



Space Vector Pulse Width Modulation for the Control of an Induction Motor through Simulation and Experimental Validation

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Abstract

The Induction Motor is a constant-speed motor. Due to the load, the speed will change marginally. The progress in engineering technology that led to the speed of the Induction Motor can vary within certain limitations. Techniques exist to control and run the Induction Motor in variable-speed drive applications. The basic method is a 2-level inverter controlled by a microcontroller, using the space vector modulation method for the Volts/Hertz principle. The inverter's output is non-sinusoidal due to the load, resulting in a Common Mode Voltage at the star point concerning the ground. which induces electromagnetic interference and causes disturbance to the nearby control circuits, communication, and electronics equipment. Reduce the Common Mode Voltage to a higher level of inverter, viz., By using the 3-level inverter, the number of devices will be increased to twelve from 6 for the 2-level scheme. Due to the increase in the number of devices, the circuits will have more complexity.

The author presents a detailed exploration of the 2-level Space Vector Pulse Width Modulation scheme using an Arduino microcontroller and Volts/Hertz principles. This inverter has DC voltage as input, the duty cycle modulation requires DC voltage to vary proportional to the square of the frequency to maintain, V_{rms} to frequency as constant. This method gives superior performance for variable speed control of the induction motor for slow, varying loads. The fast Fourier transform uses the signal analysis software and results with frequency versus voltage. The parameters using a 4-channel mixed signal oscilloscope.

Index Terms- Common Mode Voltage (CMV), Induction motor (IM), Space Vector Pulse Width Modulation (SVPWM).

I INTRODUCTION

The non-sinusoidal output voltage from the inverter produces the common mode voltage (CMV) in an adjustable speed drive of a 3-phase induction motor (IM). The existence of CMV by B. Muralidhara [1-2]. The issue of shaft voltage caused by an inner race modulation (IM) was identified by Alger in 1924 and S. Chen [3-4] in 1996. Additionally, the asymmetrical flux through the shaft loop induces common-mode voltage (CMV). A. Muetze [5] reported the existence of a high-frequency (HF) component in the CMV. Hence, it is necessary to minimise the

CMV within limits [6,15] so that there will be a reduction of bearing current. In addition to insulation problems with the winding of the IM [11-13]. The three-phase 2-level inverter is widely used in variable speed AC 3phase I'm driven systems, which produce a three-phase AC output voltage of the desired amplitude and frequency from a fixed DC voltage source. In a 2-level inverter, the output waveform of an inverter is a stepped square wave. The output waveform of an inverter should be sinusoidal for efficient operation. A Nabae [7] 1981 discussed the multi-level inverter (MLI) concept. The advantages include low switching losses, reduced Electromagnetic Interference (EMI), and improved power quality, making it suitable for medium and high-voltage industrial applications. The drawbacks of circuits include their complexity, the number of switching devices, and various DC voltage levels. The microcontroller that generates gate pulses is interfaced with necessary opt isolator modules and the 3phase bridge circuit is used to drive the switching devices of the 2-level inverter as per the SVM in Table 1.

II. CMV IN INVERTER-DRIVEN THREE-PHASE IM

In mathematical form, the CMV is represented to check its characteristics among various types of sources and load combinations. In the three-phase, the phase-to-ground voltages can be written as the sum of the phase voltages and the voltage across the star point of the load to the common ground of the source power supply. In the sinusoidal balanced system, the sum of all three phases to neutral voltages is zero; the voltage from the star point of load to common ground can be defined in terms of phase-to-ground voltage as shown in Fig 1.

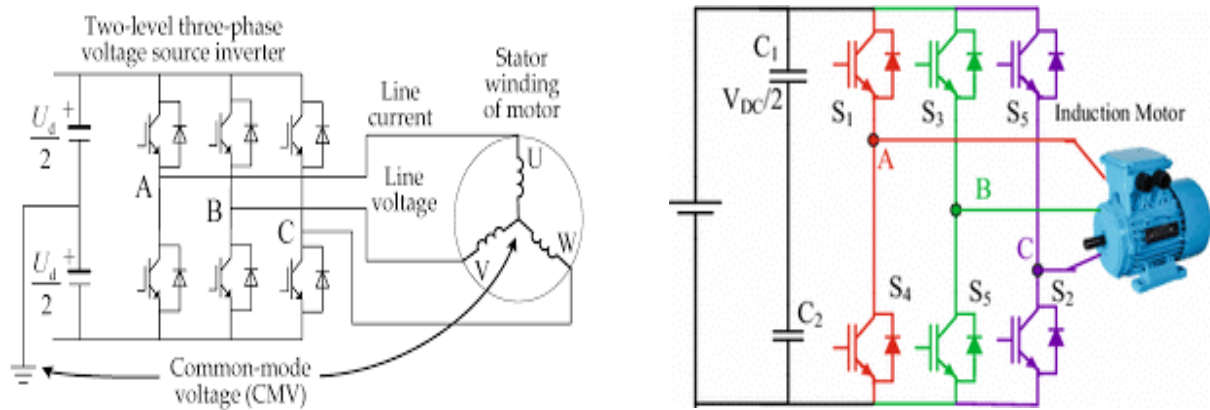


Fig 1, Schematic diagram of Inverter fed IM.

