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# Modeling and Simulation Analysis of Bearing Current in Two-Level and Multilevel Inverter Fed Induction Motor Drive

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**Abstract: Adjustable Speed Drives (ASDs) are increasingly used in many commercial and industrial applications because of many advantages in control and efficiency. But ASDs use PWM inverter with high speed switching devices such as Insulated Gate Bipolar Transistors ( IGBTs) having rise time of 0.1µSec.,that generate fast switching transients (high dv/dt) about 6000V/µSec for 400V system and common mode voltage. This common mode voltage causes unwanted shaft voltage and resulting bearing currents. Parasitic capacitive couplings create a path to discharge current in the rotor and bearings results in premature bearing failure. There are mainly two types of bearing currents such as Electric Discharge Machining (EDM) bearing current and high frequency circulating bearing current. Various mitigation techniques for bearing current have been proposed in the literature each technique has certain limitations. Advanced mitigation techniques include dual bridge inverter and multilevel inverters. This paper presents modeling, simulation and analysis of bearing current using Sinusoidal Pulse Width Modulation (SPWM) diode clamped multilevel inverter fed induction motor drive. Simulation is carried out using MATLAB / Simulink software for three phase, 3 H.P (2.2kW) induction motor and inverter switching frequency of 2 kHz.**

**Keywords**: Bearing current, common mode voltage, induction motor drive, multilevel inverter, SPWM.

## I. INTRODUCTION

The phenomenon of bearing currents in induction motors has been known for decades. It has been reported by Alger *[1]* in the 1920's that the basic reason for these currents is asymmetric flux distribution inside of the motor .This problem has been effectively solved with modern motor designing and manufacturing practices. However, unexpectedly the problem has returned since power electronic devices are becoming common in Adjustable Speed Drives (ASDs). PWM inverters with IGBT operate at switching frequencies of 2 to 20 kHz and rise time of 0.1µsec with voltage rise of 6000V/µsec for 400V system. The high dv/dt has adverse effects on bearing damage caused by bearing currents due to common mode voltage *[3]-[6].*

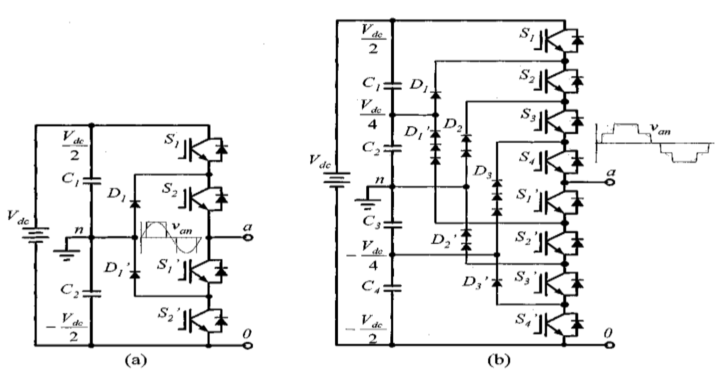

Fig.1 Diode-clamped multilevel inverter circuit topologies. (a) Three-level. (b) Five-level

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The bearing current faults are most frequent in PWM fed ASDs, nearly 30% according to an IEEE motor reliability studies. The bearing currents cause premature bearing failure within 1-6 months of installation. In order to protect ASD investment, predictive maintenance is highly recommended for early detection and schedulable replacement of defective bearing to avoid the hidden costs involved in downtime and lost product.

There are mainly two types of inverter induced bearing currents:
i) Electric Discharge Machining (EDM) bearing current: An electrically insulated lubrication film normally has thickness ranging from 2-3 microns, the bearing voltage $V_b$ mirrors the common mode voltage $V_{com}$ at the stator terminals via capacitor voltage divider i.e Bearing Voltage Ratio (BVR).The electrically loaded oil film between balls and races breaks down when threshold voltage of the film exceeds dielectric strength of lubricating oil of about15Vpk/µm (approx.5-30V) ,thereby causing the EDM current pulses and results in premature bearing failure *[2].*

ii) High frequency circulating bearing current: The high dv/dt at the motor terminals causes mainly because of the stator winding to frame capacitance ( $C_{sf}$) a part of an additional HF common mode current $I_b$=$C_{sf}$ d$V_{com}$/dt. The ground current excites a circular magnetic flux around the shaft of the motor (circulating bearing current).If shaft voltage is large enough to puncture the lubricating film of the bearing and destroy its insulating properties, it causes a circulating bearing current in the loop ' stator frame—non-drive end—shaft—drive end'. Peak amplitude varies depending on the motor size *[2].*

