



SWITCHING LOSSES ANALYSIS OF MULTI-LEVEL INVERTER FED 3- Φ INDUCTION MOTOR DRIVE

Dr. MODE LAXMANA RAO, D. PRASAD RAO, G. SURESH

4. JAIL SINGH, 5. B. SURYA NARAYANA RAJU

Associate professor & HOD, ELLENKI COLLEGE OF ENGINEERING AND
TECHNOLOGY, HYDERABAD.

Abstract; Multilevel inverters are emerging as a viable alternative for high power, medium voltage applications. This paper compares total harmonic distortion and switching losses in conventional two-level inverters with multilevel inverters (three-level and five-level) at different switching frequencies. An optimized switching frequency has been obtained for a lower level of total harmonic distortion and switching losses.

Keywords: *Harmonics, Multilevel inverters, Pulse width modulation, Switching losses, Total harmonic distortion.*

I. INTRODUCTION

Practical inverters are non-sinusoidal and contain certain harmonics. For low- and medium-power applications, square wave or quasi-square wave voltage may be acceptable, but for high-power applications, sinusoidal waveforms with low distortion are required. Harmonic contents present in the output of a dc-ac inverter can be eliminated either by using a filter circuit or by employing pulse width modulation (PWM) techniques. Use of filters has the disadvantage of large size and cost, whereas use of PWM techniques reduces the filter requirements to a minimum or to zero depending on the type of application. Traditional two-level high-frequency PWM inverters have some drawbacks, such as production of common-mode voltages, more switching losses, requirement of switches with very low turn-on and turn-off times, large dv/dt rating, problem of voltage sharing in series connected devices and introduction of large amount of higher order harmonics. [1][2][3]. Multilevel inverters have found better counterparts to the conventional two-level pulse

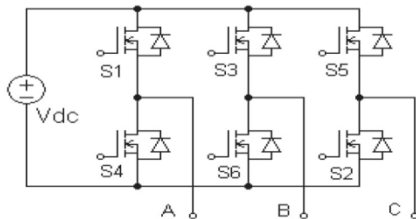
width modulated inverters to overcome the above problems. In addition, they offer the advantage of less switching stress on each device for high voltage, high power applications, with a reduced harmonic content at low switching frequency. A comparative study of three-level and five-level diode clamped, capacitor clamped and cascaded inverters has been presented in [4]. The effect of a passive LC filter on the inverter performance was studied. Simulation results indicate reduction in the total harmonic distortion (THD) by using higher number of levels. Switching losses become a dominant part of the total inverter losses at higher switching frequencies. Therefore, optimization of the switching frequency is necessary to reduce both THD and switching losses in the power devices. Switching frequency optimization was not considered in [4]. Switching losses and THD in three-level and five-level diode clamped inverters can also be optimized by using space vector PWM technique [5][6][7]. This paper investigates two-level inverters and three-level and five-level diode clamped three-phase inverters on the basis of the THDs and switching losses at different switching frequencies. An extensive simulation study to optimize the switching frequency based on the corresponding switching losses and THD contents in line voltage have been presented in this paper. A sinusoidal pulse width modulation (SPWM) technique is used for control. Section II of the paper gives a system description of two-level, three-level and five-level inverters, whereas Section III presents the methodology for the switching loss calculation. Section IV discusses the for two-level, three-level and five-level inverters and the last

section compares these topologies on the basis of switching losses and THD at different switching frequencies. Switching frequency optimization has been carried out to achieve a low level of both THD and switching loss.

II. Basics of Two-Level and Multilevel inverters

1. Two-Level Inverters

This is the most widely used topology in various low- and medium-power applications. The full-bridge configuration of the three-phase voltage source inverter is shown in



Three phase two level inverter

Table 1: Switching states of a two-level three-phase inverter

Load line voltage (V_{AB})	Switching states					
	S_1	S_2	S_3	S_4	S_5	S_6
$+V_{dc}/2$	1	0	0	0	0	1
$+V_{dc}/2$	1	1	0	0	0	0
0	0	1	1	0	0	0
$-V_{dc}/2$	0	0	1	1	0	0
$-V_{dc}/2$	0	0	0	1	1	0
0	0	0	0	0	1	1

The switching logic to obtain output voltage for a 120° mode of operation is shown in .This topology can be used at a very high switching frequency to obtain low THD by using PWM techniques. Power devices are to be connected in series-parallel to achieve a large power capability. They suffer from static and dynamic voltage sharing problems in series and parallel connection of power devices, high rate of change of voltage due to synchronous commutation of series devices and inclusion of high switching frequency harmonic contents in inverter output voltage[3]

