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Common Mode Voltage Reduction In Three Phase Neutral Point Clamped Inverter Fed Ac Motor Drive

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Abstract

This study proposes an effective Induction Motor Drive system designed using Common Mode Active Filter (CMAF) to completely eradicate the Common Mode Voltage (CMV) which is induced in the induction motor drive. Two different Pulse Width Modulation (PWM) strategies has been proposed for three phase Neutral Point Clamped (NPC) inverter fed Induction Motor drive to completely mitigate the Common Mode Voltage. The Multi Carrier PWM technique and Space Vector PWM technique has been implemented to control three level and five level NPC inverter fed induction motor drives. A comparative study of PWM techniques are carried out in both three level and five level o NPC inverter. The simulation is done to measure the CMV generated by each system individually. After determining the effective system which produces less Common Mode Voltage, Common Mode Active Filter (CMAF) is designed for that system and the CMV is brought almost zero. The Induction motor drive along with CMAF is designed in MATLAB/simulink software and their parameters are observed.

Keywords: Common mode voltage (CMV), Neutral point clamped (NPC) inverter, PWM techniques, Common mode active filter (CMAF)

Introduction

The induction motor drives are implemented in numerous applications. The induction motor has many advantages like robust and simple construction, good efficiency and operates in direct AC supply. In recent times they are implemented in controlling robotics, hybrid vehicle, etc [1]. The induction motor driver system is controlled by Pulse Width Modulation technique. By controlling the switching PWM we can control the turn on and off time of switches and thereby controlling the output speed, torque and position of the induction motor. Although the induction motor has many advantages, one of the most important problems faced is the generation of Common Mode Voltage in the drive system [2]. This CMV causes creation of shaft voltage with results in shaft failure, generates bearing current with leads to bearing failure and also causes electromagnetic interference.

The induction motor drive system consists of Neutral Point Clamped inverter to convert DC voltage to AC voltage and provide input to the induction motor. The NPC inverter, also termed as diode clamped inverter which has the diode midpoints, clamped by the balancing capacitors [3].

The n-level diode clamped inverter requires 2(mn1) active devices (IGBT/GTO) per phase, (n-1) capacitors and (n-1) (n-2) clamping diodes. The advantages of using NPC are that the capacitors will divide the input voltage equally and thus the voltage stress experienced by the switches will be reduced. Also this balancing of voltage by capacitor will help to reduce switching losses of the switches, and has fewer ripples in output current. Increasing the number of output level will significantly reduces the harmonic content thus no need for other filters in the system.

The Multi Carrier PWM and Space Vector PWM are the two PWM techniques used in the proposed system [4]. In Multi Carrier PWM two or more carriers used. For n level inverter n-1 carrier waves required. The carrier wave used is a triangular wave which has amplitude Ac and switching frequency fc. The reference wave used is sinusoidal wave with amplitude Am<Ac and frequency fm equal to fundamental frequency. As soon as the reference signal is greater than the carrier signal PWM generates and corresponding pulses will turn on the switches.

Space Vector PWM technique is a specially designed switching sequence for the positive and negative power switches of a three-phase inverter. The advantage is that it has higher efficiency as it reduces third order harmonics. Thus generates fewer harmonics distortion in the output voltages applied to the phases of AC motor.

The CMAF [5] consist of parallel capacitors which senses the line voltage, a balancing capacitor to maintain the CMV to its low value, a dc source and two switches to supply Common Mode Transformer (CMT) and series connected inductor (CMT) to inject voltage opposite to CMV to nullify it.

As per literature reducing common mode voltage involve balancing capacitors voltage. This can be achieved by implementing control strategies like Particle Swarm Optimization technique and synchronous reference frame technique through controller. The drawback of above method is that their controllers technique involves more mathematical analysis and difficult to implement in real time hardware systems. Another method is by maintaining the sum of three line voltages to zero (Van+Vbn+Vcn=0). This is achieved by operating the drive with linear load. But in practical cases it is impossible to operate the induction motor as a linear load [6].

In proposed system have two different PWM techniques like Multi Carrier PWM and Space Vector PWM [7] to control both three level and five level NPC inverter. From the simulation output results we can determine which PWM technique produces less common mode voltage and how CMV depends on number of output levels of the NPC inverter. After determining the efficient induction motor driver system which produces less CMV compared with others, the Common Mode Active Filter (CMAF) is designed for that particular system and the CMV is completely eradicated from the drive system. The advantage of using CMAF is that the system does not require any additional filters and increases motor reliability.