The various mitigation techniques used for bearing current reduction include shaft grounding, insulated bearing, ceramic bearing, conducting grease, the Faradays shield, passive and active filters, symmetrical cable with shielding and dual bridge inverter every technique has certain limitations *[9].* The root cause of bearing current is the common mode voltage. In order to minimize the CM voltage, shaft voltage and bearing current with high quality output voltage which is closer to sinusoidal and also to get lower %THD. The advanced mitigation techniques such as multilevel inverter topologies (with a novel PWM scheme) are preferred. Fig .1 Shows the 3-level and 5 level diode clamped multilevel inverters.

The paper is organized as follows: Section I gives introduction about bearing currents, its causes, types and various mitigation techniques. Section II deals with common mode voltage and multilevel inverters helps to understand background of related work and simulink modeling. Section III explains simulink modeling of inverter, HF induction motor with common mode equivalent circuit. Section IV shows the simulation results .Section V includes the conclusion about the paper and followed by reference and bibliography.

## II. COMMON MODE VOLTAGE AND MULTILEVEL INVERTER

### *A. Common Mode Voltage*

At the PWM inverter output, instantaneous summation of all the three phase voltages is non zero, an average voltage in a neutral point w.r.t ground create so called common mode voltage.

$$V_{cm} = \frac{V_{an} + V_{bn} + V_{cn}}{3} \quad \text{--- (1)}$$

In which $V_{an}$, $V_{bn}$ and $V_{cn}$ are the phase voltages generated by the PWM inverter. The common mode voltage is a stair case function of amplitude equal to the DC bus voltage and the frequency equal to the inverter switching frequency. The waveform of common mode voltage is schematically shown in Fig 2.

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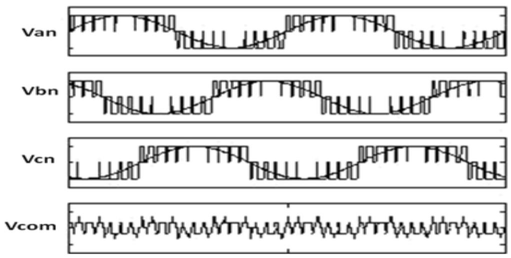


Fig. 2 Common mode voltage

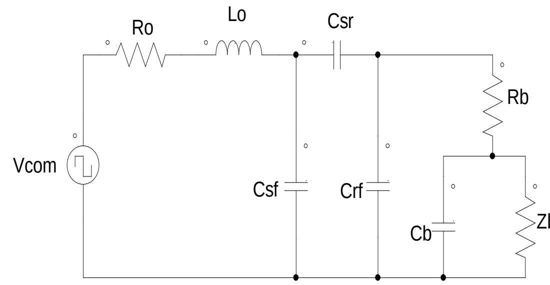


Fig. 3 Common mode equivalent circuit

The shaft voltage has the same shape as the common mode voltage, because the shaft voltage is formed as a result of common mode voltage and capacitive voltage divider circuit. The source of common mode voltage at the output of inverter is the cause of a voltage emerging on shaft, because of the distribution of parasitic capacitances inside of the motor. These create an internal capacitive divider and the BVR can be expressed as in *[3][4].*

$$BVR = \frac{V_{sh}}{V_{cm}} = \frac{C_{sr}}{C_{sr} + C_{rf} + C_b} \qquad \text{--- (2)}$$

Where , $V_{sh}$ is shaft voltage , $C_{sr}$ is capacitance between stator winding and rotor, $C_{rf}$ is capacitance between stator frame and rotor or air gap capacitor ( $C_g$), $C_b$ is bearing capacitance .The ratio $V_{sh}$ /$V_{com}$ is typically in the range of 1:10 because the value of the $C_g$ is much larger than that of $C_{sr}$. The $C_{sr}$ value is small when compared with other capacitances because of the relatively large distance and small area between stator and rotor. However it has significant influence on the value of BVR .Fig .3.Shows the common mode equivalent circuit with various parasitic capacitances in an AC motor that become relevant when the motor is driven by PWM voltage source inverter *[3][4].*

### *C. Multilevel Inverter*

Several multilevel inverter topologies and modulation technologies have been developed and applied to high power and high voltage systems. The main advantages of multilevel inverter topologies is the reduction of voltage stress on the semi conductor devices used in the inverter bridge and the generation of high quality output voltages. They generate smaller Common-Mode (CM) voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, CM voltages can be eliminated *[8].* Presently there are three kinds of multilevel inverters: (1) Neutral Point Clamped inverter (NPC) (2) Flying Capacitor inverter and (3) Cascaded inverter. This paper presents modeling and simulation analysis of neutral point clamped multilevel inverter fed induction motor drive using SPWM technique.

