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Simulation and Experimental measurement of Shaft Voltage, Bearing current in Induction Motor drive using Micro-controller

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ABSTRACT

Generally the Induction Motor (IM) is considered to be a constant speed motor. But due to the advancement in electronics, the IM speed can be controlled as per requirement within limits. While doing the speed control of IM, the ratio of Voltage to frequency to be constant at all speeds. For efficient operation, the 2-level inverter with Pulse Width Modulation (PWM) can be used. However, in this method the inverter output will not be sinusoidal. It will be a stepped square wave, due to that the voltage at the star point of the IM stator winding will not be zero. Hence there exists a voltage with respect to the common ground. This is known as Common Mode Voltage (CMV). The CMV will induce a voltage in the rotor shaft; there by a current will flow to the common ground via the bearing. Due to the flow of current through the bearing the electrical discharge machining (EDM) will takes place at the inner race of the bearing. Hence the life of the bearing will get reduced. To minimize the effect of shaft voltage and bearing current a 3-level inverter can be used. The 3-level inverter output will produce less shaft voltage and bearing current when compared to 2-level inverter. In this paper the authors have done both the 2-level and 3-level inverter for running the IM. The Arduino Micro-controller is used for generating the Space Vector Modulation (SVM) signals and the necessary isolation has been done using opto-isolators. Simulation has been done using MATLAB/Simulink and the results are verified with the experimental results. The Fast Fourier Transform (FFT) has been done for the experimentally recorded shaft voltage and the bearing current for the 2-level and 3-level inverter outputs by using signal analysis software. The experimental and simulated results are compared.

Keywords: Common mode voltage, Induction Motor, space vector modulation, Shaft voltage, Bearing current.

I. INTRODUCTION

It is impossible to get zero Voltage at the star point of the stator winding of the IM [3, 15], if the 3Φ inverter is fed from a single DC source. Hence there will be a common mode voltage (CMV) at the star point. Due to the CMV there will be a voltage induced in the shaft of the IM. The 3Φ inverter is widely used in variable speed IM drive System.

The 2- level inverter has 2-levels of voltage [$\pm 2/3V_{dc}$, $\pm 1/3V_{dc}$], hence the output waveform of two level inverter is stepped square wave. To minimize the CMV the 3-level inverter can be used.

The earlier researchers found that there will be a premature /frequent failure of the bearing used in the speed control of IM

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using inverter, than operating the motor with sinusoidal mains at supply frequency of 50/60Hz [8]. From the references [4, 5, 6, 7 & 8] the inverter fed IM bearings have more probability of failing than mains operated 50/60Hz supply. Also in the year 1924, P. Alger and H. Samson [13] have discussed about the shaft current in electric machines. Due to the existence of CMV, the currents flowing from the shaft to the common ground through the bearing in variable speed drive systems using Converter-Inverter and also by fast switching of the inverter devices has been reported for almost a decade ago [9, 10 & 11]. Annette Muetze et al. [5] also reported about shaft to ground currents due to the existence of CMV and the capacitance between stator and rotor windings with high dv/dt at the input of the IM [4, 5 & 12]. In addition, B. Muralidhara etal. [1, 2] has reported about the CMV and shaft voltage results in the flow of current to the common ground. D. Busse etal. [8], in the year 1997 discussed about the characteristics of shaft voltage and bearing currents. As summarized by Chen etal. [9 & 13] there are three general types of motor bearing currents (stator to rotor bearing current, stator winding to ground current, rotor to shaft current) that can be associated with PWM voltage source inverter (VSI) drive [5, 7 & 12]. Therefore for the safe operation of the motor connected with inverter system, it is essential to reduce the shaft voltage and there by the current flows from shaft to the ground [14, 15]. To reduce the shaft voltage it is necessary to measure and reduce the CMV.