Proposed System

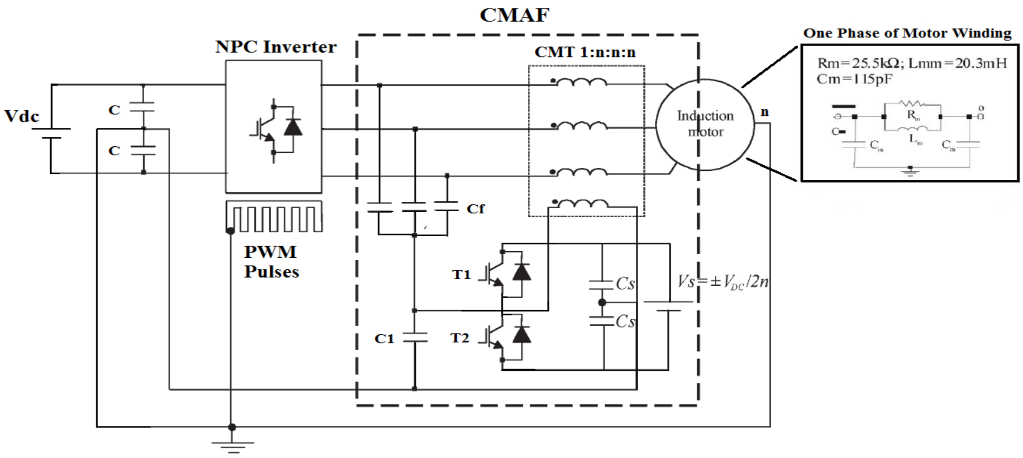

Figure 1: Schematic representation of NPC based Induction motor drive with Common Mode Active Filter

The dc input (Vdc) is given directly from the dc main. The balancing capacitor C does two important functions. First one is that it acts as voltage divider and divides the input dc voltage into two for three level and four for five level NPC inverter. The Second is that the balancing capacitor will produces a constant and reliable dc voltage to the NPC inverter.

The simulation of the induction motor has been modeled with passive elements. Each phase of induction motor consist of a resistor, an inductor and a couple of capacitors. Their values are chosen accordingly from the reference paper [5]. The induction motor is modeled in MATLAB/Simulink software such that it has a neural point in load and thus voltage between load neutral and source ground can be measured which is called CMV.

vThe NPC inverter used here is a multi level inverter. In this project we chose multilevel inverter because the output of the multi level inverter will vary in a step by step manner. Thus there won't be sudden variation in the output voltage rather it varies gradually. It helps to reduce the voltage stress experienced by the windings present in the induction motor increasing its lifetime and efficiency. Here two different levels of NPC are used which are three level and five level NPC's. A three level NPC requires four power switches, two clamping diodes per phase and two capacitors which act as voltage divider. The three level of output produced are +Vdc/2, 0 and –Vdc/2 [8]. The switching table of a single leg three level NPC is given in the table 1.

Table 1: Switching table of single leg three level NPC Inverter

T1	T2	T1□	T2□	Output Voltage
1	1	0	0	+Vdc/2
0	1	1	0	0
0	0	1	1	-Vdc/2

For five level NPC eight power switches, twelve clamping diodes per phase are required along with four capacitors which act as voltage divider. The five level output produces are +Vdc/4, +Vdc/2, 0, -Vdc/2 and –Vdc/4. The switching table for a single leg five level NPC is given in table 2.

Table 2: Switching table of single leg five level NPC Inverter

T1	T2	T3	T4	T1□	T2□	T3□	T4□	Output Voltage
0	1	1	1	1	0	0	0	+Vdc/4
1	1	1	1	0	0	0	0	+Vdc/2
0	0	1	1	1	1	0	0	0
0	0	0	0	1	1	1	1	-Vdc/2
0	0	0	1	1	1	1	0	-Vdc/4

The PWM technique will operate the power switches at higher switching frequency. The main advantage of using high switching frequency is that it reduces Total Harmonic Distortion (THD). Here multi carrier and space vector PWM are implemented in controlling NPC inverter and results are compared [9].

The Multi Carrier PWM has multiple (many) carrier waves. The type that used here is Phase Opposition Disposition. In other words, the carriers for the positive/upper leg switches are phase shifted 180° from those carrier waves for the negative/lower leg switches. The reference wave number depends on the number of phase used. For three phase system three reference waves are required which are phase shifted by 120° from each other. For three level NPC number of carriers required is two and for five level NPC number of carriers required is four. To turn on a switch the reference signal should be greater that the carrier signal, else it will turn off.

The second method is Space Vector PWM [10]. The induction motor drive mainly has third order harmonics. The SVPWM completely eliminates the third order harmonics due to their switching sequence. Thus THD of the system is reduced. The Space Vector PWM implemented by obtaining the voltage equations with stationary *dq* reference frame from the *abc* reference frame using Clerk and Park Transformation. Space vector PWM can be implemented by first determining Vd, Vq, Vref, and angle (α), after that finding time duration S1, S2, S0 and generating the switching time of each switches (T1 to T4).

Then we need to formulate the switching period for each sectors. This is done by determining S1, S2, S0 by calculating Sz and finds the switching time of each switch in each sector. Each leg has three switching states and thus for three phase NPC system totally nine switching states present.