## III. SIMULINK MODELLING

This paper presents modeling and simulation of 2-level and diode clamped multilevel inverter fed induction motor drive using Mat lab/Simulink software. The output voltages of the inverters have been recorded and analyzed for its harmonic contents.PWM signals are generated using a high frequency triangular wave, called the carrier wave, is compared to a sinusoidal signal representing the desired output, called the reference wave. Whenever the carrier wave is less than the reference, a comparator produces a high output signal, which turns the upper switch in one leg of the inverter ON the lower switch OFF. In the other case the comparator sets the firing signal low, which turns the lower switch ON and upper switch OFF *[10].*Simulink model also includes common mode equivalent circuit with bearing model for measurement of shaft voltage and bearing current.

### *A. Modeling of High Frequency Induction Motor and Common Mode Equivalent Circuit.*

The induction motor used in this paper is a 2.2kW (3hp) , fed from a three-phase PWM Inverter using V/Hz to control the motor speed. The induction motor equivalent electrical circuit parameters are determined by two wattmeter's method i.e. no-load and the blocked-rotor tests. These tests were performed at the frequency of 50Hz *[7].*

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Induction motor specification: rated power: 3Hp (2.2kW), rated Voltage: 440V/50Hz (Δ), pole number: 4, rated current: 5A , rated speed: 1500 rpm.
Inverter specification: 2.2kW, switching frequency:2 kHz, output frequency:50Hz, sine triangle PWM modulation technique is used. Table I shows the results for the no-load and blocked rotor tests. The equivalent electrical circuit parameters are determined (per phase) and presented in the in Table II. Fig.4. Shows the per phase equivalent circuit used in the simulation.

TABLE I: INDUCTION MOTOR TEST RESULTS

| Vo(V) | Io(A) | Wo (W) | No (rpm) |
|---|---|---|---|
| 440 | 2.2 | 350 | 1500 |
| Vs (V) | Is (A) | Ps (W) | $R_1$ (`Ω) |
| 150 | 5 | 540 | 0.72 |

TABLE II: COMMON MODE EQUIVALENT CIRCUIT PARAMETERS

| Elements of the model | Simulation values |
|---|---|
| Csf | 11Nf |
| Crf | 1.1Nf |
| Csr | 100Pf |
| Cb | 200Pf |
| $Z_b$ | 7e6`Ω |
| $R_b$ | 10 `Ω |