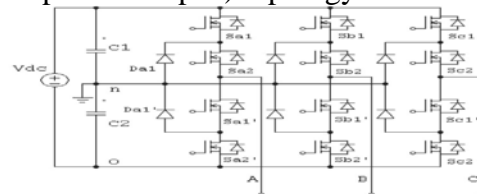
2. Multilevel Inverters

Multilevel inverters have grown as better counterparts to conventional two-level inverters. Commonly employed multilevel inverter topologies are Diode Clamped, Capacitor Clamped and Cascaded Multilevel inverters. In all these topologies, the output voltage is synthesized from several levels of input voltages obtained from several capacitors connected across the dc bus. In a capacitor

clamped inverter, both real and reactive power can be controlled, but it suffers from higher switching losses due to real power transfer thus reducing the efficiency of power conversion. Also, it requires a large number of storage capacitors at higher levels. The cascaded inverter uses a large number of separate dc sources for each of the bridges. However, in the diode clamped topology, all devices are switched at the fundamental frequency resulting in low switching losses and high efficiency. Other main features of this topology are controlled reactive power flow between source and load, much better dynamic voltage sharing among switching devices and simple topological structure. Therefore, diode clamped inverter topology is considered here for study. The control logic is simple, especially for back-to-back inter-tie connections of two systems. However, it requires a large number of clamping diodes for a large number of output voltage levels. To produce an m-level output phase voltage, (m-1) switches are required for each half phase leg, a total of (m-1) dc link capacitors for energy storage and (m-1)*(m-2) clamping diodes for each phase leg[1][2].

3. Three-Level Diode Clamped Multilevel Inverter (DCMLI)

Three-phase diode clamped three-level inverter (neutral point clamped) topology is shown in

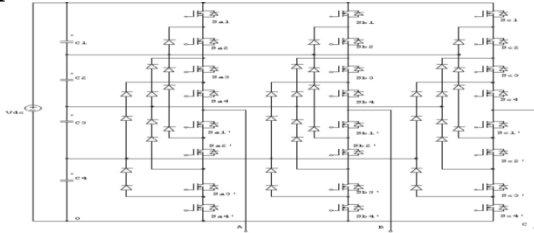


The circuit consists of two dc link capacitors, 12 power switches and six clamping diodes. The middle point of the dc bus capacitor is known as neutral point 'n'. The main feature of this topology is clamping diodes that clamp the switch voltage to half of the dc bus voltage, reducing the voltage stress of the switching device. The output voltage has three different states: +, 0 and - and the corresponding output phase voltages are $+V_{dc}/2$, 0 and $-V_{dc}/2$. Switching states to synthesize the output voltages for phase 'A' are defined in A similar logic can be applied for the other two phases.

4.. Five-Level Diode Clamped Multilevel Inverter (DCMLI)

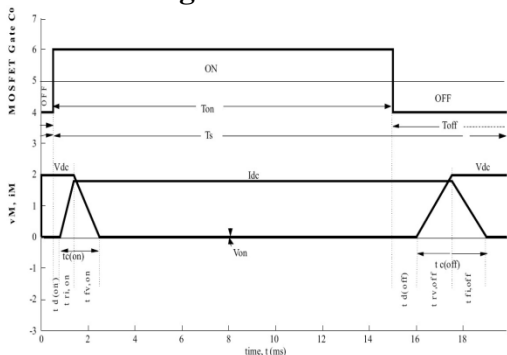
The circuit diagram of the five-level DCMLI topology is shown in It consists of 24 power switches and 36 clamping diodes. The DC bus has four capacitors for a DC bus voltage V_{dc} . The voltage across each

Figure 3: Three-phase five-level diode clamped inverter



capacitor is $V_{dc}/4$; thus, the voltage stress across each device will be limited to $V_{dc}/4$ through the clamping diode. shows the switching combinations and corresponding output phase voltage levels where switching state '1' represents the switch is in 'on' condition and state '0' indicates the switch is in 'off' condition. When the number of levels is high enough in the DCMLI, harmonic contents in the output voltage and current get reduced to avoid the need for filters.

III. Switching Loss Calculations



Consider a single MOSFET switch connected across a dc voltage of value V_{dc} . Current through switch during 'on' time is considered as I_{dc} . Shows the waveforms of the voltage across and the current through the switch when it is operated at a switching frequency of $F_s = 1/T_s$, where T_s is the switching period. To simplify the expressions, the switching waveforms are represented by linear approximations. In the figure, v_M and i_M are the voltage across and the current through the MOSFET[3][5]. Switching losses can be calculated from the turn-on and turn-off characteristics of the devices. Instantaneous voltage and current during turn on time $t_{c(on)}$ are

$$v(t) = V_{dc} - (V_{dc} - V_{on}) * (t/t_{c(on)}); \quad 0 < t \leq t_{c(on)} \quad (1)$$

