Simulation with Experimental Measurement of Voltage Total Harmonic Distortion and Harmonic Frequency in Three-Phase Induction Motor fed from Inverter

Reddy Sudharshana K, A Ramachandran, V Muralidhara and R Srinivasan

***Abstract*- In general the Induction Motor is known to be a constant speed motor. In most of the industries the induction motor is mainly used for Drive Systems. But due to the advances in computer technology the speed of the induction motor can be controlled under certain conditions. There are many ways to control the speed of the Induction Motor for variable speed applications. The basic method is 2-level inverter controlled by microcontroller using space vector modulation. In this method the output of the inverter may not be exactly sinusoidal and hence at the star point of the Induction Motor winding, causing a Voltage Harmonic Distortion in the output of the inverter. To minimize the voltage harmonic distortion a multilevel inverter can be used. In addition, the harmonic frequencies will not produce usable torque but causes heating the Induction motor windings, which are harmful to the insulation. In this paper two level and three level inverter fed induction motor driven at various frequencies are reported. Simulation, experimentation and the measurement of voltage total harmonic distortion have also been reported. In the experiment the Arduino microcontroller, Line Impedance Stabilization Network, opto-isolator, Hall Effect sensor, H-bridge inverter and other necessary electronic circuits are used. The measurements are recorded using Agilent make Mixed signal Oscilloscope. The Fast Fourier transform has been carried out for the experimental result, using signal analysis software. Simulation has been implemented using the MATLAB/Simulink. The results of simulation and experimentation are compared and tabulated.**

***Keywords*-Total Harmonic Distortion (THD), Electro-Magnetic Interference (EMI), Induction Motor (IM), three-phase Voltage Source Inverter (VSI), Space vector modulation (SVM).**

I.INTRODUCTION

The voltage harmonics present in three-phase Induction Motor (IM) drive systems using three-phase 2-level/3-level inverter is due to the presence of Non-sinusoidal voltage at the output of the inverter. The existence of Voltage harmonics has been reported by B. Muralidhara [1]. In the year 1924, Alger [2] has reported the Voltage harmonics that exists in an inverter fed IM drive system, results in shaft voltage and bearing current. In the year 2006, A.Ramachandran [3] discussed about the mitigation of Conducted Electro-magnetic interference (EMI) in three-phase Induction motor driven by inverter. The voltage at shaft loop induces harmonics that is due to the asymmetrical flux as reported in [4], [5]. Hence it is necessary to minimize the total harmonic distortion (THD) [4], [5], EMI [6] within limits for the reduction in bearing current and heating of IM winding.

The three-phase inverter produces three-phase AC output voltage of desired amplitude and frequency from a fixed DC voltage source. In inverter, it has various levels of voltages [for 2-level; $\pm 2/3V_{dc}$, $\pm 1/3V_{dc}$ and for 3-level inverter; $\pm 2/3Vdc$, $\pm 1/2Vdc$, $\pm 1/3Vdc$, 0] to generate the output waveform with a stepped square wave. For a better and efficient operation of the IM, the inverter output should be sinusoidal. If the output of inverter is a stepped square wave then it contains harmonics. The minimization of harmonics has been reported using the multilevel inverter concept [7]. The H-bridge circuit of 2-level/3-level three-phase inverter uses Arduino microcontroller [8] to generate gate pulses, which is interfaced with necessary opto-isolator electronics circuits to drive the MOSFET's of 3-level inverter.