II CMV, SHAFT VOLTAGE, BEARING CURRENT AND SUM OF PHASE CURRENT IN INVERTER DRIVEN AC IM

It is important to define the CMV in mathematical terms in order to compare its characteristics among different types of source and load combinations. In 3Φ AC loads, the phase to ground voltages (V_{a-n}, V_{b-n} and V_{c-n}) can be written as the sum of the voltages to the neutral point of the load and the neutral point of the load to system ground (V_{N-n}). In a three phase symmetrical, sinusoidal and balanced system, the sum of all three phase voltages is zero. The voltage from the neutral to common ground can be defined in terms of phase to ground voltage as shown in Fig 1 and equations (1-4).

$$V_{a-n} = V_{aN} + V_{N-n} \quad (1)$$

$$V_{b-n} = V_{bN} + V_{N-n} \quad (2)$$

$$V_{c-n} = V_{cN} + V_{N-n} \quad (3)$$

For balanced three phase system

$$V_{aN} + V_{bN} + V_{cN} = 0$$

$$V_{N-n} = (V_{a-n} + V_{b-n} + V_{c-n}) / 3 \quad (4)$$

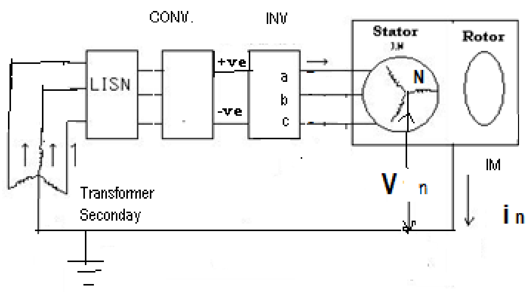

Fig 1 Schematic diagram

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III THE PROPOSED WORK

Simulation, experiment of 2-level, 3-level inverter using SVM for the speed control of induction motor, has been done. The CMV, Phase voltage, sum of phase currents, shaft induced voltage, and the current flowing from the shaft to the common ground (bearing current) using MSO, associated with isolation module are measured. The Hall-effect sensor is used for the measurement of line current and the high frequency current probe is used for the measurement of bearing current. The inverter is built using the MOSFET devices, DC link capacitors and other electronic components.

SVM methodologies have the advantages of more output voltage when compared to sine triangle pulse width modulation (SPWM) method [16]. The advantage of using the SVM is that the gating signal for the power devices can be easily programmed using µ-controllers / digital signal processor (DSP) which offers improved dc bus utilization [17] and reduced switching losses.

SPACE VECTOR MODULATION

The experimental work uses a SVM method, which produces the output voltage by using the 3 nearby output vectors. When one of the reference vector moves from one sector to another, results in an output vector 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. The main advantages are to overcome the variation in DC bus voltage, the ratio V/f of IM is maintained constant by compensating for regulation in inverters. SVM treats sinusoidal voltage as a rotating constant amplitude vector rotating with constant frequency. This PWM technique represents the reference voltage V_{ref} by a combination of the eight switching patterns in a Hexagon. The a-b-c reference frame can be transformed into the stationary α-β reference frame that consists of the horizontal (α) and vertical (β) axes (Coordinate Transformation). The 3Φ voltage vector is transformed into a vector in the stationary α-β coordinate frame which represents the spatial vector sum of the 3Φ voltages. The voltage vectors (V_1-V_6) divide the hexagon plane into six sectors(i.e., sector-1to sector-6) which is generated by two adjacent non-zero vectors. Fig 2 shows the switching vectors of 2-level inverter in hexagon. The 3Φ voltages are shown in equations (5-7).