$$i(t) = I_{dc} * (t/t_{c(on)}); \quad 0 < t \leq t_{c(on)}$$

Instantaneous power during the interval $t_{c(on)}$ is

$$p(t) = v(t) * i(t) = \{V_{dc} - (V_{dc} - V_{on}) * (t/t_{c(on)})\} * \{I_{dc} * (t/t_{c(on)})\} = \{V_{dc} * I_{dc} * (t/t_{c(on)})\} - (V_{dc} - V_{on}) * (t^2/t_{c(on)}^2)$$

and energy dissipated during this interval

$$E_{c,on} = \int_0^{t_{c(on)}} [\{V_{dc} * I_{dc} * (t/t_{c(on)})\} - (V_{dc} - V_{on}) * (t^2/t_{c(on)}^2)] dt$$

$$E_{c,on} = (V_{dc} * I_{dc} * t_{c(on)})/2 - (V_{dc} - V_{on}) * I_{dc} * t_{c(on)}^2/3 = (V_{dc} * I_{dc} * t_{c(on)})/6 - (V_{on} * I_{dc} * t_{c(on)})/3 \quad (4)$$

and during turn-off transition, of $t_{c(off)}$, the current falls from I_{dc} to zero and the V_{on} rises linearly to V_{dc} . The instantaneous voltage and current during this period are

$$v(t) = V_{on} + (V_{dc} - V_{on})/t_{c(off)} \quad (5)$$

$$i(t) = I_{dc} - I_{dc}/t_{c(off)} \quad (6)$$

The instantaneous power dissipated during the interval $t_{c(off)}$ is

$$p(t) = v(t) * i(t) = \{V_{on} + (V_{dc} - V_{on}) * (t/t_{c(off)})\} * \{I_{dc} - I_{dc} * (t/t_{c(off)})\} = V_{on} * I_{dc} + (V_{dc} - V_{on}) * I_{dc} * (t/t_{c(off)}) - V_{on} * I_{dc} * (t/t_{c(off)}) - (V_{dc} - V_{on}) * I_{dc} * (t^2/t_{c(off)}^2) \quad (7)$$

Hence, the energy dissipated can be found as

$$E_{c,off} = \int_0^{t_{c(off)}} [V_{on} * I_{dc} + (V_{dc} - V_{on}) * I_{dc} * (t/t_{c(off)}) - V_{on} * I_{dc} * (t/t_{c(off)}) - (V_{dc} - V_{on}) * I_{dc} * (t^2/t_{c(off)}^2)] dt = (V_{dc} * I_{dc} * t_{c(off)})/6 - (V_{on} * I_{dc} * t_{c(off)})/3 \quad (8)$$

With a switching frequency of F_s , the average switching loss in the switch during each transition of turn on and turn off can be found as

$$P_{c,on} = (V_{dc} * I_{dc} * t_{c(on)}/T_s)/6 + (V_{on} * I_{dc} * t_{c(on)}/T_s)/3 \quad (9)$$

$$P_{c,off} = (V_{dc} * I_{dc} * t_{c(off)}/T_s)/6 - (V_{on} * I_{dc} * t_{c(off)}/T_s)/3 \quad (10)$$

Hence, the average switching loss P_{sw} in the switch is

$$P_{sw} = (1/6) * V_{dc} * I_{dc} * \{t_{c(on)} + t_{c(off)}\}/T_s + (1/3) * V_{on} * I_{dc} * \{t_{c(on)} + t_{c(off)}\}/T_s \quad (11)$$

Modulation techniques for voltage source inverters may be carrier based or carrier-less and open loop or closed loop. These modulation or control techniques for multilevel voltage source inverters are classified in Simulation investigation of different multilevel control techniques have been presented in[11] The SPWM technique is considered for study in this paper. It is the simple technique to be implemented. In the SPWM technique, a triangular carrier wave at a high switching frequency is compared with the sinusoidal reference wave at a fundamental output frequency. The SPWM technique is again divided into Alternate Phase Opposition Disposition, Phase Opposition Disposition and In Phase (PH)[12]

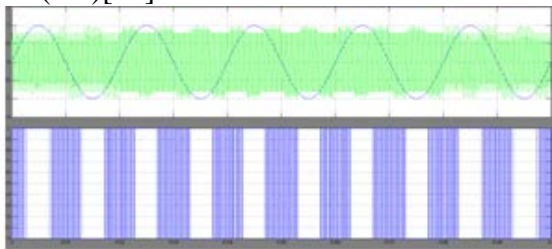
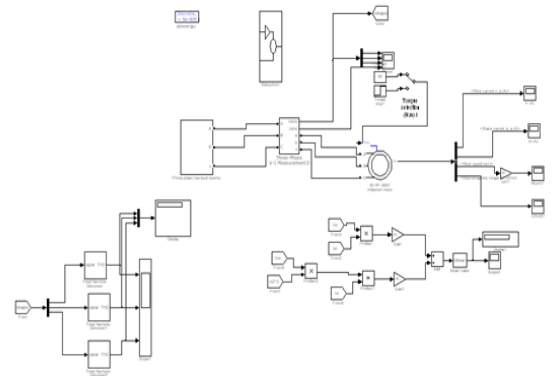