1.1 SPACE VECTOR MODULATION

In the experimental setup uses SVM method. Generally every switching state produces specific three phase voltages. The three nearby output vectors generates the output voltage illustrated in Fig. (1-2). When one of the reference vector moves from one sector to another, result in an output vector with abrupt change. In addition, it is necessary to find the switching patterns and switching time of the states at each change of the reference voltage. SVM treats sinusoidal voltage as a rotating constant amplitude vector with constant frequency. This pulse width modulation (PWM) technique represents the reference voltage V_{ref} by a combination of the eight switching patterns in a Hexagon shown in Fig.1. The a-b-c reference frame can be transformed into the stationary d-q reference frame that consists of the horizontal (α) and vertical (β) axes (Coordinate Transformation). The three-phase voltage vector which is transformed into a vector in the stationary α-β

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1. Reddy Sudharshana K, *Research Scholar, Electrical and Electronics Engineering, Jain University, Bangalore (India),* email: reddy3690@gmail.com

2. A Ramachandran, Scientist (Retd), National Aerospace Lab, Bangalore, *Prof., ECE, Vemana Institute of Technology, Bangalore (India),* email: arama1947@gmail.com

3. V Muralidhara, *Associate Director, Electrical and Electronics Engineering, Jain University, Bangalore (India),* email: v.muralidhara@jainuniversity.ac.in

4. R.Srinivasan, *Prof., ECE, Vemana Institute of Technology, Bangalore (India),* email:rsrini47@gmail.com

coordinate frame represents the spatial vector sum of the three-phase voltages. The voltage vectors (V_1-V_6) divide the hexagon plane into six sectors (Sector-1 to Sector-6) which is generated by two adjacent non-zero vectors. Fig.2 shows the sampled reference switching vector of 2-level inverter in sector -1 of hexagon. The three-phase voltages are

$$V_a = V_m \, \mathrm{Sin}\omega t \quad \text{-- (1)}$$
$$V_b = V_m \, \mathrm{Sin}(\omega t-2\pi/3) \quad \text{-- (2)}$$
$$V_c = V_m \, \mathrm{Sin}(\omega t-4\pi/3) \quad \text{-- (3)}$$

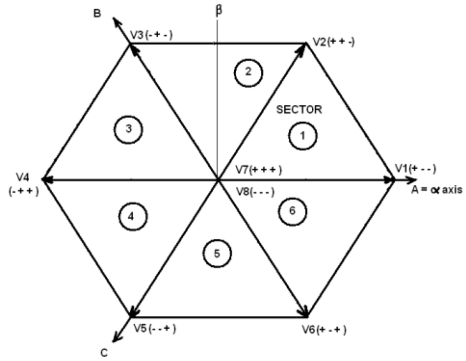

Fig.1 Switching vectors and sectors for 2-level

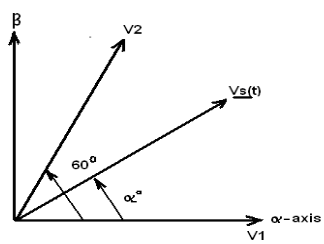

Fig.2 Sampled reference vector in sector-1

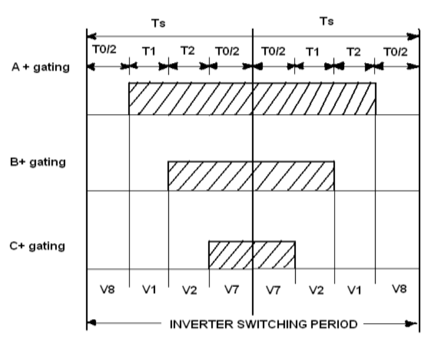

Fig.3 SVM pattern in Sector-1

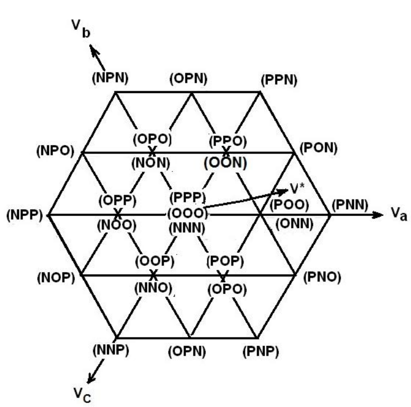

Fig .4 Switching vectors and sectors for 3-level

SVM is a better technique for generating a fundamental output (~sine wave) that provides a higher output voltage to the three-phase IM and lower THD, when compared to sinusoidal PWM. The switching vectors pattern for sector-1 is shown in Fig.3. Table I shows the switching sequence of vectors for 2-level three-phase inverter. The Hexagon for the 3-level three-phase inverter is shown in Fig.4 and the Table II shows the switching ON/OFF details.

