input to d-component of current is 0 and input signal to q component of current is supplied through gain block which transforms input torque signal to current signal .To acquire plant model to tune PI controller ,motor equations are linearized at 15Nm constant torque and further converted to transfer function by using Laplace transform .The PI controllers are tuned using MATLAB PID tuner and also bandwidth of controller is kept low to avoid or eliminate high frequency disturbances .

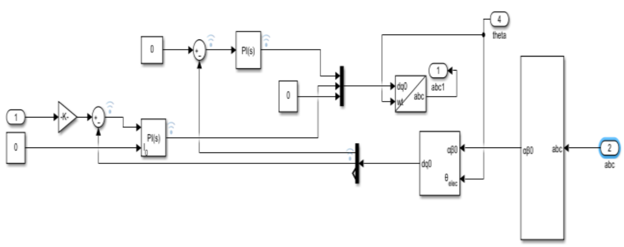

Fig -15: FOC MATLAB model

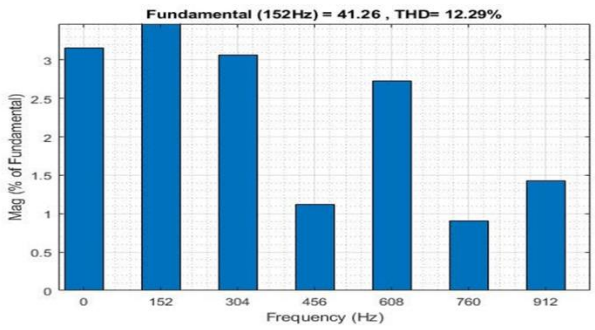

Fig -16: Total Harmonic Distortion (THD)

Figure no 16 Shows the total harmonic distortion achived from the proposed model which is 12% which is less than conventional 2 level inverters.

4. CONCLUSIONS

In this paper we Designed and analyzed motor controller for Three phase PMSM three level inverter with diode clapped topology and FOC algorithm. The proposed design is done for 80kW system. The simulation results show proper Staircase waveform of Voltage. The PID tuner works for the FOC algorithm. The Total harmonic distortion achieved were 12% which improves the overall efficiency and stability, further improvements can be done using Space vectoring method which can reduce THD even further.

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