The Space vector PWM in less effective and more complicated to implement compared to Multi carrier PWM.

The Common mode active filter is an effective way to reduce the CMV compared to other methods which are discussed above [11] – [14]. The CMAF consist of three capacitors C connected in parallel with the line and these capacitors acts as the line voltage sensing unit. The fourth capacitor C1 is the CMV balancing capacitor which helps to maintain the CMV value as minimum as possible. The main role of these capacitors is to deliver the divided CMV Vs/n, n is the CMV partition ration, as input to the power switches. A value of n = 5 has been chosen as a tradeoff between a suitable CMT sizing and better CMV detection. The CMT is designed with single primary and three secondary windings which are made of toroidal magnetic core. The primary winding is connected with the CMAF dc source and Vcm/n delivered by the sensing capacitors. The value of the dc source used in CMAF is chosen as Vs= Vdc/2n. The CMT secondary side windings are connected in series with the three phase lines of the induction motor. The CMT ratio is chosen as 1: n: n: n. The two capacitors which are used after Vs will act as voltage divider and provides equally divided voltage to two power switches used. The CMT is used for the reinjection of the CM voltage with opposite polarity on the three-phase line, connecting the inverter and the induction motor. Thereby bringing the CMV created in the driver system to almost zero. Thus CMAF completely eradicates the CMV form the induction motor driver system [4].

The simulation is first done with 120° and 180° mode operated Voltage Source Inverter (VSI). The common mode voltage is observed and tabulated. The amplitude of the CMV depends on the capacitor voltage or input voltage and frequency of the CMV depends on the switching frequency of the NPC inverter.

Simulation Results

A.Voltage Source Inverter

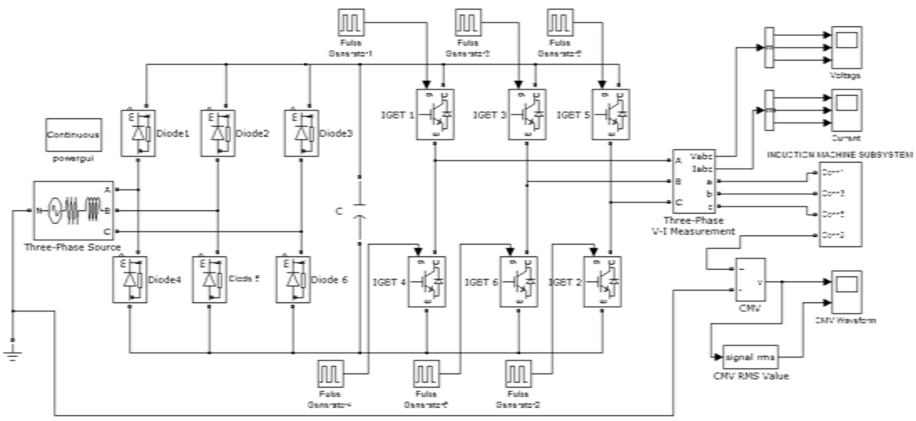

Figure 2: CMV measured in Voltage Source Inverter operated in both 120° and 180° modes of operation.