TABLE I
Switching vectors for 2-level Inverter using SVM

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 means ON, 0 means OFF [+ Top switch, - Bottom switch]

Table II
Switching vectors for 3-level three-phase Inverter

Switching states	S_{1x}	S_{2x}	S_{3x}	S_{4x}	S_{xN}
P	ON	ON	OFF	OFF	Vdc/2
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	-Vdc/2

III. THE PROPOSED WORK

Simulation and experimentation of 3-level inverter with nine MOSFET's using SVM method, for the adjustable speed control of three-phase induction motor has been done. The measurement of Phase voltage, Line Voltage, CMV and line current have been carried out in this paper using Agilent mixed signal oscilloscope (MSO) associated with necessary opto-isolation module and interface circuits. The three-level inverter is constructed using the DC link capacitors, MOSFET devices and with necessary electronic components.

The main advantage of SVM is that the gating signal of the power devices can be easily programmed using microcontroller, which offers reduced switching losses, total harmonic distortion and improved dc bus utilization [9]. The SVM method provides ~15% more output voltage when compared to sine triangle pulse width modulation technique (SPWM). The THD is calculated using the known standard formula [7].

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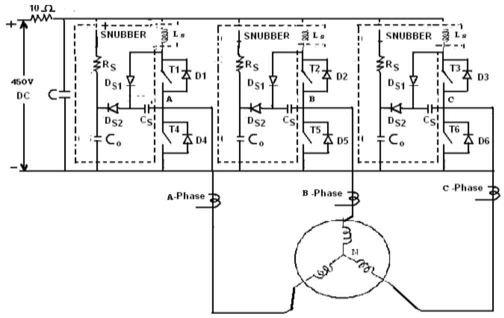


Fig.5 Experimental Circuit(2-level, three-phase inverter)

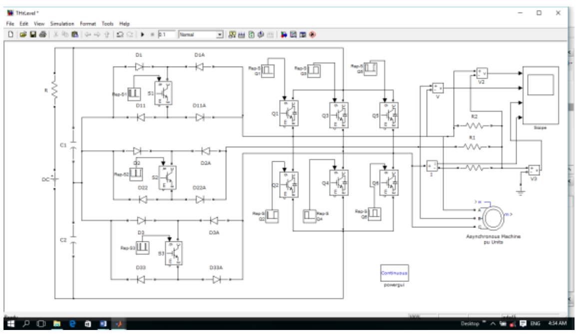


Fig..6 Simulation circuit(3-level, three-phase inverter)

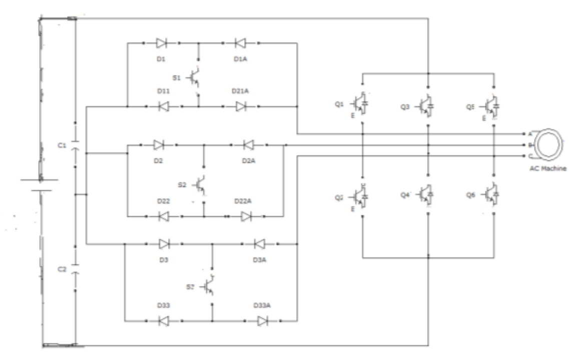


Fig.7 Experimental Circuit(3-level, three-phase inverter)