$$V_a = V_m \sin\omega t \qquad (5)$$

$$V_b = V_m \sin(\omega t-120^0) \qquad (6)$$

$$V_c = V_m \sin(\omega t-240^0) \qquad (7)$$

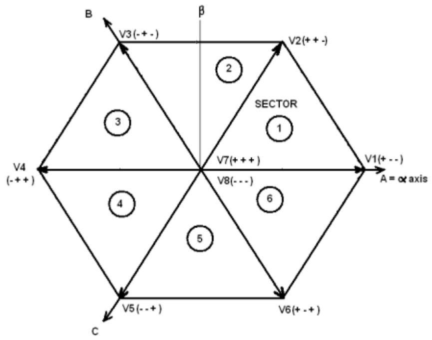

Fig 2 Switching vectors and sectors for 2-level

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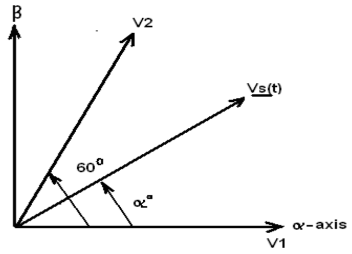

Fig 3 Sampled reference vector in sector-1

SVM is a better technique for generating a fundamental output (~sine wave) that provides a higher output voltage to the 3Φ IM when compared to sinusoidal PWM. The switching vectors and sectors is shown in the Fig (2-4). Table I shows the switching sequence of vectors for 2-level 3Φ inverter.

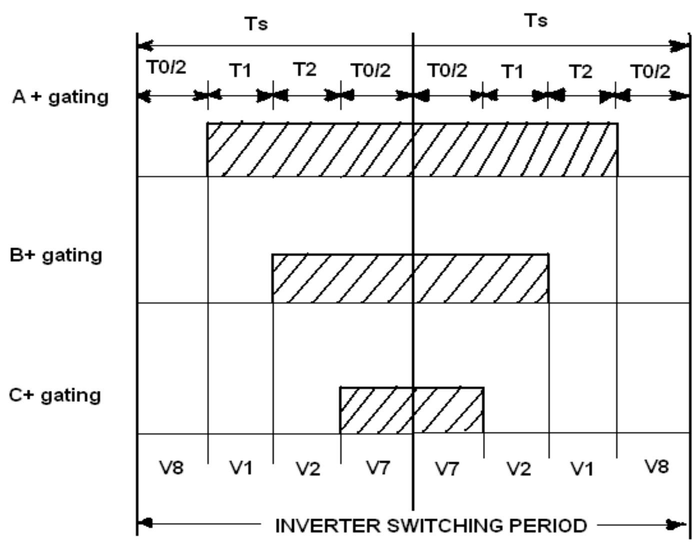

Fig 4 SVM pattern in Sector-1

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	$+V_D$	$-V_{DC}$
V_3[010]	0	1	0	1	0	1	$-V_{DC}$	$+V_D$	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 of 3Φ inverter]

The Hexagon for the 3-level 3Φ inverter is shown in Fig 5 and the Table II shows the switching ON/OFF details.

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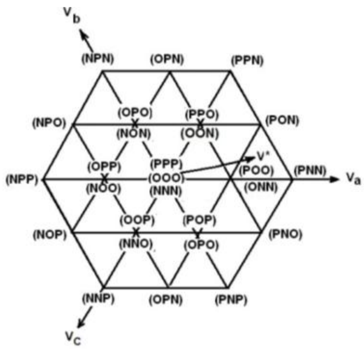

Fig 5 Hexagon of 3-level inverter

TABLE II

Switching vectors for 3-level 3Φ 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

Simulation: The simulation circuit for 2-level, 3-level inverter is shown in Fig (6, 8) and the results of simulated output is shown in Fig (7, 9) for 2-level and 3-level inverter.