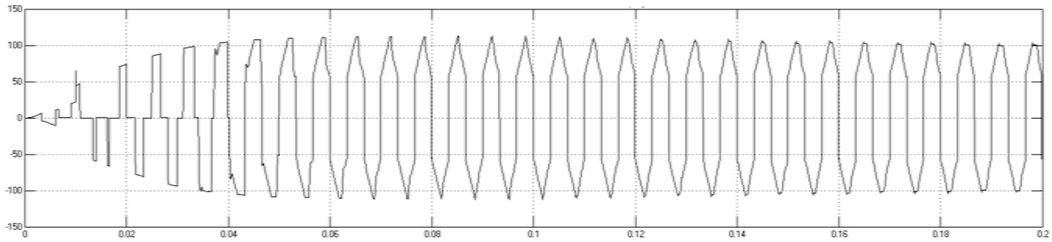

Figure 3(a): CMV waveform observed in VSI operated in 120° mode

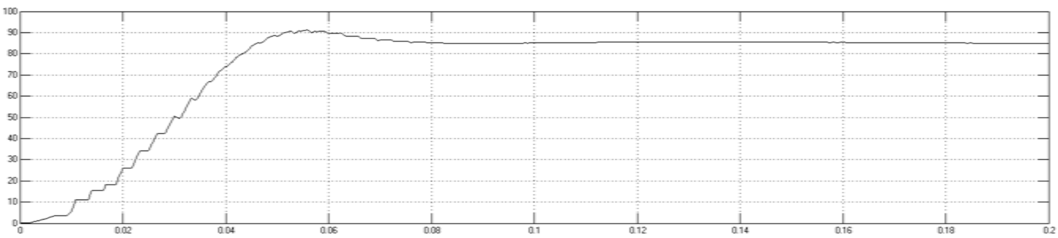

Figure 3(b): CMV RMS Value observed in VSI operated in 120° mode

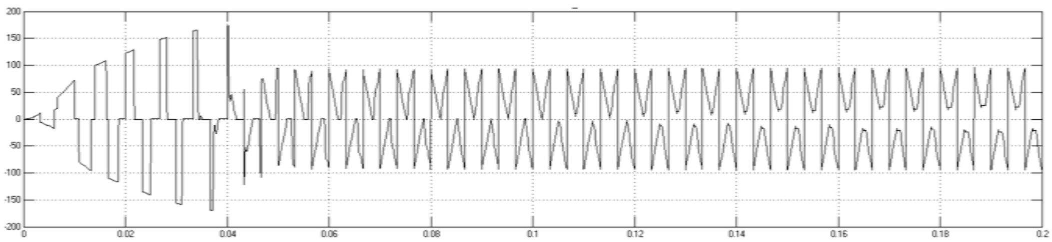

Figure 4(a): CMV waveform observed in VSI operated in 180° mode

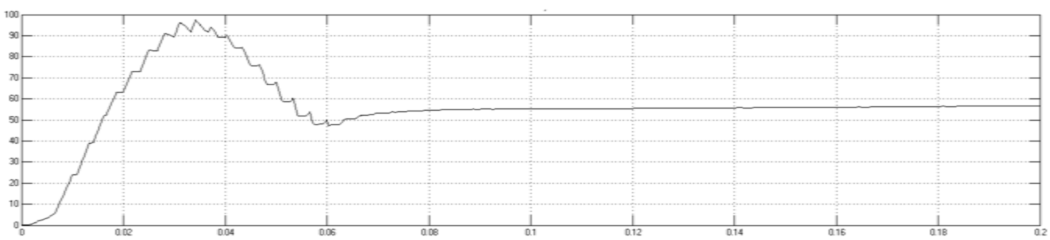

Figure 4(b): CMV RMS Value observed in VSI operated in 180° mode

The figure 3 and 4 shows the actual CMV generated and its RMS value. The RMS value is calculated to make the comparative study. The figure 3(a) shows the actual CMV waveform generated by VSI operated in 120° mode. The equivalent RMS value is represented in figure 3(b) and it is 85.87V. The figure 4(a) shows the CMV waveform generated by VSI operated in 180° mode and the equivalent RMS value is

57.82V which is represented in figure 4(b). In both cases the CMV is significantly high and so VSI is not an effective system in reducing the CMV hence not suitable for drive system.

B. Three Level NPC Inverter

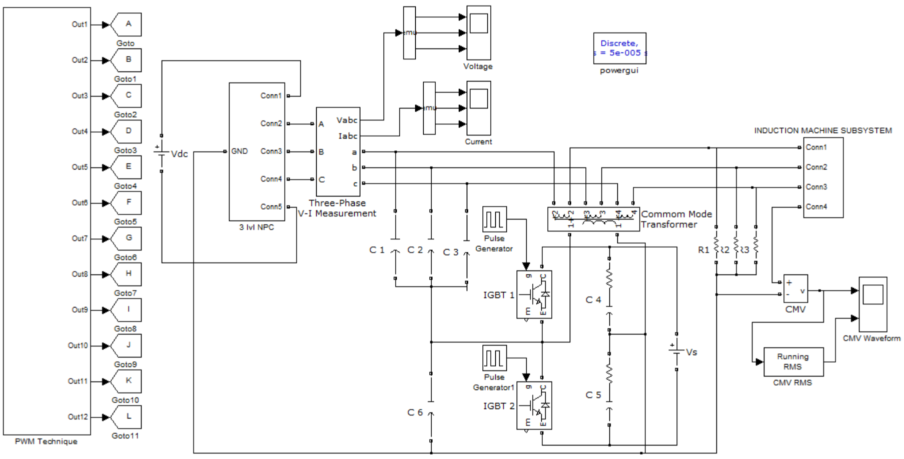

Figure 5: CMV measured in 3 Phase 3 Level NPC Inverter with CMAF operated with both Multi Carrier PWM and Space Vector PWM Techniques

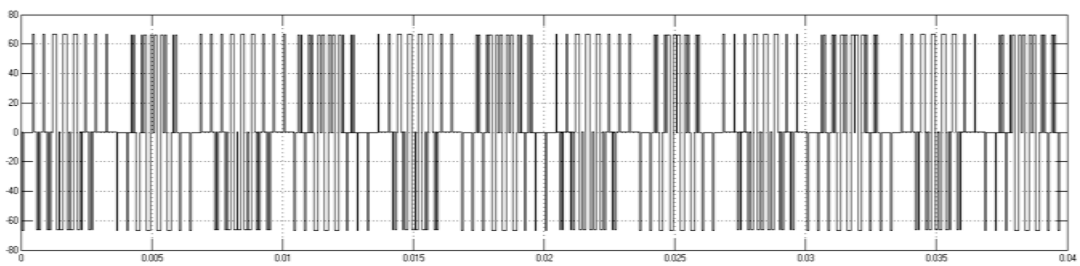

Figure 6(a): CMV waveform observed in 3 Phase 3 Level NPC Inverter operated by Multi Carrier PWM Technique without CMAF