IV. EXPERIMENTAL SETUP

Fig.5 and Fig.7 show the experimental set up with MOSFET's as switching devices with necessary snubber circuit for 2-level and 3-level inverter circuits. The gate pulses are generated by Arduino microcontroller with necessary opto-isolation and interface circuits fed to gate of the MOSFET's. The Arduino microcontroller is programmed for 30Hz, 40Hz, and 50Hz frequencies. Fig. (8a) shows the gate pulses (3-level inverter) generated using the microcontroller. The FFT analysis has been implemented in simulation using MATLAB/Simulink and the experimental analysis using 'Origin' signal software. The THD of Phase Voltage is analyzed for 30Hz, 40Hz and 50Hz. Fig.6 shows the MATLAB simulation circuit of the 3-level inverter. The 3-level inverter with 12 devices, the THD and Harmonic frequency results are taken from the earlier published results [7].

V. SIMULATION AND EXPERIMENTAL RESULTS

Figs. (6-7) show the simulation and experimental circuits of 3-level three-phase inverter. The simulated waveforms are shown in Fig. (8b) and the experimental waveforms are shown in Fig. (8c). The phase voltage, line voltage, CMV and line current are recorded using Agilent MSO.

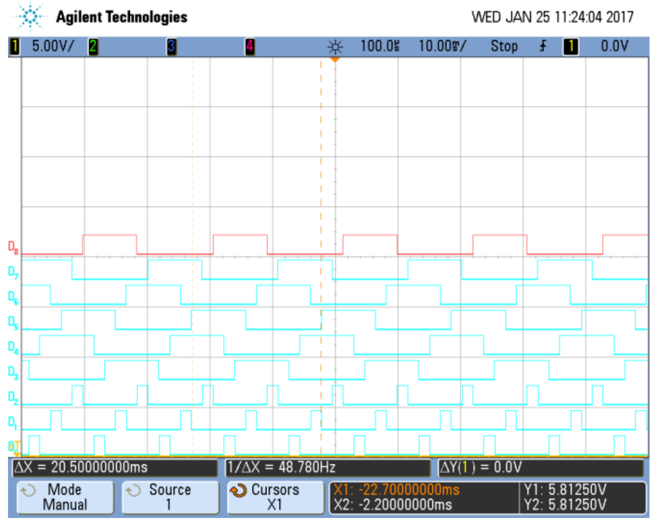
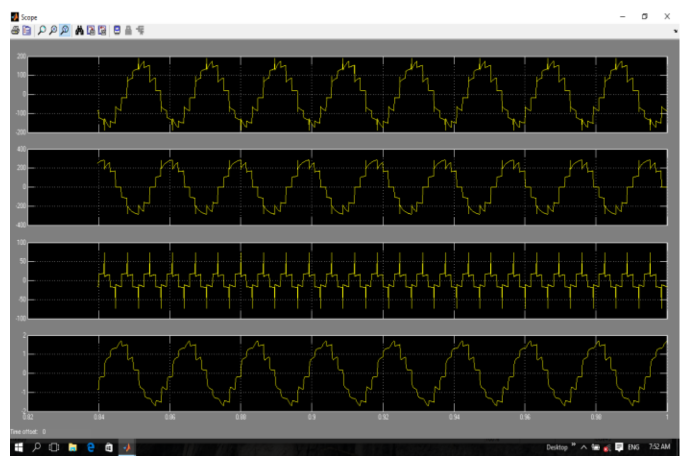
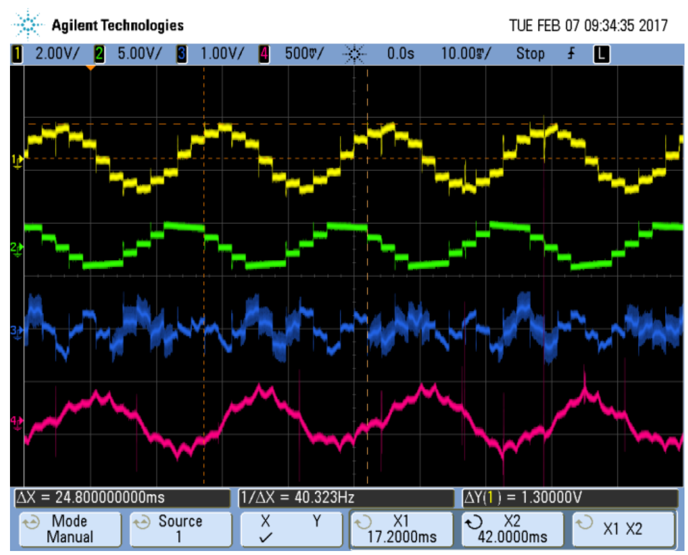