$$V_{An} = V_{AN} + V_{Nn} \quad (1)$$

$$V_{Bn} = V_{BN} + V_{Nn} \quad (2)$$

$$V_{Cn} = V_{CN} + V_{Nn} \quad (3)$$

For a balanced 3-phase system, $\sum V = 0$

$$V_{AN} + V_{BN} + V_{CN} = 0 \quad (4)$$

$$V_{Nn} = [(V_{An} + V_{Bn} + V_{Cn}) / 3] \quad (5)$$

III. SPACE VECTOR MODULATION [9], [10].

The space vector modulation (SVM) scheme is used for the simulation and experimentation which produces the output voltage by using the three nearby output vectors. When one of the reference vectors moves from one sector to another, it results in an output vector abrupt change. The states' necessary switching patterns and switching time at each change of the reference voltage have been incorporated. The main advantages are to overcome the variation in DC bus voltage, the ratio V/f of IM is constant by compensating for regulation in inverters.

SVM treats sinusoidal voltage as a rotating constant amplitude vector rotating with constant frequency. This Pulse width modulation (PWM) technique represents the reference voltage V_{ref} by combining the eight switching patterns in a Hexagon. The a-b-c reference frame into the stationary d-q reference frame consists of the horizontal (α) and vertical (β) axes (Coordinate Transformation). The three-phase voltage vector is transformed into a vector in the stationary α - β coordinate frame representing the spatial vector sum of the three-phase voltages. The voltage vectors (V_1 - V_6) divide the hexagon plane into six sectors(i.e., sector-1 to sector-6) which is generated by two adjacent non-zero vectors. Fig.2 shows the switching vectors of a 2-level inverter in a hexagon. The three-phase voltages are

$$V_a = V_m \sin \omega t \quad (6)$$

$$V_b = V_m \sin(\omega t - 2\pi/3) \quad (7)$$

$$V_c = V_m \sin(\omega t - 4\pi/3) \quad (8)$$

SVM is a better technique for generating a fundamental output ($\sim$ sine wave) that provides a higher output voltage to the three-phase IM and lower Total Harmonic Distortion (THD) when compared to sinusoidal PWM. The switching vectors for 2 - level and sectors are shown in Fig (2-4). Table I shows the switching sequence of vectors for the 2-level three-phase inverter.

TABLE I

SVM switching vectors of Inverter

Vector	A+	B+	C+	A-	B-	C-	V _{AB}	V _{BC}	V _{CA}
V ₀ [000]	0	0	0	1	1	1	0	0	0
V ₁ [100]	1	0	0	0	1	1	+V _{DC}	0	-V _{DC}
V ₂ [110]	1	1	0	0	0	1	0	+V _{DC}	-V _{DC}
V ₃ [010]	0	1	0	1	0	1	-V _{DC}	+V _{DC}	0
V ₄ [011]	0	1	1	1	0	0	-V _{DC}	0	+V _{DC}
V ₅ [001]	0	0	1	1	1	0	0	-V _{DC}	+V _{DC}
V ₆ [101]	1	0	1	0	1	0	+V _{DC}	-V _{DC}	0
V ₇ [111]	1	1	1	0	0	0	0	0	0

Note: 1 ON, 0 OFF of inverter switches [+ Top and, - Bottom]

The advantage of SVM is that the gating signal of the power devices can be easily programmed using micro-controller offers improved DC bus utilization [9], reduced switching losses and lower THD. The SVM method has the advantage of more output voltage when compared to the sine triangle pulse width modulation (SPWM) method [10].

IV THE WORK

The V/f approach for variable speed control of an induction motor (IM) is commonly used for slow speed changes. In this method, the voltage is adjusted in proportion to the frequency using pulse width modulation (PWM). The gating pulses generated for space vector PWM (SVPWM) can be single or multiple pulses. In the case of multiple pulses, the generated PWM gate signals are combined with a carrier frequency. However, because the carrier frequency lacks phase correlation with the gating pulses, the width of the first pulse becomes uncertain. This report proposes a method to generate a 2-pulse gated signal that is in sync with the gating pulse, ensuring the full pulse width gating. The 2-pulse scheme helps reduce the torque ripple of the induction motor. Additionally, the theory demonstrates that the duty cycle of the gating pulses must be proportional to the square of the frequency to maintain a constant ratio of V_{rms}/f for variable speeds.