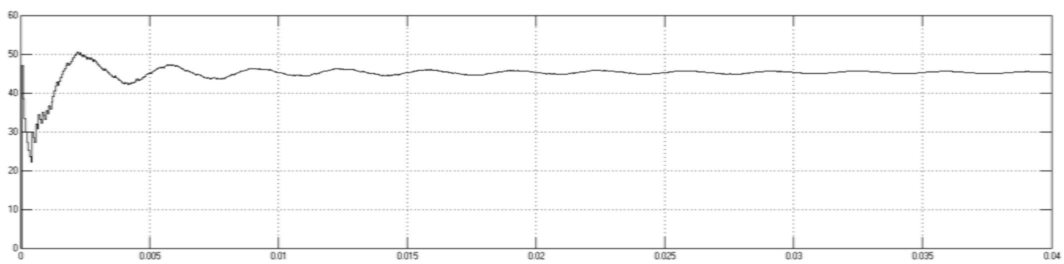

Figure 6(b): CMV RMS Value observed in 3 Phase 3 Level NPC Inverter operated by Multi Carrier PWM Technique without CMAF

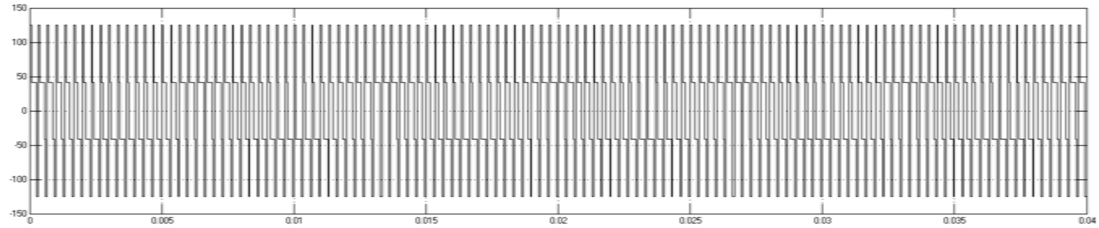

Figure 7(a): CMV waveform observed in 3 Phase 3 Level NPC Inverter operated by Space Vector PWM Technique without CMAF

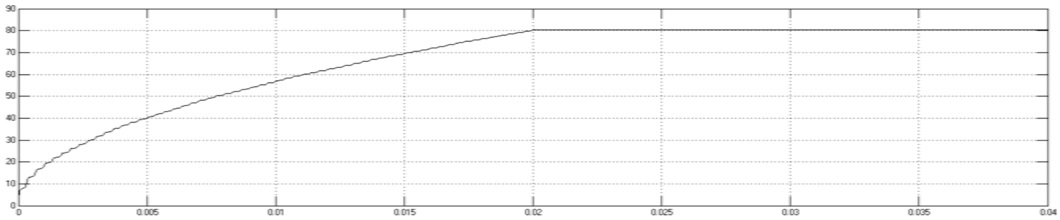

Figure 7(b): CMV RMS Value observed in 3 Phase 3 Level NPC Inverter operated by Space Vector PWM Technique without CMAF

The CMV is measured in 3 phase 3 level NPC inverter without the CMAF. The CMV waveform represented in figure 6(a) is when operated using Multi Carrier PWM and figure 7(a) is when operated using Space Vector PWM. The CMV RMS value is represented in figure 6(b) and 7(b) which is 44.09V when operated using Multi Carrier PWM and 80.33 when operated using Space Vector PWM respectively. Thus the CMAF is designed and implemented in the effective driver system operated using Multi Carrier PWM which produce less CMV.

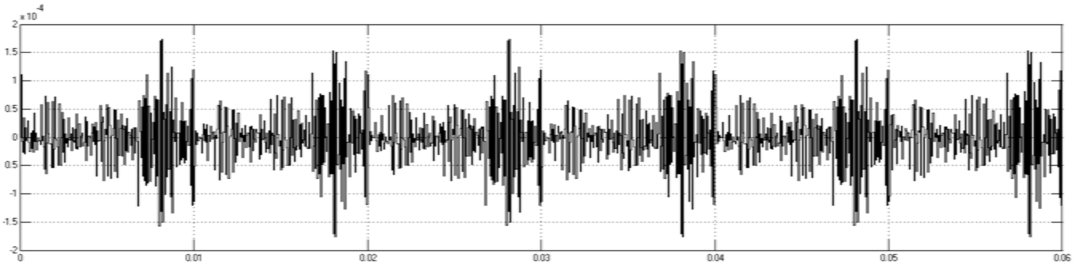

Figure 8(a): CMV waveform observed in 3 Phase 3 Level NPC Inverter operated with Multi Carrier PWM Technique with CMAF