Fig. (8a); Gate pulses generated using Arduino Microcontroller



Ch-1; Phase Voltage, Ch-2; Line Voltage, Ch-3; Common Mode Voltage, Ch-4; Line Current

Fig. (8b) Simulation output waveforms of 3-level Inverter



Ch-1; Phase Voltage [200:1], Ch-2; Line Voltage [200:1],
Ch-3; Common Mode Voltage [200:1], Ch-4; Line Current [1:1]
Fig. (8c) Experimental output waveforms of 3-level inverter

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The even harmonics and its multiples will be zero since there is symmetry of waveform. The odd triplen harmonics (i.e., 3rd, 6th, 9th harmonic order, etc.) cancel out each other since it circulates in the transformer windings and will not appear in the load. The only harmonics present are 5th, 7th, 11th and 13th etc. The harmonics magnitude of voltage will not produce useable torque to the IM. Generally the harmonic frequencies will produce heat to the winding and some harmonic frequencies produce opposing torque. The production of heat in the winding causes the insulation of the IM to deteriorate. Figs. (9), (10), (11), (12a) (12b), (14a) and (14b) show the simulated FFT of phase voltage using MATLAB Simulink while Figs. (9a), (10a), (11a), (13a), (13b), (15a) and (15b) show the FFT results from experimental data.

FFT ANALYSIS

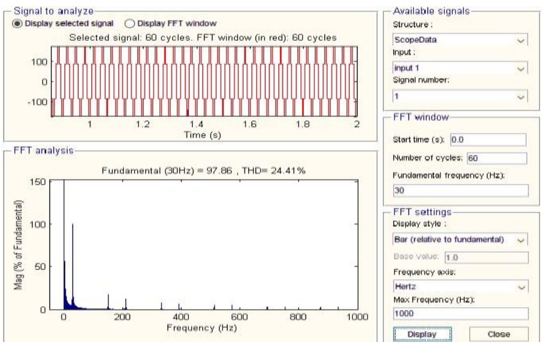

Fig. (9): FFT of Phase Voltage (30Hz, 2-level)

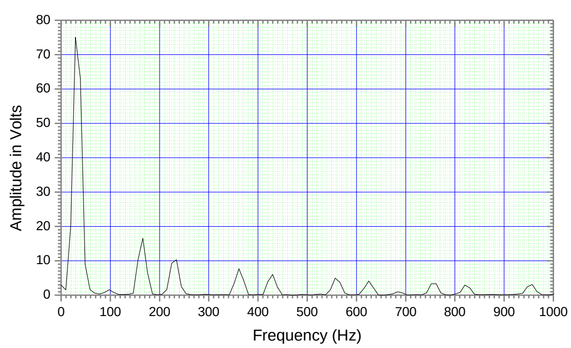

Fig. (9a): FFT of Phase Voltage (Exptl., 30Hz, 2-level)

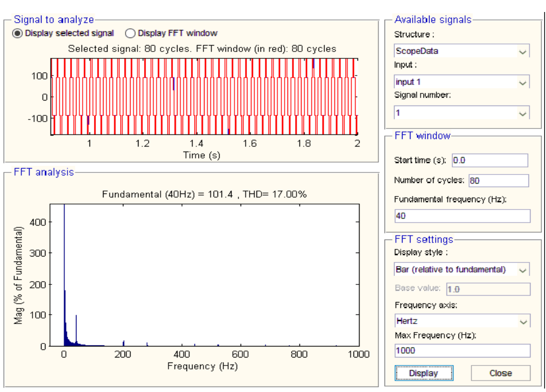

Fig. (10): FFT of Phase Voltage (2-level, 40Hz)