V 2-PULSE PWM

In Space Vector modulation, without PWM $V_{rms} = \sqrt{2} V$, where V is the DC bus voltage.

The equation with PWM can be written as $V_{rms(PWM)} = \sqrt{2} V \sqrt{\delta}$

Where δ is the duty cycle. To keep the (V_{rms}/f), constant, for varying speeds of IM,
 $[(\sqrt{2} V \sqrt{\delta})/f] = \text{const. and } \delta \propto f^2$.

This equation is adopted in determining the duty cycle for the different frequencies. The pulse waveform is shown in Fig. 5 for reference.

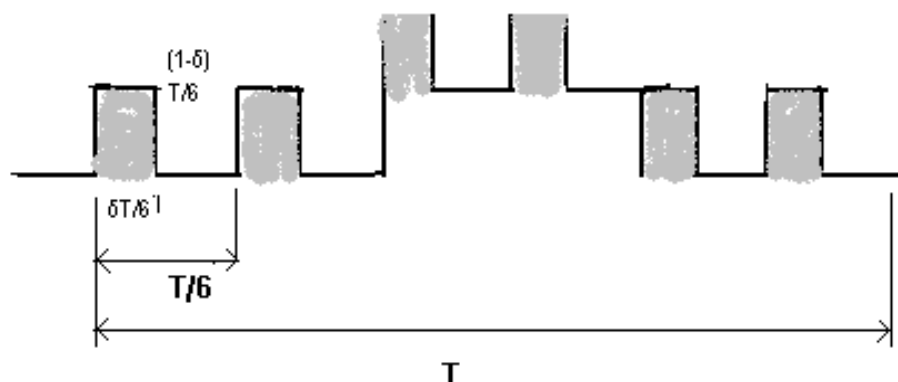


Fig 5, pulse waveform shown for a segment

The program flowchart is below.

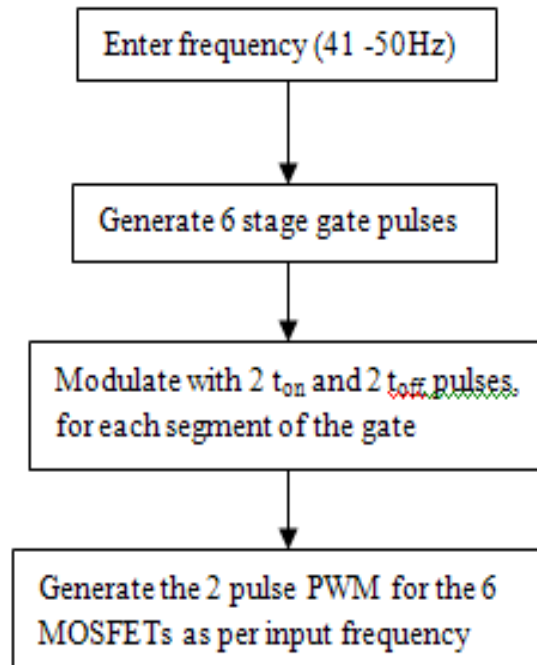


TABLE II

Frequency (Hz)	Phase Voltage V_{rms} (Volts)	Ratio V/f	Actual Speed of IM (rpm)
40.98	146.8	3.581	1223
42.017	152.1	3.619	1249
43.103	155.7	3.581	1288
43.86	158.9	3.622	1307
44.643	161.8	3.624	1331
45.872	165.7	3.612	1363
46.296	167.1	3.609	1383
47.170	170.3	3.576	1410
47.619	172.4	3.614	1429
48.544	175.6	3.617	1452
49.505	180.6	3.648	1489

Table II shows the frequency, True Vrms, speed, and (V/f) ratio of the IM as the load to the inverter.