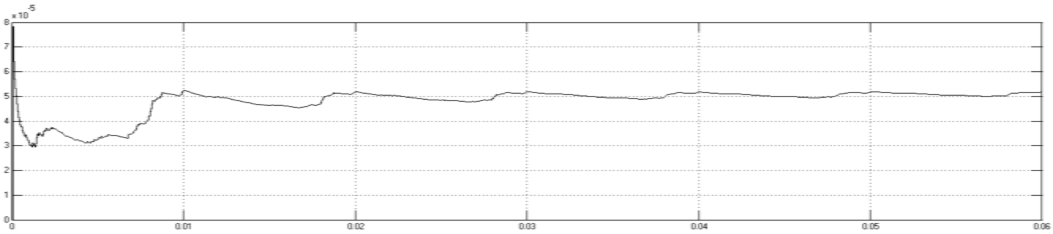

Figure 8(b): CMV RMS Value observed in 3 Phase 3 Level NPC Inverter operated with Multi Carrier PWM Technique with CMAF

The figure 5 represents the CMV waveform of 3 phase 3 level NPC inverter with the CMAF. The waveform has more distortions but the amplitude of the waveform is reduced to almost zero. The equivalent RMS value of the CMV generated in this driver system with CMAF is 0.00005V represented in figure 8(b) in which CMV is completely eradicated.

C. Five Level NPC Inverter

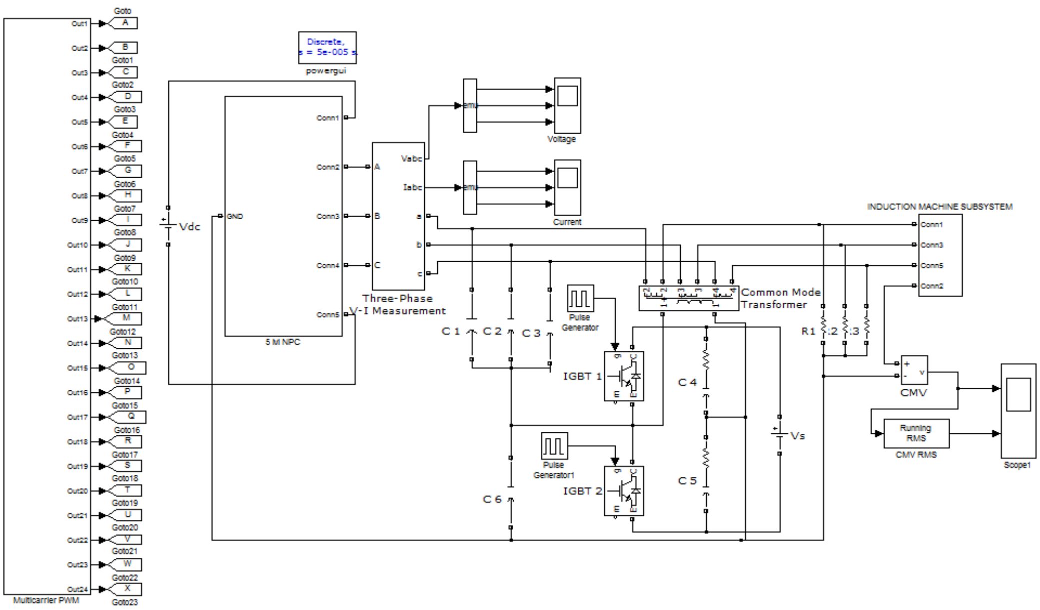

Figure 9: CMV measured in 3 Phase 5 Level NPC Inverter operated with both Multi Carrier PWM and Space Vector PWM Technique with CMAF

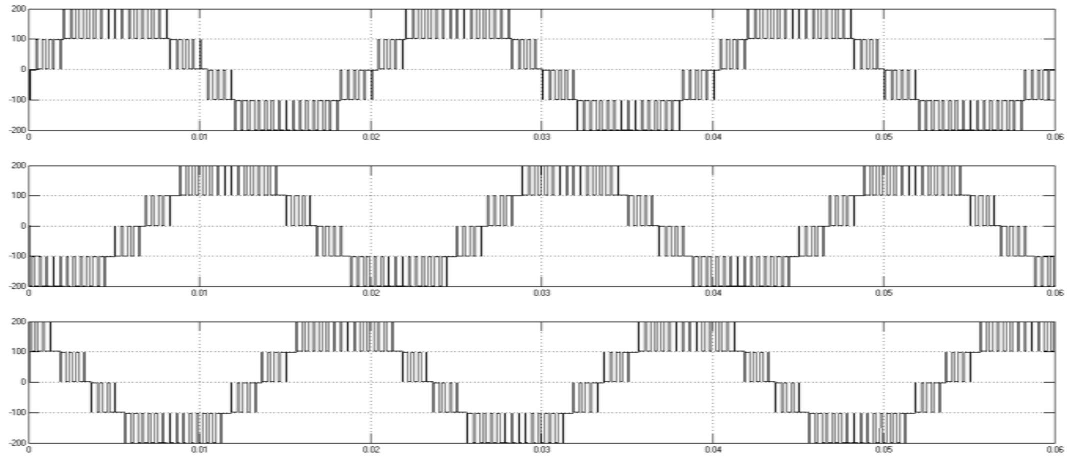

Figure 10: Output Phase Voltage measured in Three Phase Five Level NPC Inverter

Figure 11(a): CMV waveform observed in 3 Phase 5 Level NPC Inverter operated with Multi Carrier PWM Technique without CMAF