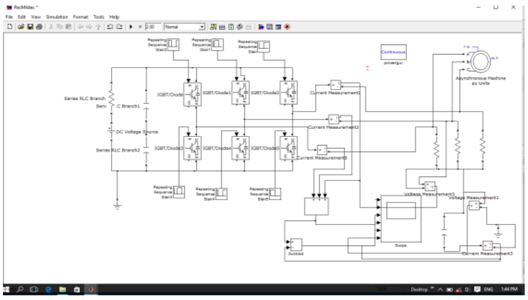

Fig 6, Simulation Circuit 2-level inverter (Matlab/simulink)

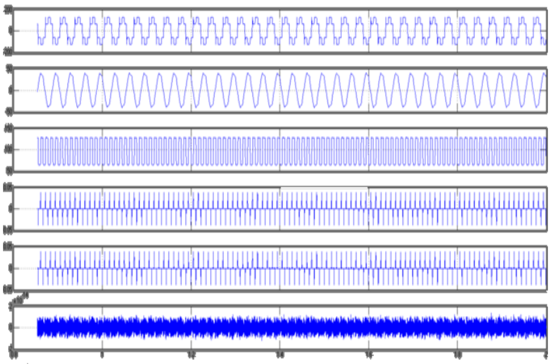

Fig 7 Simulation Results of 2-level Inverter [top to bottom] (Simulation, 30Hz) CH1phase voltage, CH2 line current, CH3 CMV, CH4 Sum of phase current, CH5 Bearing current, CH6 (Sum of ph Ct. – Bearing Ct.) = [(CH4)-(CH5)]

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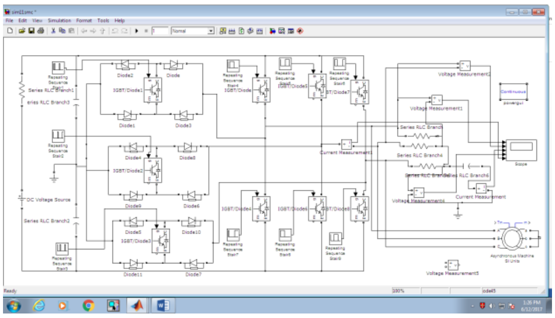

Fig 8 Simulation circuit of 3-level Inverter (Matlab/simulink).

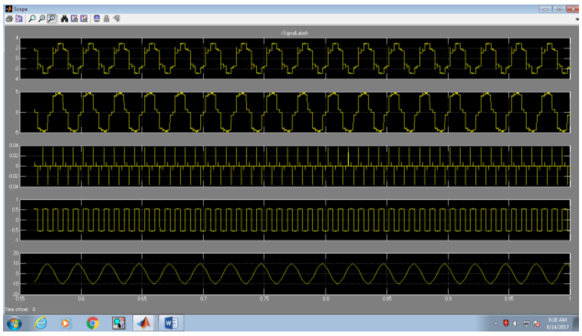

Fig 9 Simulation output of 3-level Inverter (top to bottom)
CH1 Phase Voltage, CH2 Line Voltage, CH3 Bearing Current,
CH4 Common mode Voltage, CH5 Line Current

IV . EXPERIMENTAL SETUP

The Fig 1 shows the schematic diagram. Fig (10, 11) show the experimental circuit diagram of 2-level and 3-level inverter. Fig 12 shows the photograph of the experimental setup. In the 2-level and 3-level inverter, the MOSFETs are used as devices with necessary snubber circuit. The microcontroller output after isolation is given to the gate of the devices [3, 15 & 16]. The microcontroller is programmed for different frequencies of operation of the IM for 2-level, 3-level and the typical output of the microcontroller is given in the Fig (13). While running the IM with the above said setup the shaft voltage, CMV, phase voltage, the current flowing from shaft to common ground and the sum of phase current are recorded using the high frequency current probe and Agilent MSO for further analysis are shown in the Fig (14) & (15).