Figure 6: Pulse generation for two-level inverter

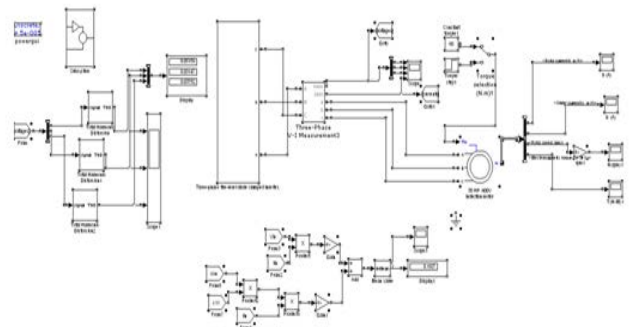
shows the generation of switching pulses for power device S_1 of the two-level inverter shown in fig 6 One triangular carrier wave is compared with a sinusoidal reference wave to generate switching pulses. For power device S_4 , the complementary of this pulse is to be given. The control principle of the SPWM is to use several triangular carrier signals keeping only one modulating sinusoidal signal. If an m-level inverter is employed, (m-1) level shifted carriers will be needed. Two and four triangular carrier signals are needed for three- and five-level inverters, respectively. The carriers have the same frequency f_c and the same peak-to-peak amplitude A_c . The zero reference is placed in the middle of the carrier set. The modulating signal is a sinusoid of frequency f_m and amplitude A_m . At every instant, each carrier is compared with the modulating signal. Each comparison switches the switch 'on' if the modulating signal is greater than the triangular carrier assigned to that switch. Obviously, the actual driving signals for the power devices can be derived from the results of the modulating-carrier comparison by means of a control logic circuit.

IV. SIMULATION ANALYSIS

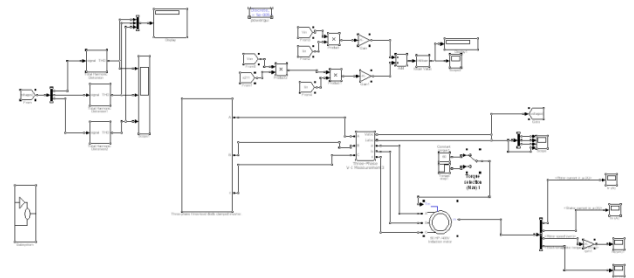
simulation studies have been performed on two-level, three-level and five-level diode clamped three-phase inverters. The output voltage waveform and its frequency spectrum for a two-level inverter at a switching frequency of 1 kHz are gives the THD and switching losses in each phase voltage at different switching frequencies. As the switching frequency is increased THD is reduced. The total switching losses are calculated as discussed in section 3, and tabulated in table1 for the different carrier frequencies ranging from 1500 to5000Hz.