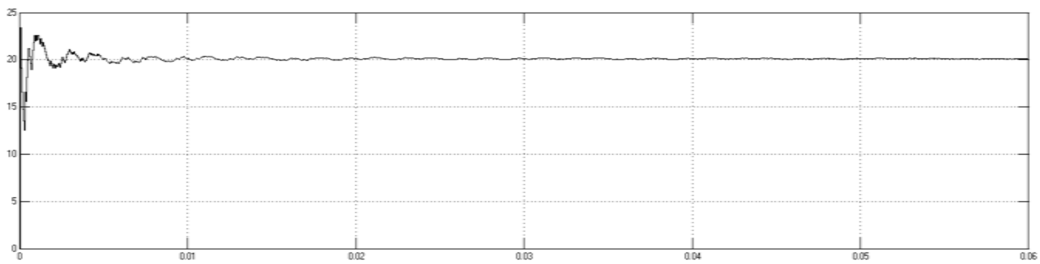

Figure 11(b): CMV RMS Value observed in 3 Phase 5 Level NPC Inverter operated with Multi Carrier PWM Technique without CMAF

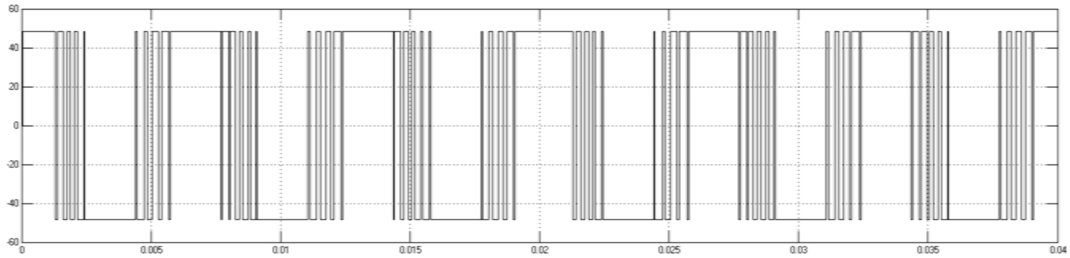

Figure 12(a): CMV waveform observed in 3 Phase 5 Level NPC Inverter operated by Space Vector PWM Technique without CMAF

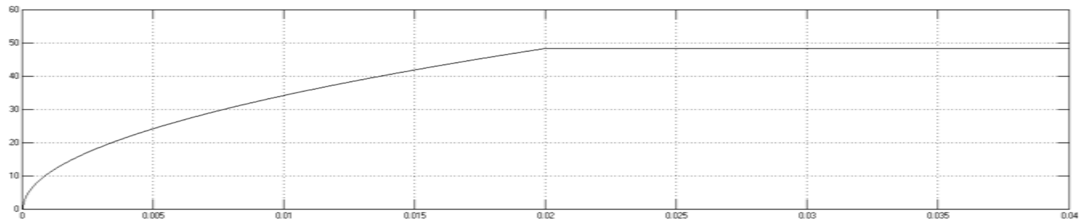

Figure 12(b): CMV RMS Value observed in 3 Phase 5 Level NPC Inverter operated by Space Vector PWM Technique without CMAF

The figure 10 represents the output phase voltage measured in 3 phase 5 level NPC inverter. The CMV generated using multi carrier PWM and space vector PWM are represented in figure 11 and 12 respectively. The equivalent RMS value is represented in figure 11(b) and 12(b).The CMV RMS value is 20.33V when operated using Multi Carrier PWM and when Space Vector PWM is implemented its value is 48.33. The CMV generated by the five level NPC inverter is less compared to the CMV generated by the three level NPC inverter. As the Multi Carrier PWM produces less CMV compared to Space Vector PWM, CMAF is designed and implemented in 5 level NPC operated using Multi Carrier PWM.