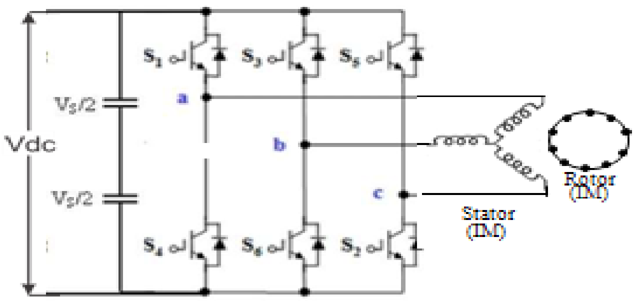

Fig 10, 2-level Inverter Circuit diagram

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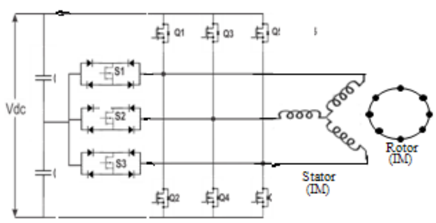

Fig.11.3-level Inverter Circuit diagram.

The necessary FFT has been done in simulation using MATLAB/Simulink and the experimental results using signal analysis software. At the end, the results are discussed showing the sum of phase current and the bearing current are same in magnitude and phase. Also the CMV, the shaft voltage is the same in magnitude and phase, for different frequencies of operation of the IM viz 30Hz, 40Hz and 50Hz.

Fig.12, Photograph of Experimental setup

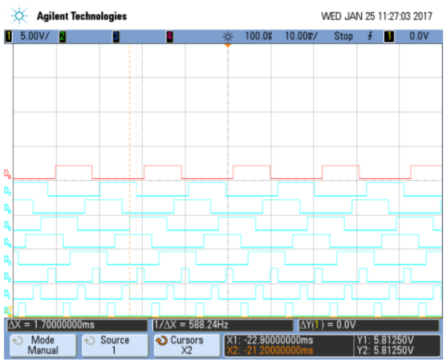

Fig. 13, Gate pulses generated by µ controller (3-level Inverter)

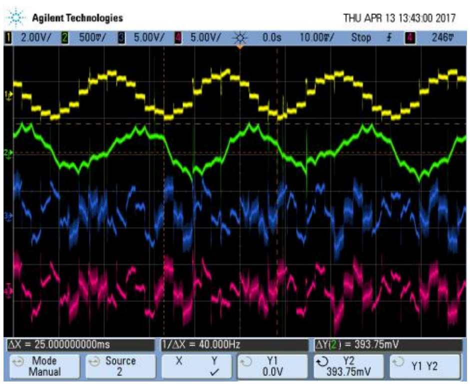

Fig.14, 3-level Inverter output: CH1 Phase Voltage
CH2 line current, CH3 CMV, CH4 Shaft Voltage.

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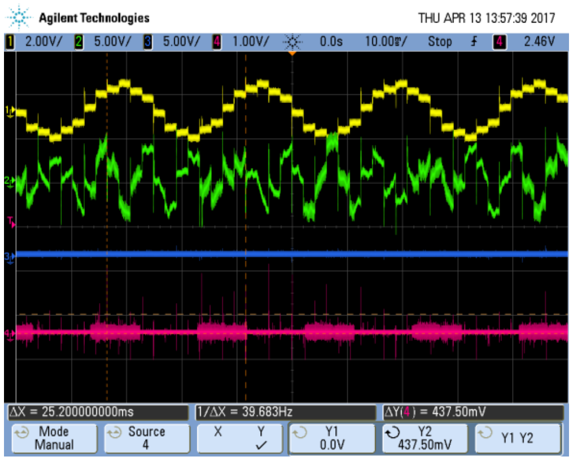

Fig.15, 3-level Inverter output,

CH1-Phase Voltage, CH2 CMV, CH3 Shaft Voltage,

CH4 Bearing current.