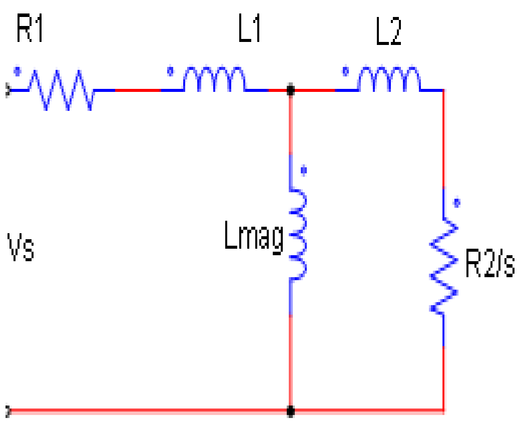



Fig. 4 Per phase motor equivalent electrical circuit

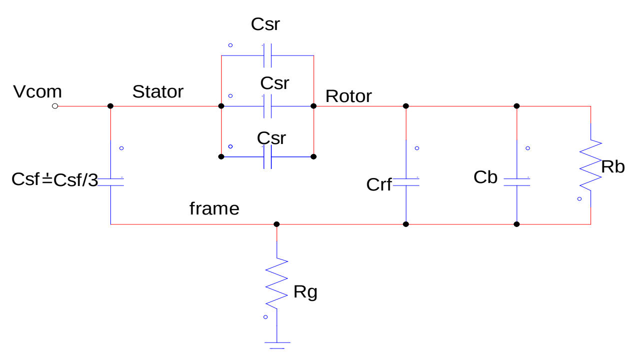
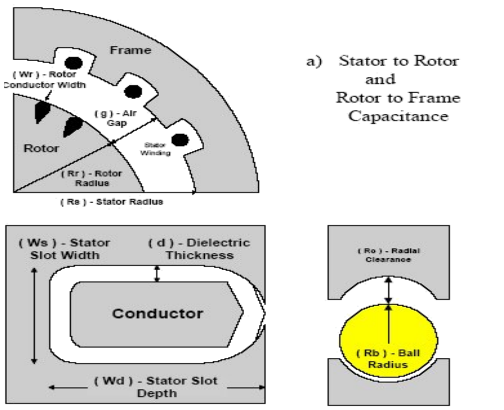



Fig. 5 Simplified high frequency motor equivalent electrical circuit.

The values of parasite capacitances of the induction motor are obtained from curves shown in Fig.7.The capacitance variations as a function of the motor H.P rating and from the capacitance characteristic equations presented as in *[4][5]* .Which show that these parasite capacitances are dependent only on the physical and constructive characteristic of the motor according to Fig.8.

Electrical circuit is drastically simplified as it can be seen impedance between stator winding and rotor Zsr for frequencies under 200 kHz has capacitive behavior and impedance between stator winding and stator frame Zsf is a series RC circuit. Under the inverter switching frequencies the motor parasite impedances have pure capacitive characteristic, so the high frequency induction motor electrical equivalent circuit gets simplified as shown in Fig.5*[7]*.




b) Stator to Frame Capacitance    c) Bearing capacitance

Fig .8 Capacitance model physical description

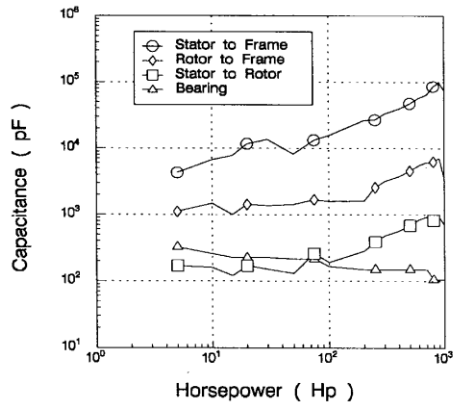



Fig.7 Parasitic capacitor values for different H.P ratings

## *B. Simulink Model*

Fig.7 shows the complete Simulink model of 2-level SPWM inverter fed induction motor drive implemented using MATLAB /Simulink. Similarly for diode clamped multilevel inverters (3,5and7level) fed induction motor drive is implemented. The inverter switching frequency is 2 kHz and the output frequency is 50Hz.