Twolevel inverter fed induction motor drive



three level inverter fed induction motor drive



five level inverter fed induction motor drive

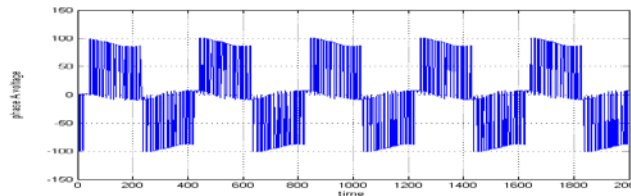


fig 1.two level inverter phase A voltage

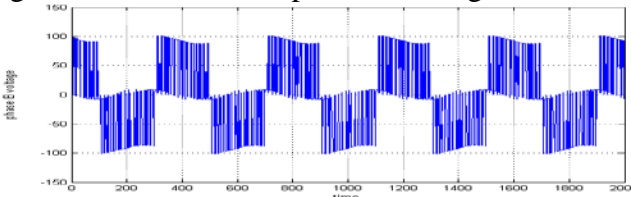


fig 2.two level inverter phase B voltage

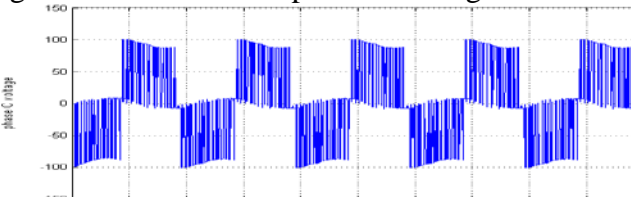


fig 3.two level inverter phase C voltage

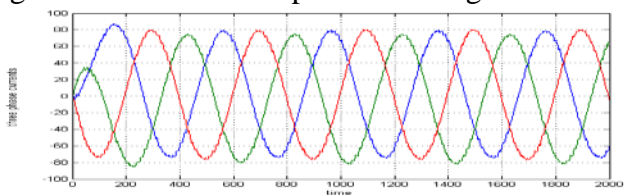


Fig 4. Three phase stator currents

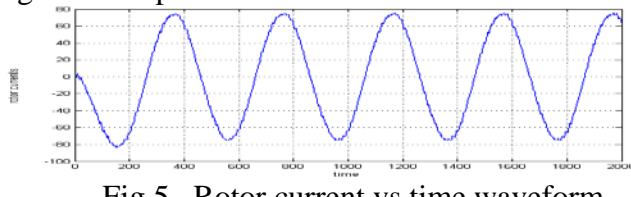


Fig 5 . Rotor current vs time waveform

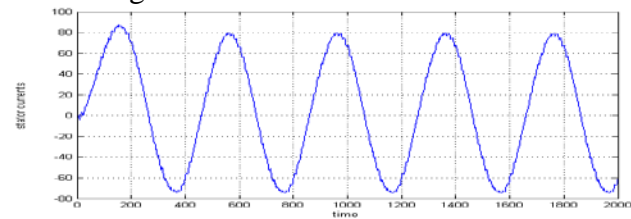


Fig 6. Stator current vs time waveform

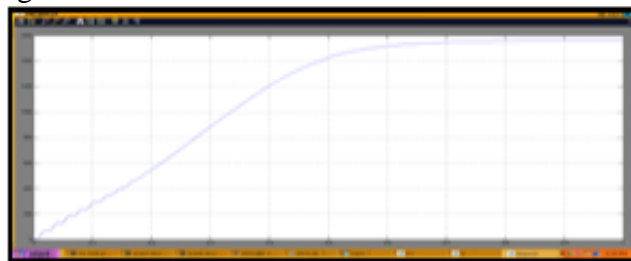


Fig.7 Speed vs time wave form

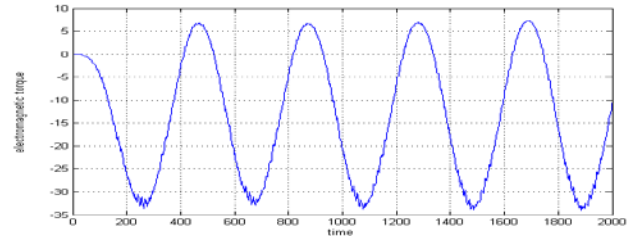


Fig 8. Electromagnetic torque vs time

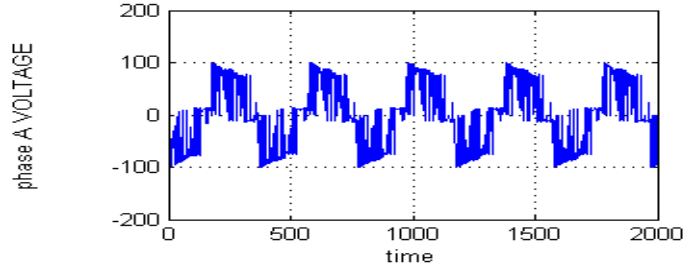


Fig 9 .three level multilevel inverter phase A voltage

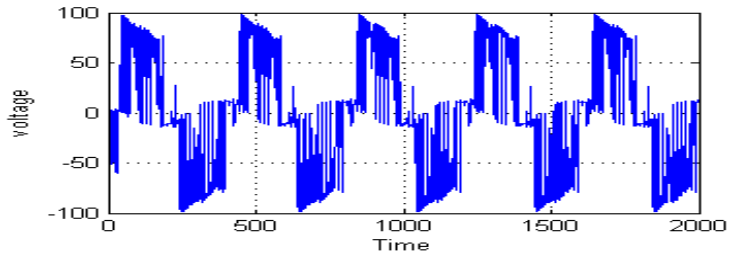


Fig 9 .three level multilevel inverter phase B voltage

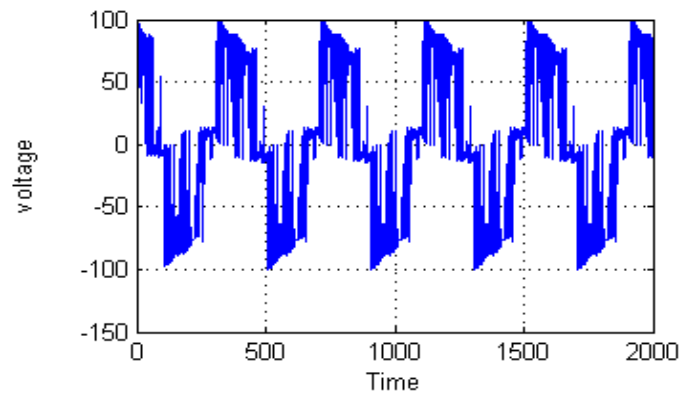


Fig 9 .three level multilevel inverter phase C voltage

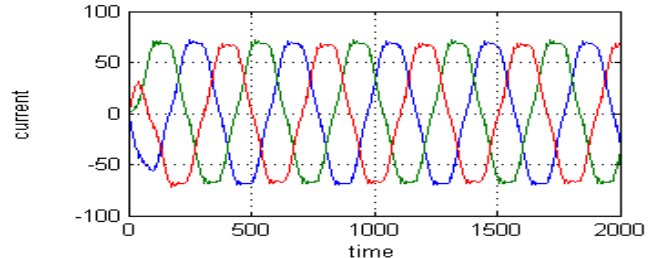


Fig 10 .three level multilevel inverter phase Currents

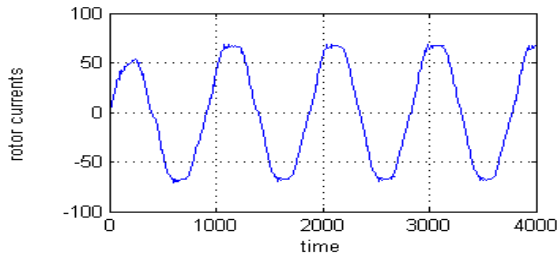


Fig 11. Rotor current vs time waveform

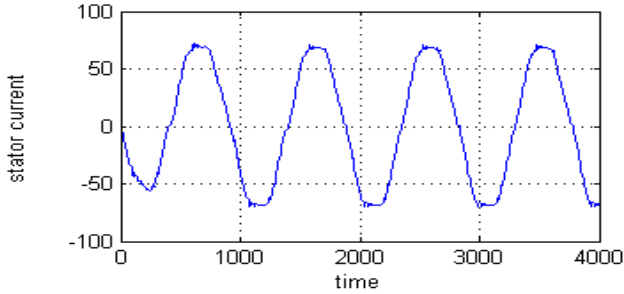


Fig 12. Stator current vs time waveform