FFT Analysis of Simulation and Experimentation

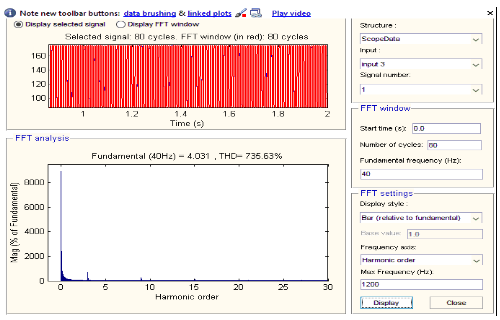

Fig.16, FFT of CMV 2-level, 40Hz

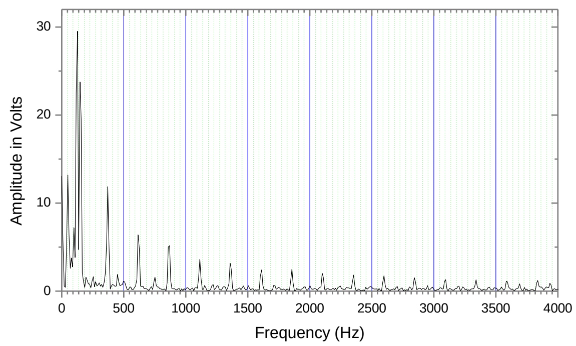

Fig.17, FFT of CMV Exptl. 2level, 40Hz

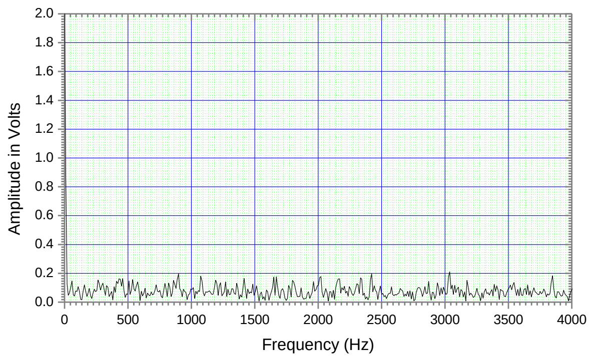

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Fig.18, FFT of shaft voltage, Exptl. 2level, 40Hz