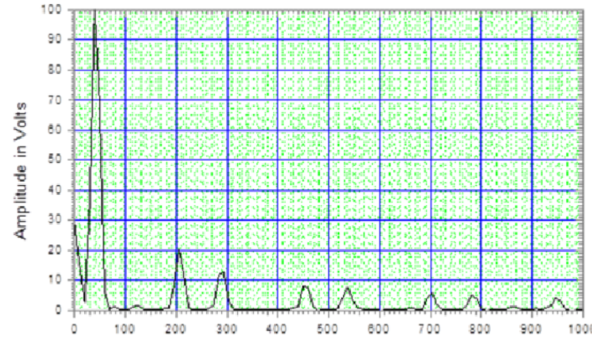

Fig. (10a): FFT of Phase Voltage (Exptl., 2-level, 40Hz)

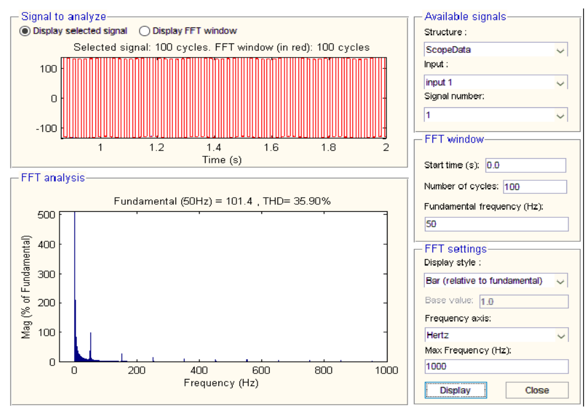

Fig. 11: FFT of Phase Voltage (50Hz, 2-level)

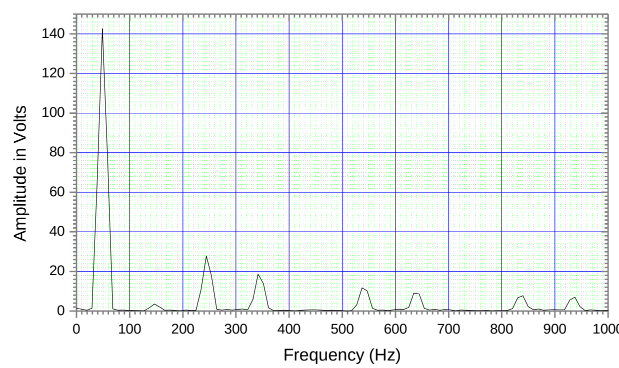

Fig. (11a): FFT of Phase Voltage (Exptl., 50Hz, 2-level)

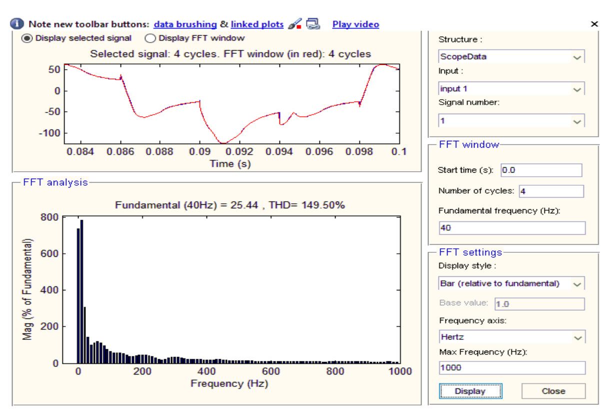

Fig. (12a): FFT of Phase Voltage (40Hz, 3-level)