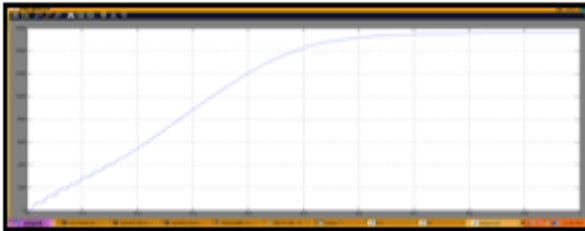


Fig.13 Speed vs time wave form

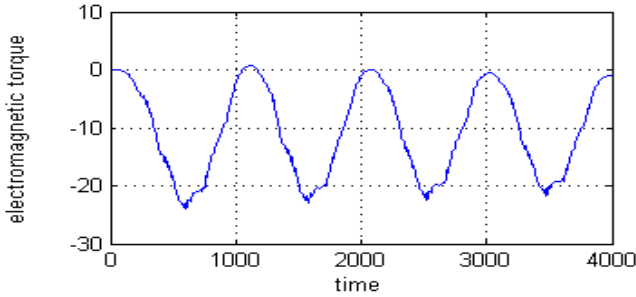


Fig 14. Electromagnetic torque vs time

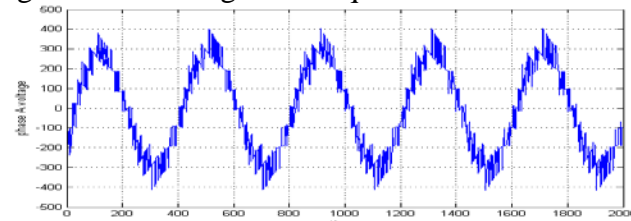


Fig 15 .five- level multilevel inveter phase A

A

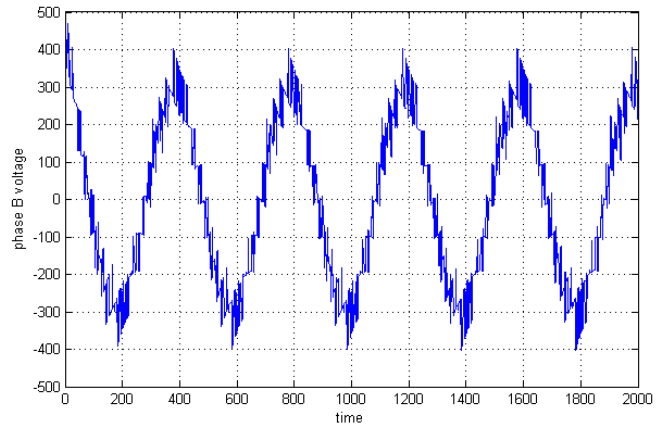


Fig 16 .five- level multilevel inveter phase A

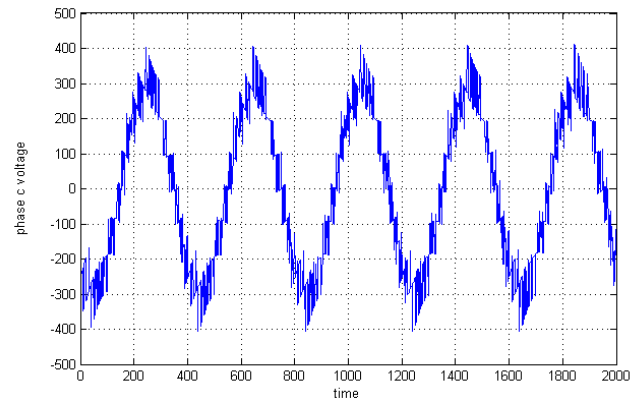
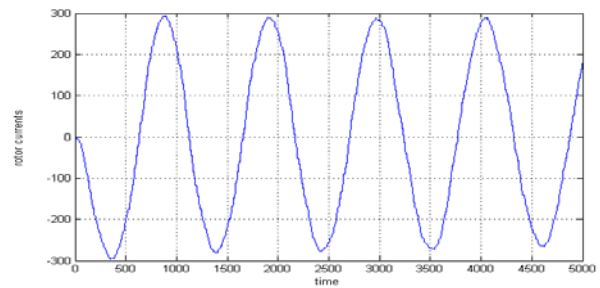


Fig 17 .five- level multilevel inveter phase C



18. Rotor current vs time waveform

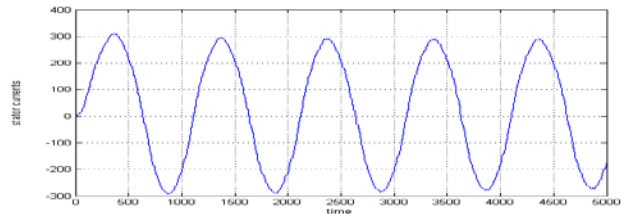


Fig 19. Stator current vs time waveform

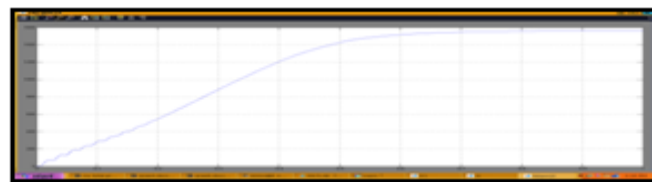


Fig20 Speed vs time wave form

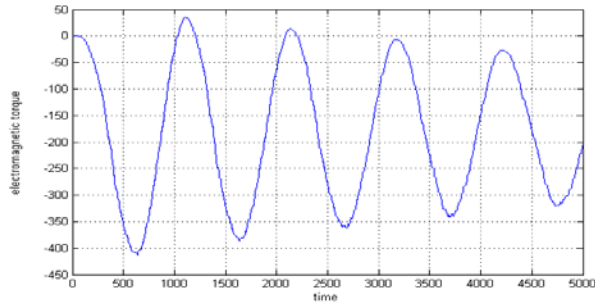


Fig21. Torque vs time waveform

V. RESULT DISCUSSION

That a decrease in the carrier frequency results in a lower value of switching losses. This is due to the reduced number of 'sampling points' at reduced carrier frequencies, which in turn limit the number of switching transitions in one PWM switching cycle, resulting in lower switching losses. Lowering the value of the carrier frequency still preserves the average shape of the fundamental 50 Hz sinusoidal but exhibits an increase in the THD due to increased 'notches' within the width of each generated output pulse. To locate the optimum point whereby both THD and switching losses are optimized, the performance of the two-level converter is observed at several carrier frequencies and the values of THD and switching losses are noted. The THD and the total switching losses are calculated and tabulated in

table1 ;THD and switching losses for a two-level inverter at different switching frequencies

Carrier frequency (hz)	Phase A(thd)	PhaseB(thd)	Phase C(thd)	Total Switching lossess(mj)
1500 HZ	44.26	44.35	44.82	25.80
2500	40.48	40.73	40.63	47.68
3500	37.56	37.42	37.61	62.35
5000	31.83	31.54	31.67	88.18

unequal device rating would be necessary for the five-level inverter as well, similar to that of the three-level topology. From Output voltage waveform and its frequency spectrum for the three-level inverter at a switching frequency of 1 kHz are shown in The THD and the total switching losses are calculated and tabulated in

for different carrier frequencies ranging from 1500 to 5000 Hz. From the simulation results and analysis taken for the three-level three-phase inverter, it is observed that with the increase in the number of levels, the system performance is improved in terms of the THD and switching losses. The voltage impressed across the terminals of the switches is reduced from 200 to 100 volts as compared to the two-level inverter. However, it is also observed that an unequal device rating would be necessary for the three-level inverter.