VI SIMULATION AND EXPERIMENTAL SETUP

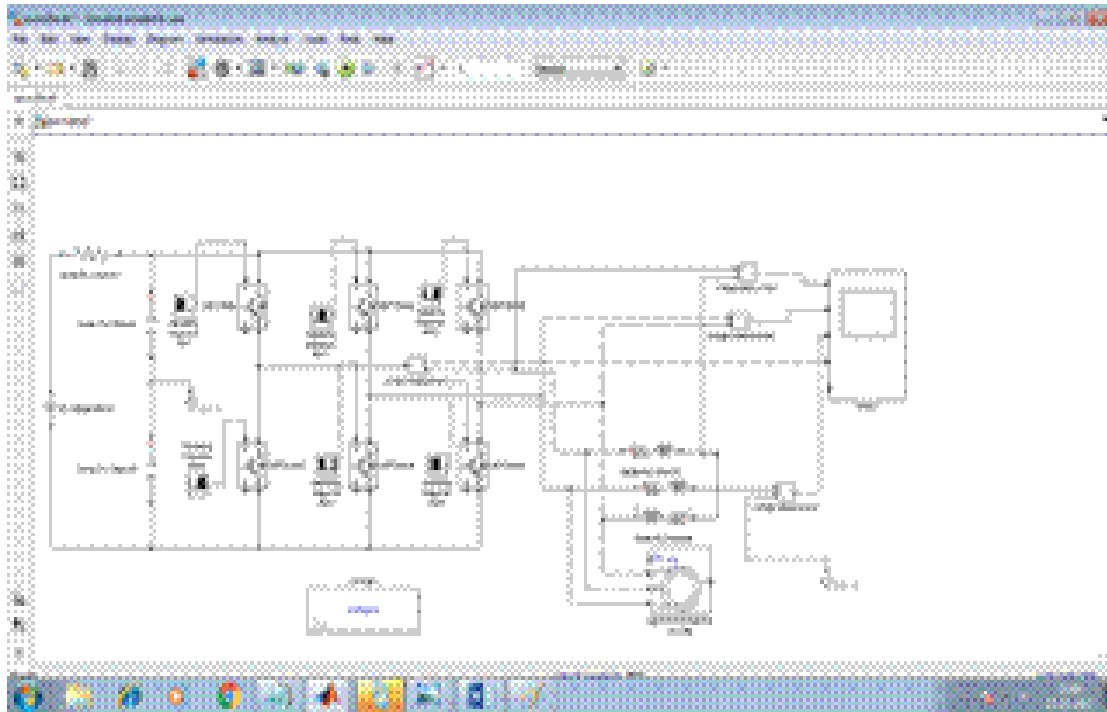


Fig 6 Simulation Circuit

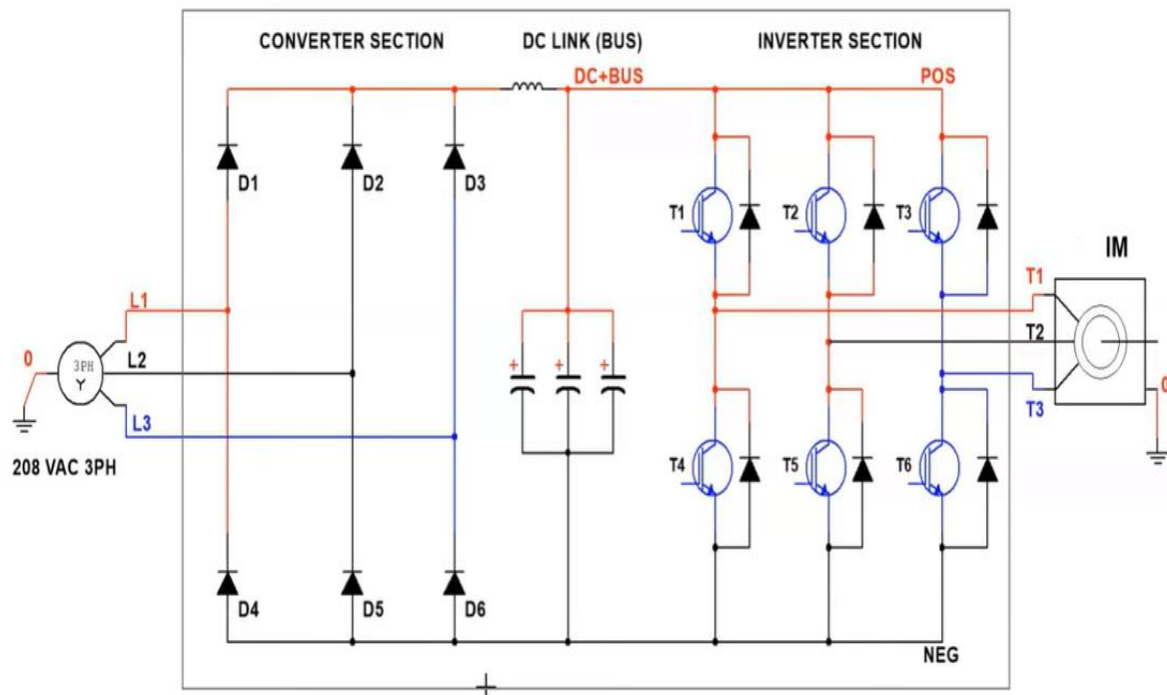
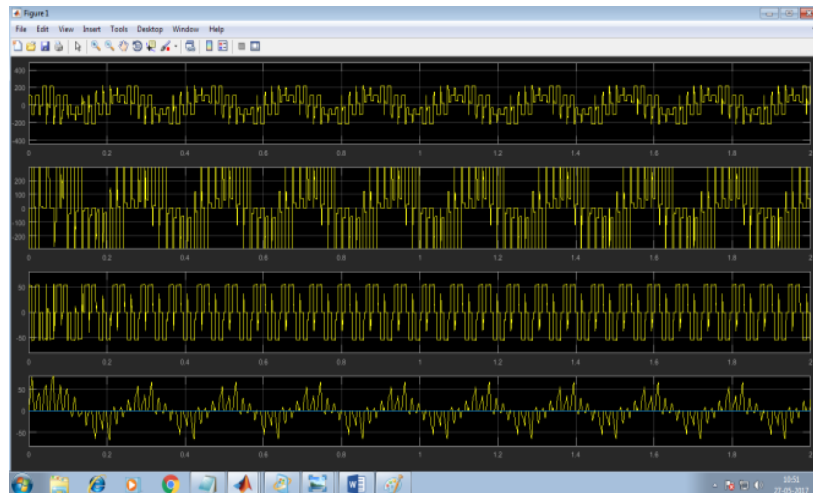