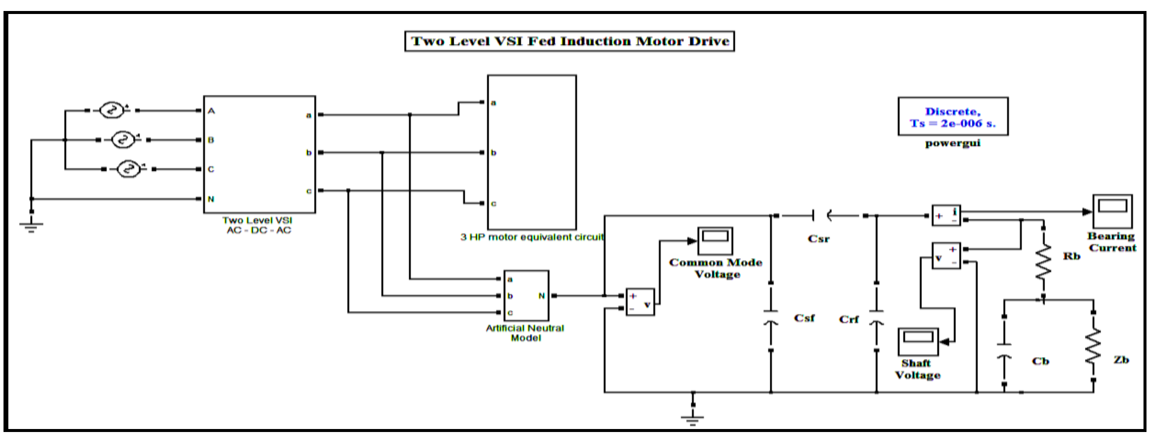



Fig. 9 Simulink model of 2- level PWM VSI fed induction motor

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## IV. SIMULATION RESULTS

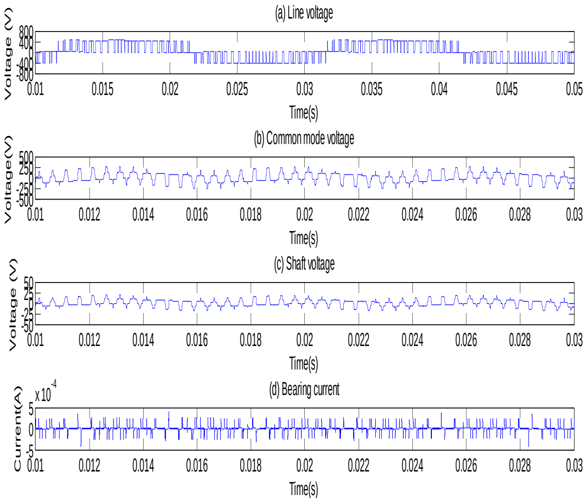


Fig .10 a) Line voltage b) common mode voltage c) Shaft voltage d) bearing current (2-LEVEL)

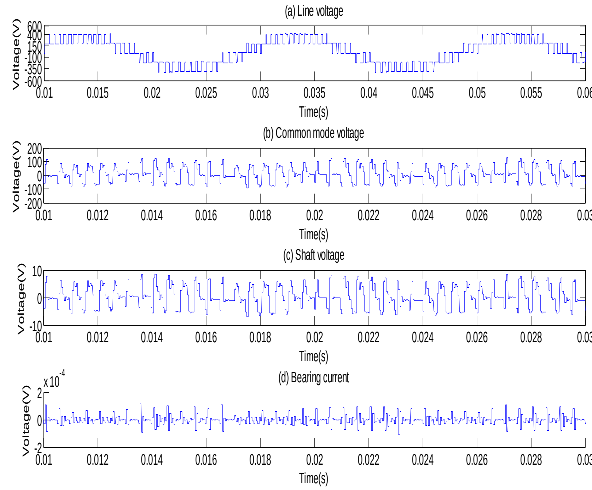


Fig. 11 a) Line voltage b) common mode voltage c) shaft voltage d) bearing current ( 3-LEVEL)

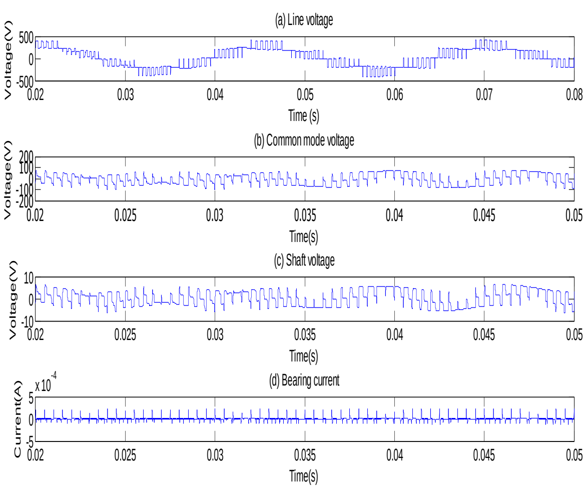


Fig. 12 a) Line voltage b) common mode voltage voltage d) bearing current ( 5-LEVEL)

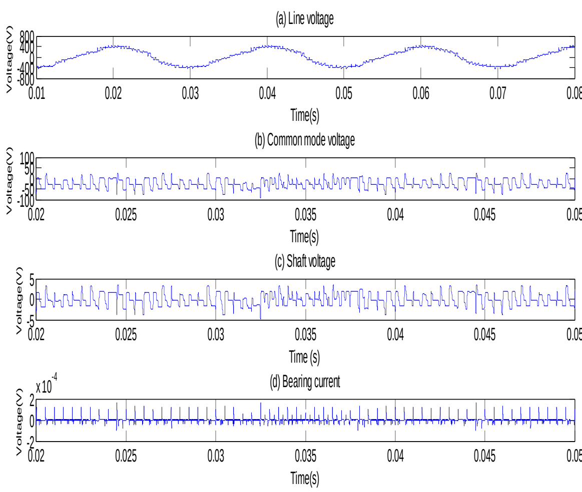


Fig .13 a) Line voltage b) common mode voltage c) shaft c) shaft voltage d) bearing current ( 7-LEVEL)