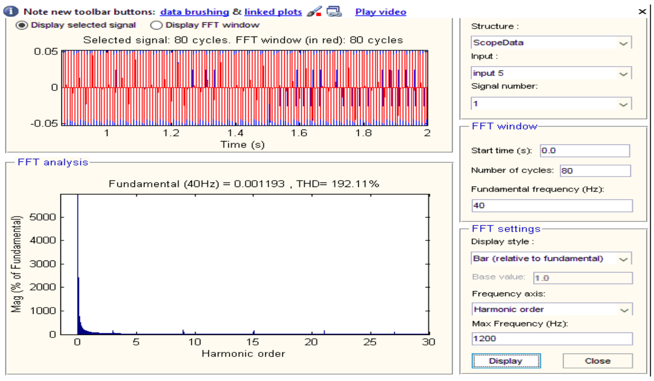


Fig.19, FFT of Bearing current, 2level, 40Hz

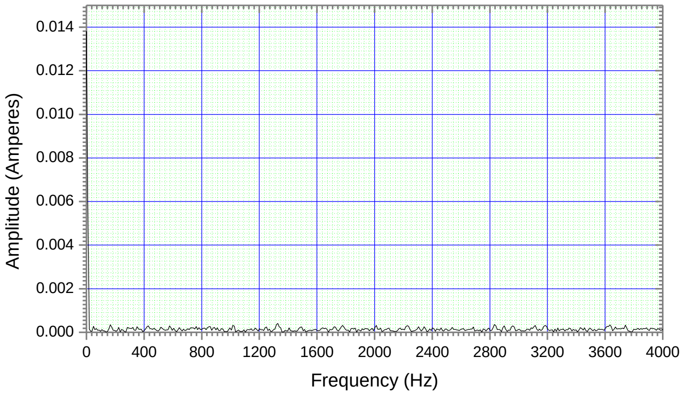


Fig.20, FFT of bearing current, Exptl. 2level, 40Hz

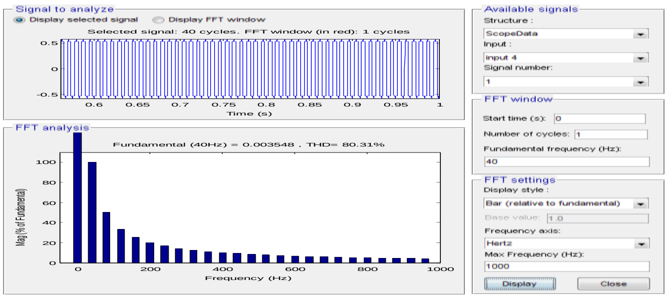
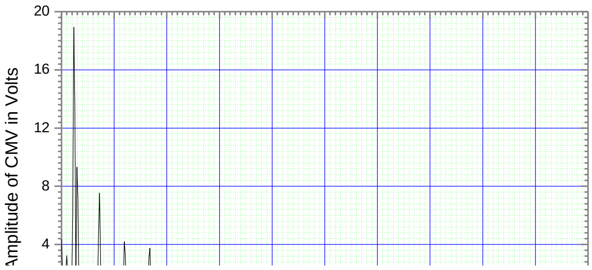


Fig.21, FFT of CMV, 3level, 40Hz



. **Fig.22, FFT of CMV, Exptl. 3level, 40Hz**

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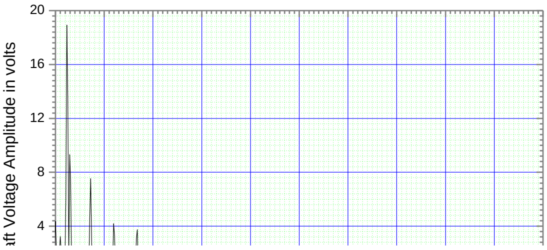

Fig.23, FFT of Shaft voltage, Exptl.3level, 40Hz

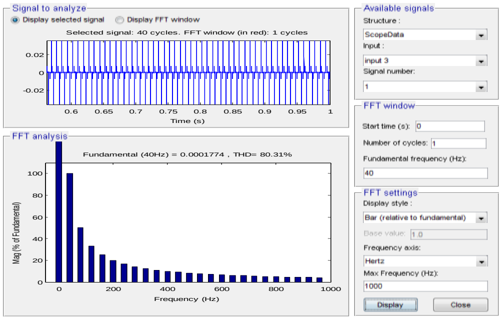

Fig. 24, FFT of Bearing current, 3 level, 40Hz

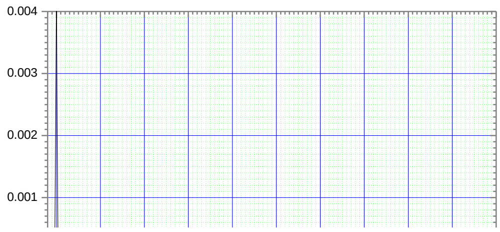

Fig.25, FFT of Bearing current, Exptl. 3 level, 40Hz

V. RESULTS AND CONCLUSION

The Simulated FFT results of 2-level, 3-level CMV, Shaft Voltage, Bearing current are shown in the Fig (16, 19, 21 & 24). The experimental FFT results of 2-level and 3-level for CMV, Shaft voltage, Bearing current are shown in Fig (17, 18, 20, 22, 23& 25).Table-III gives the actual values of fundamental components of CMV, Bearing current in Simulation and the CMV, Shaft voltage, Bearing current of experimental results. It is concluded that in 3-level inverter the CMV, Shaft Voltage and Bearing current are less than that of the 2-level inverter.

TABLE-III

Comparison of CMV, Shaft Voltage and Bearing Current in 2-level, 3-level inverter fed to IM

parameters	Simulation Results (40HZ operation)		Experimental Results (40HZ operation)		
	CMV(in Volts)	Bearing current(mA)	CMV (in Volts)	Shaft voltage (in Volts)	Bearing current(mA)
2-level	36	7.7	29	25	8.1
3-level	25	1.17	18	18	1.15

VI .ACKNOWLEDGEMENT

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