Fig 7, Experimental circuit. (2-level inverter)

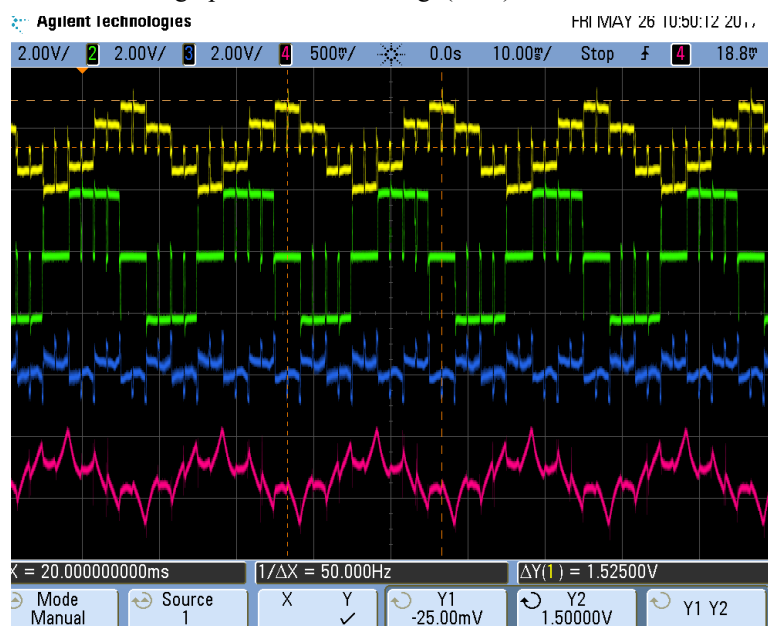
VII SIMULATION AND EXPERIMENTAL RESULTS



CH1: Phase Voltage, CH2: Line Voltage, CH3: Common Mode Voltage, CH4: Line Current

Fig 8, Simulation Output of 2-level inverter

The simulation and the experimental circuits are shown in Fig (6-7) for the 2-level inverter. MOSFETs are used as switching devices within the circuit [14-15]. The microcontroller generates the gating pulses which are given to the MOSFETs as per 2_Pulse PWM and the necessary opt isolation has been done. The microcontroller is programmed for SVPWM to run the Induction motor from 41-50Hz. The FFT analysis has been done in simulation using MATLAB/Simulink and the graphs are shown in Fig. (8-10).