Proposed system output waveforms and results

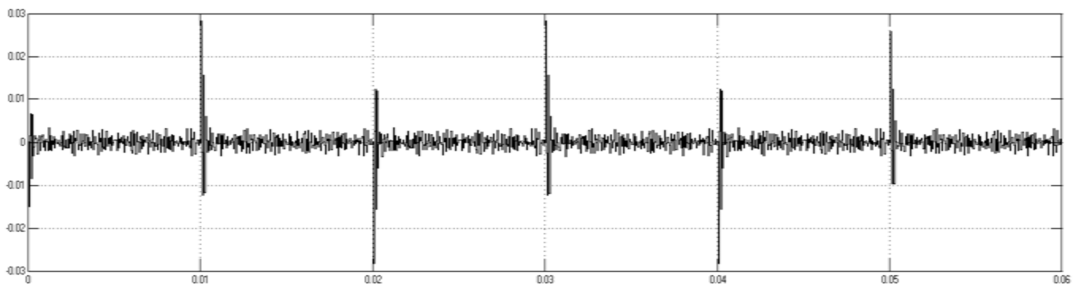

Figure 13(a): CMV waveform observed in 3 Phase 5 Level NPC Inverter operated by Multi Carrier PWM Technique with CMAF

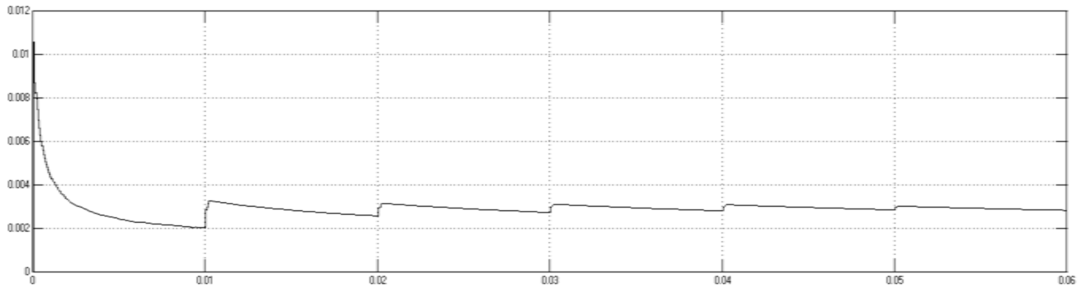

Figure 13(b): CMV RMS Value observed in 3 Phase 5 Level NPC Inverter operated by Multi Carrier PWM Technique with CMAF

The figure 9 represents the 3 phase 5 level NPC with CMAF implemented in the driver system. The CMV waveform is measured and its equivalent RMS voltage is represented in figure 13 and its value is 0.0028. Thus employing CMAF in driver system will completely eradicate the CMV for the system.

Comparison of Results

The obtained results from the MATLAB/simulink software have been tabulated with respect to different inverter configuration and PWM techniques.

Table 3: The CMV RMS value measured in different driver system with different PWM techniques without CMAF

Inverter	**PWM Used**	**Common Mode Voltage Generated**
Voltage Source Inverter 120° operating mode	Pulse Generator	85.87V
Voltage Source Inverter 180° operating mode	Pulse Generator	57.82V
Neutral Point Clamped 3 Level Inverter	Space Vector PWM	80.23V
	Multi Carrier PWM	44.09V
Neutral Point Clamped 5 Level Inverter	Space Vector PWM	48.33V
	Multi Carrier PWM	20.33V

From the table 3 it is clear that the Multi Carrier PWM produce less CMV compared to SVPWM. It is also clear that when number of output level of NPC increased the CMV generated reduced significantly. Thus the CMAF is designed and implemented for the three level and five level NPC inverter operated with Multi Carrier PWM technique and results are compared

Table 4: The CMV RMS value measured in 5 level NPC driver system with CMAF

Inverter	PWM Used	Common Mode Voltage Generated
Neutral Point Clamped 3 Level Inverter	Multi Carrier PWM	0.00005
Neutral Point Clamped 5 Level Inverter	Multi Carrier PWM	0.0028

From the table 4, it is clear that the implementation of CMAF completely eradicates the CMV generated by the drive system.

Conclusion

The simulation result shown in table 3 concludes that the CMV is reduced when Multi Carrier PWM techniques is employed, compared to Space Vector PWM technique. It is also observed that the CMV generated is less in five level NPC inverter driver system compared to three level NPC inverter driver system. Thus it is also concluded that the CMV will reduce significantly when number of level in output voltage of inverter is increased. So when inverter produces voltage waveform closer to sinusoidal wave then the CMV generated will be less. The CMAF is designed and implemented in both three level and five level NPC Inverter with Multi Carrier PWM technique as it is the efficient system compared to others. The CMAF based induction motor drive has been proposed and the CMV has been reduced nearly to zero. Although employing Multi Carrier PWM and increasing number of output level only reduces the CMV thus Common Mode Active Filter is implemented to completely eradicate CMV. From the simulation results shown in table 4 it is clear that implementing CMAF brings the CMV almost zero in both three level and five level NPC inverter operated with Multi Carrier PWM. The implementation of CMAF means the driver system does not require additional filters. The operation of CMAF with three level and five level NPC inverter base induction motor drive has been successfully evaluated.

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