Table2 THD and switching losses for a three-level inverter at different switching frequencies

Carrier frequency (hz)	Phase A(thd)	PhaseB(thd)	Phase C(thd)	Total Switching lossess(mj)
1500 HZ	34.10	34.13	33.94	21.88
2500	22.05	22.39	22.52	31.86
3500	14.68	14.93	14.89	39.40
5000	8.97	8.64	9.16	46.64

it can be seen that to obtain an output voltage corresponding to that of V_{dc} of the input voltage, all top switches have to be turned on. However, to produce the level of $0.75V_{dc}$, switches S_{a2} , S_{a3} and S_{a4} remain on while S_{a1} turns off and its complement S_{a1}' turns on. This continues until a voltage output of $0.5V_{dc}$ is required, which in turn causes S_{a2} to turn off and its complement S_{a2}' to be turned on. When a voltage level of $0.25V_{dc}$ is needed, S_{a3} turns off while S_{a4} remains on. Hence, it can be seen that S_{a4} remains on for three switching sequences allowing it to conduct over the entire cycle except when the output voltage required is zero. Such unequal conduction duty cycle requires the switches to be sized differently in terms of both their current and their voltage ratings. When the inverter design is to use the average duty for all devices, the outer switches may be oversized and the inner switches may be undersized as in the three-level inverter. shows the total switching losses and % THD in each phase voltage for different carrier frequencies ranging from 1500 to 5000 Hz for a

five-level inverter. It is noted that switching losses are considerably reduced than that of the two-level and three-level inverters mainly due to the fact that the voltage across the terminals of the switch is considerably lesser.

Table 3. THD and switching losses for the five-level inverter at different switching frequencies

Carrier frequency (Hz)	Phase A (thd)	Phase B (thd)	Phase C (thd)	Total Switching losses (mJ)
1500 HZ	25.94	25.66	24.93	13.42
2500	19.18	19.64	19.64	19.47
3500	8.18	8.83	8.83	26.60
5000	6.31	5.37	5.37	33.33

VI. CONCLUSIONS

A comparative study of THD of the output voltage waveform and switching losses of two-level, three-level and five-level three-phase diode clamped inverters has been presented in this paper using the SPWM technique. It has been observed that both THD and switching losses decrease with the increase in the number of levels in the output voltage. However, with the decrease in carrier frequency, the THD level increases and switching losses reduce proportionately

REFERENCES

- [1] F. Z. Peng & J. S. Lai, 'Multilevel Converters - A new breed of power converters', *IEEE Transaction on Industry Applications*, Vol. 32, No. 3, May/June, 1996, pp. 509-517.
- [2] Jose Rodriguez, J. S. Lai & F. Z. Peng, 'Multilevel Inverters: A Survey of Topologies, Controls, and Applications', *IEEE Transaction on Industrial Electronics*, Vol. 49, No. 4, Aug 2002, pp. 724-738.
- [3] Mohan Ned, Undeland T.M. & Robbins W.P., 'Power Electronics: Converters, Applications and Design', John Wiley and Sons, Second Edition, 2001.
- [4] G. Bhuvaneswari & Nagaraju, 'Multilevel Inverters - A Comparative Study', *IETE Journal of Research*, Vol. 51, No.2, Mar-Apr 2005, pp. 141-153. †
- [5] B. Kaku, I. Miyashita & S. Sone, 'Switching Loss Minimized Space

Vector PWM Method for IGBT Three-Level Inverter', *IEE Proceedings, Electric Power Applications*, Vol. 144, No. 3, May 1997, pp 182-190.

- [6] Markku Jokinen & Anssi Lipsanen, 'Fundamental Study of 2-Level and 3-Level frequency Converters', Assignment on converter Losses, SMOLA, Norway, 2005.
- [7] Trzynadlowski A. M., 'Space Vector PWM Technique with Minimum Switching Losses and a Variable Pulse Rate', *Conference Proceedings of IECON 1993*, pp. 689-694.
- [8] Richard Lund, Jonas B., Sigurd O. & Roy Nilsen, 'Analytical Power Loss Expressions for diode Clamped Converters', *EPE-PEMC*, Dubrovnik and Cavtat, 2002.
- [9] A.D. Rajapakse, A.M. Gole & P.L. Wilson, 'Approximate Loss Formulae for Estimation of IGBT Switching Losses through EMTP-type Simulations', *IPST-2005*, Montreal, Canada, Jun 19-23, 2005, Paper no, IPST05-184.
- [10] Alain Laprade & Ron H. Randall, 'Numerical Method for Evaluating IGBT Losses', *Application Notes, Fairchild Semiconductors*, Jan 2000, AN-7520. †