Ch1: Phase Voltage, Ch2: Line Voltage, Ch3: Common Mode Voltage, Ch4: Line Current,

Fig 9, Experimental Output

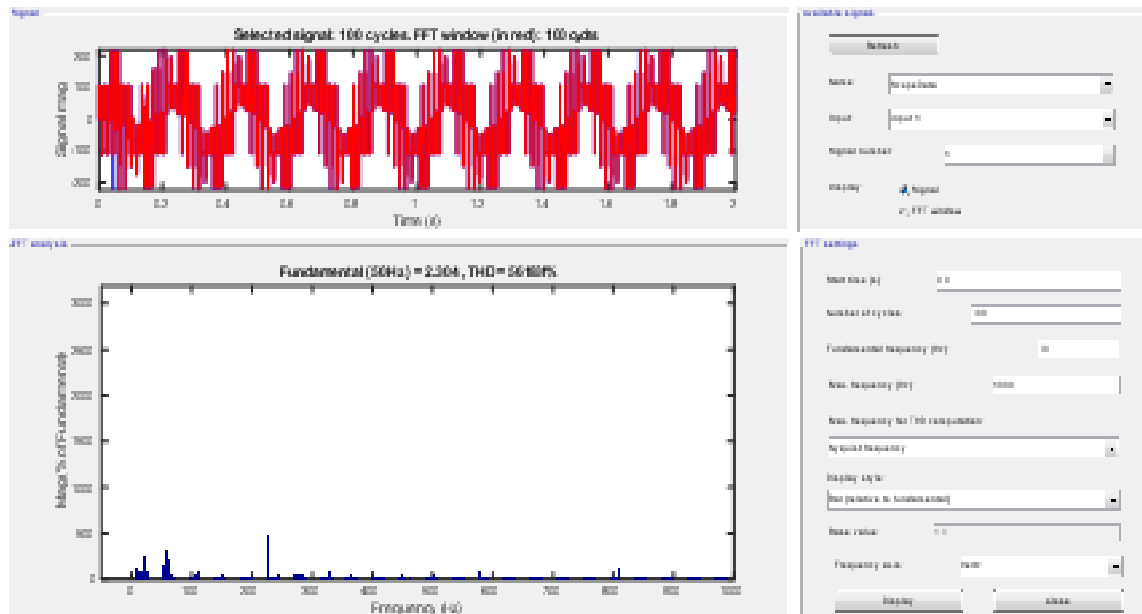


Fig 10, Simulation, FFT of Phase Voltage

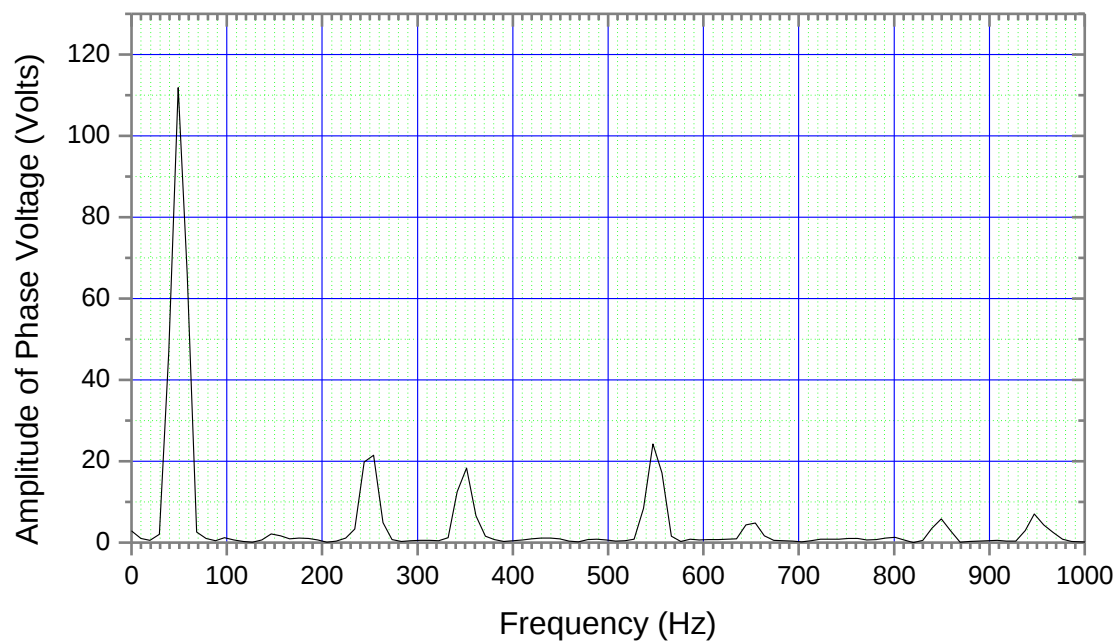


Fig 11, FFT of Phase Voltage (Exptl.)