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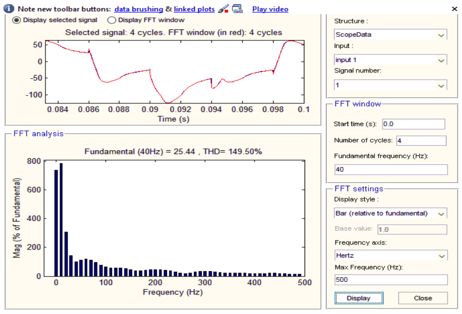

Fig. (12b}: FFT of Phase Voltage with reduced Scale (40Hz, 3-level)

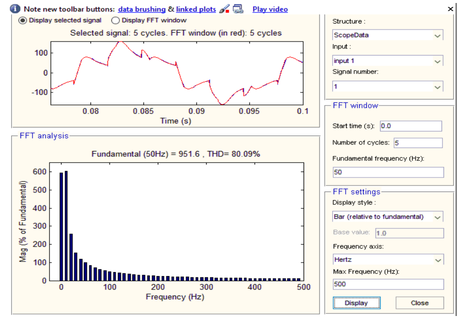

Fig. (14b): FFT of Phase Voltage with reduced Scale (50Hz, 3-level)

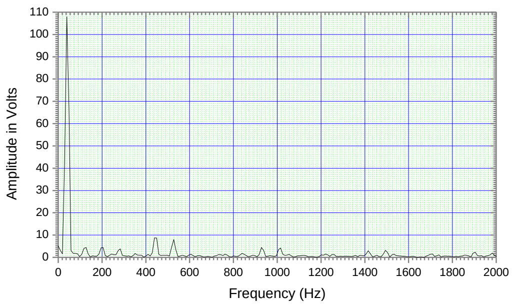

Fig. (13a}: FFT of Phase Voltage (Exptl. 40Hz, 3-level)

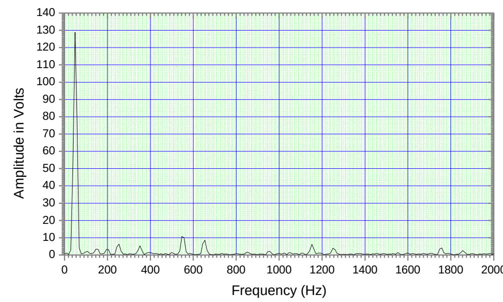

Fig. (15a): FFT of Phase Voltage (Exptl. 50Hz, 3-level)

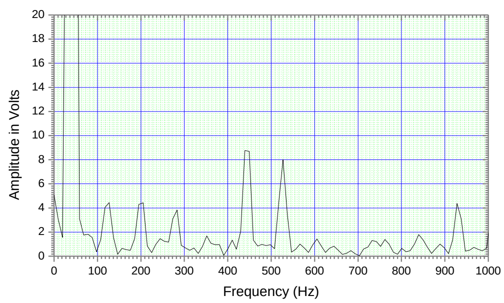

Fig. (13b): FFT of Phase Voltage with reduced Scale (Exptl. 40Hz, 3-level)

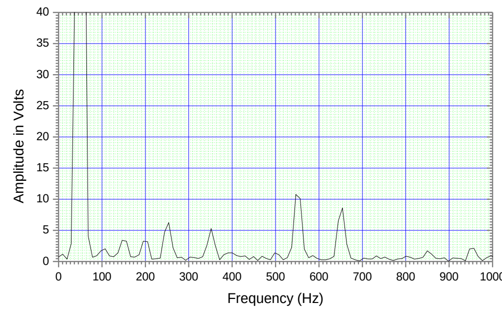

Fig. (15b): FFT of Phase Voltage with reduced Scale (Exptl. 50Hz, 3-level)