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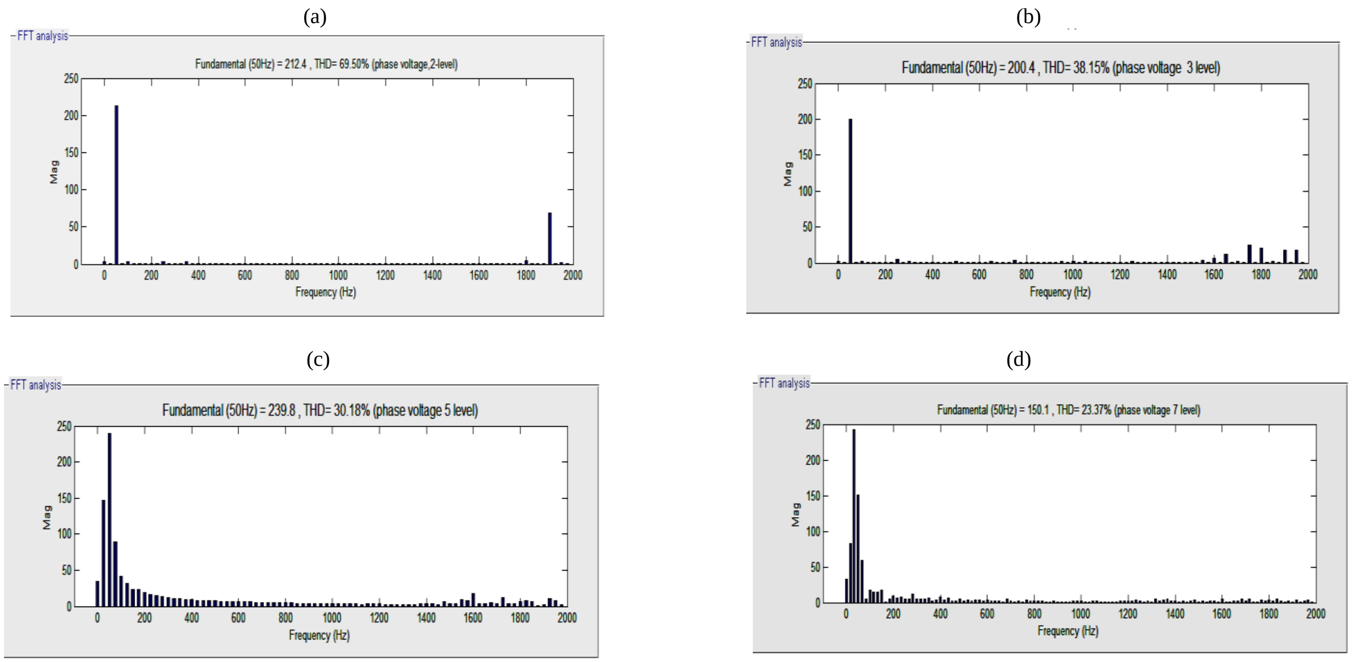


Fig .14 % THD for phase voltage a) 2-level b) 3-level c) 5-level d) 7-level

TABLE IV: COMPARISON OF SIMULATION RESULTS

| Parameter\Level | 2-Level | 3-Level | 5-Level | 7-Level |
|---|---|---|---|---|
| Line voltage(V) | 440 | 440 | 440 | 440 |
| Common mode voltage(V) | 260 | 140 | 74 | 50 |
| Shaft voltage (V) | 20 | 10 | 5 | 3.5 |
| Bearing current (mA) | 0.45 | 0.15 | 0.12 | 0.1 |
| %THD (phase voltage) | 69.05 | 38.15 | 30.18 | 23.37 |

## V. CONCLUSION

In this paper modeling and simulation analysis of the shaft voltage and bearing current for SPWM 2-level and diode clamped multilevel inverters fed induction motor has been presented. A simplified high frequency modeling of induction motor and common-mode equivalent circuit is carried out. It is observed from simulation results , common mode voltage, shaft voltage, bearing current and %THD reduction with 3, 5 and 7 level inverter fed induction motor compared to 2-level inverter fed induction motor. Hence reduction in common mode voltage, shaft voltage, bearing current and harmonics increases the life of the motors as well as reduces many more hidden problems in the motors.

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## BIOGRAPHY

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