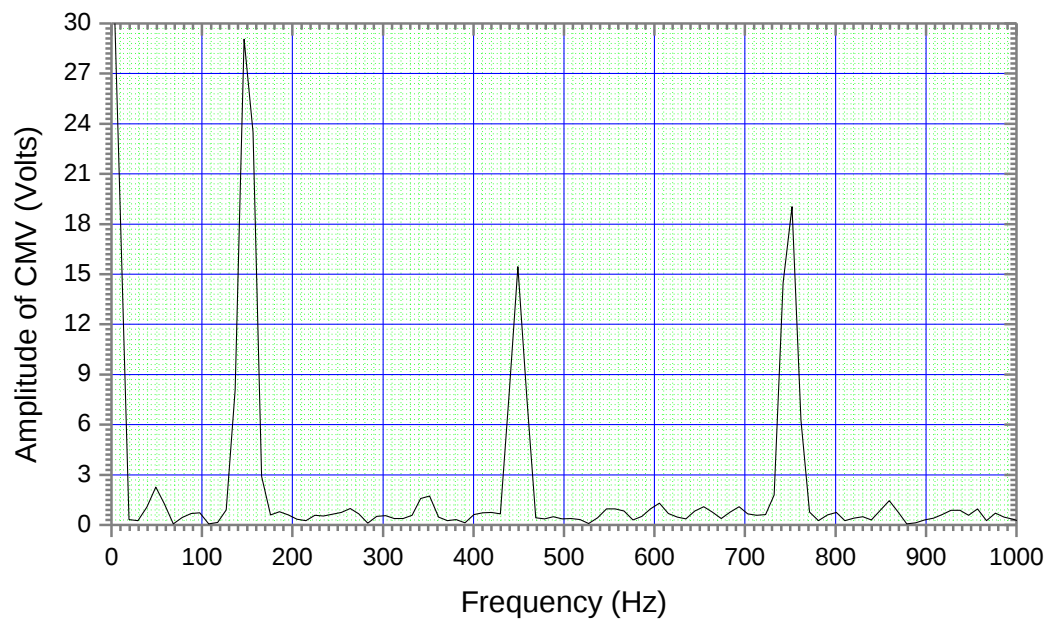


Fig 12, FFT of CMV (Exptl.)

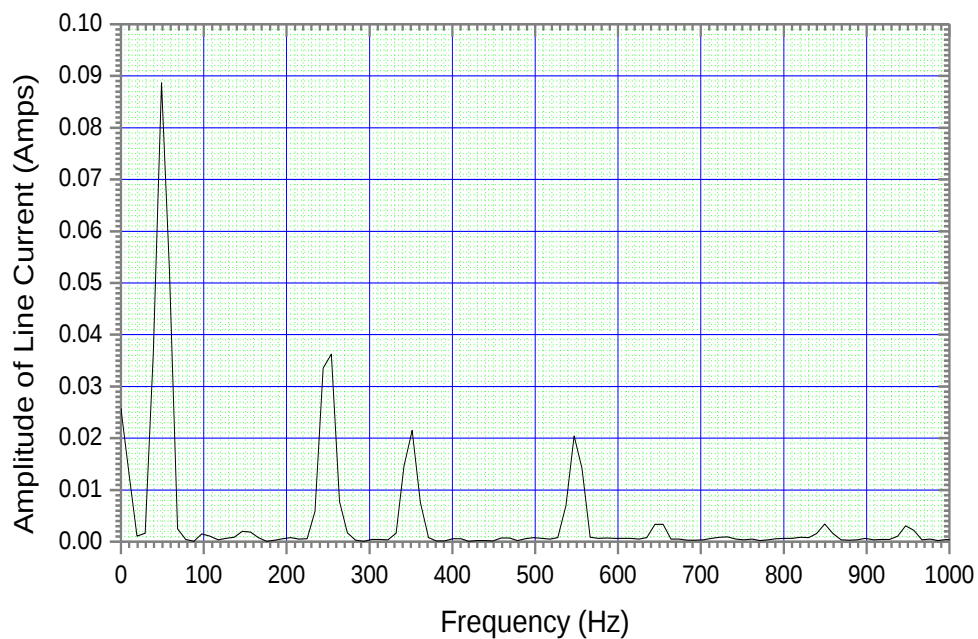


Fig 13, FFT of Line Current (Exptl.)

The experimental and simulation of a 2-level inverter for the speed control of three-phase IM is done. The measurement of Phase voltage, Line Voltage, CMV, and line current have been carried out in this paper using an Agilent Mixed Signal Oscilloscope (MSO) associated with an isolation module, interface circuits, Line Impedance Stabilization Network and Hall Effect sensors.



IX RESULTS AND CONCLUSION

The simulated and experimental output waveforms of the inverter circuit are shown in Fig (8-9). The simulated FFT result of phase voltage is Fig.10. The FFT of the experimental result using signal Analysis software and the results of Phase voltage, CMV and line current in Fig. (11-13). The calculated value of THD_V from the experimental results is $\sim 31.89\%$ and from the simulation using MATLAB/Simulink is 24.2% , however, the profile of the harmonic frequencies coincides in both the simulation and experimental results. In addition, the profile of waveform phase Voltage, Line voltage, CMV and the line current in simulation (Fig.8) and the profile of experimental waveforms in Fig.10 are almost the same.