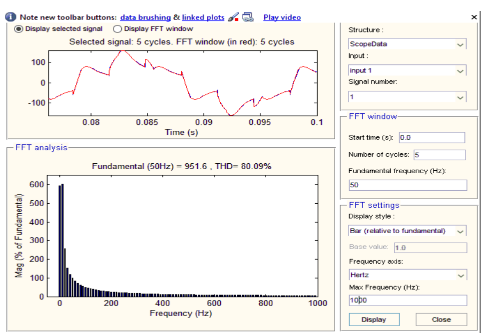

Fig. (14a): FFT of Phase Voltage (50Hz, 3-level)

VI. CONCLUSION

This paper presents a three-phase, 2-level/3-level VSI fed IM drive system and also analyze the harmonic components of the output phase voltage. It is to be noted that the phase voltage harmonics under steady state conditions in simulation and the experimental results are almost the same (5^{th}, 7^{th}, 11^{th} 13^{th} etc.). The magnitudes of harmonics are diminished when the harmonics frequency increases. Also in the simulation and experimental FFT analysis, the THD of phase voltages are shown in Table III. The amplitude of harmonic content is reduced as frequency increases and this would cause less stresses on insulation of the IM.

TABLE III
Comparison of Phase Voltage %THD of the Experimental Results of 2-level and 3-level inverter fed Induction Motor at different frequency.

Parameters	2-level with 6-devices			3-level with 12-devices [7]	3-level with 9-devices		
Frequency (Hz)	30Hz	40Hz	50Hz	40Hz	30Hz	40Hz	50Hz
Phase Voltage % THD (Simulation)	12	10	9	9	10	9	8
Phase Voltage %THD (Exptl.)	10	9	7.7	6.06	8	6.2	5.9

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Mr.Reddy Sudharshana K received the B E, and M. E degree in Electrical engineering from Bangalore University, Bangalore .He is working as an Assistant Professor, Vemana I. T., Bangalore- 560034. India. He has guided many Undergraduate students in Power Electronics field. At present pursing for Ph.D. Degree (Research Scholar) with Jain University, Bangalore, India. He is the member of ISTE, IEEE and Branch counselor, IEEE Student Branch at Vemana I.T. In his credit he has 2 papers published in reputed International conferences / Journal. (email:reddy3690@gmail.com).

Dr.A Ramachandran obtained his Bachelor’s, Master’s and doctoral Degree in Electrical Engineering from Bangalore University, Bangalore, India. He was with National Aerospace Laboratories Bangalore, India, as scientist in various capacities, and was working in the areas of Power Electronics & drives for the past 41years. He was heading the Instrumentation & controls group of Propulsion Division, and guided many Bachelors and Masters Degree students for their dissertation work. He has also guided Ph.D., for the dissertation work and earlier worked has principal, after superannuation and at present professor ECE department, Vemana I.T.Bangalore-34, having number of papers to his credit both in the national/international Journals / conferences. (email:arama1947@gmail.com).

Dr.V Muralidhara obtained his B.E, and M.E degrees from University of Mysore and earned Ph.D. from Kuvempu University. He has a teaching experience of over 40 years inclusive of research as a par at of his Ph.D. Started his teaching career at PES College of Engineering Mandya, served there for 6 years and served for 31 years at Bangalore Institute of Technology [BIT], Bangalore and retired from there as Prof. & Head of EEE. Presently working has an Associate Director at Jain University. His area of interest is Power Systems and HV Engineering. In his credit he has 11 papers published in reputed International conferences and one paper in a Journal. At Present he is guiding five doctorate scholar. email:v.muralidhara@jainuniversity.ac.in).

Dr.R Srinivasan obtained his Bachelor’s, Master’s and doctoral Degree in Electrical Engineering from Indian Institute of Science, Bangalore, India. He was with National Aerospace Laboratory as Scientist and also with Indian institute of Astro-Physics as Professor. After superannuation he is at present as professor in the ECE department at the Vemana Institute of Technology, Bangalore India. He has guided many Bachelor’s, Master’s and Ph.D. Students for the dissertation work. He has also published number of papers in the national/international conferences and Journals. (email:rsrini47@gmail.com).