VII ACKNOWLEDGEMENT

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REFERENCES

- 1) B. Muralidhara, A. Ramachandran, R. Srinivasan, M. Channa Reddy, "Common Mode Voltage and EMI as the Source of Disturbance to Communication Network Caused by Modern AC Motor Drive," Proceedings of the 42nd IETE Mid-Term Symposium, dated 15-17 April 2011, Bangalore, India, pp. 90–94.
- 2) B. Muralidhara, A. Ramachandran, R. Srinivasan, and M. Channa Reddy, "Experimental Measurement and Comparison of Common Mode Voltage, Shaft Voltage and the Bearing Current in Two-level and Multilevel Inverter Fed Induction Motor," International Journal of Information and Electronics Engineering, vol. 1, no. 3, pp. 245-250, 2011.
- 3) P. Alger and H. Samson, "Shaft currents in Electric machines" in Proceedings AIRE Conf. Feb 1924.
- 4) S. Chen, "Bearing current, EMI and soft switching in induction motor drives," Ph.D. dissertation, Univ. Michigan, Ann Arbor, MI, 1996.
- 5) Muetze and A. Binder, "Systematic approach to bearing current evaluation in variable speed drive systems," Eur. Trans. Elect. Power, vol. 15, no. 3, pp. 217–227, 2005.
- 6) R. Paul, "Introduction to Electromagnetic Compatibility, Wiley Series in Microwave and Optical Engineering," John Wiley & Sons, Inc., 1992.
- 7) Nabae, I. Takahashi, and H. Akagi, "A New Neutral-point Clamped PWM inverter," IEEE Trans. Ind. Application., vol. IA-17, pp. 518-523, Sept./Oct. 1981.
- 8) P. Srikant Varma and G. Narayanan, "Space vector PWM as a modified form of sine triangle PWM for simple analog or digital implementation," IETE journal of research, vol. 52, no. 6, Nov/Dec. 2006, pp. 435-444.
- 9) G. Narayanan and V.T. Ranganathan, "Synchronised PWM strategies based on space vector approach: Principles of waveform generation," IEEE Proceedings- Electric Power Applications, vol. 146 No.3, May 1999, pp. 267-275.
- 10) K. Bose, "Power Electronics and Variable Frequency Drives: Technology and Applications," IEEE Press and John Wiley & Sons, Inc.
- 11) ABB Automation Inc., IEEE industry applications Magazine, July/Aug. 1999.



- 12) Gary L. Skibinski, Russel J. Kerkman, and Dave Schlegel (Rockwell Automation), "EMI Emissions of modern PWM AC drives," IEEE Trans Ind. Application., Nov/Dec. 1999, pp. 47-81.
- 13) Muralidhara B., "An Experimental evaluation of 2-level and multilevel inverters used for speed control of IM and study of Common Mode Voltage in both cases," JNTU, Ph.D. Thesis, Aug 2013.
- 14) Endika Robles, Markel Fernandez, Jon Andreu, Edorta Ibarra, Jordi Zaragoza, Unai Ugalde, "Common-mode voltage mitigation in multiphase electric motor drive systems," Elsevier, Renewable and Sustainable Energy Reviews, Volume 157, April 2022.
- 15) Yitao Cheng, Chengqun Liu, Hai Wu, Yingwei Zhao, Aihua Wu, "Common Mode Voltage-based Open-switch Fault Diagnosis for Inverters with Model Predictive Control in IM Drive System," IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics (PRECEDE), IEEE Xplore, 20-22 Nov. 2021.
- 16) Advanced power inverter topologies and modulation techniques for common-mode voltage elimination in electric motor drive systems, Author links open overlay panel Endika Robles, Markel Fernandez, Jon Andreu, Edorta Ibarra, 26 January 2021, Version of Record 26 January 2021.
- 17) Nguyen, M.H.; Kwak, S.; Choi, S. Development of Various Types of Independent Phase Based Pulse width Modulation Techniques for Three-Phase Voltage Source Inverters. Machines 2023, 11, 1054.
- 18) Modulation Techniques and Coordinated Voltage Vector Distribution: Effects on Efficiency in Dual-Inverter Topology-Based Electric Drives by Jakub Kucera, Petr Zakopal, Filip Baum and Ondrej Lipcak. Energies 2024, 17(5), 986

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