GENERALIZED SCALAR PWM ALGORITHMS FOR DIODE CLAMPED MULTILEVEL INVERTER FED VECTOR CONTROLLED DRIVES

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ABSTRACT

This paper presents simple generalized scalar PWM algorithms for three and five-level inverter fed vector controlled drive. The proposed PWM technique uses the notion of imaginary switching times and hence does not require sector and reference voltage vector calculations. Based on the magnitude tests, the minimum and maximum times will be calculated. From which the generalized offset time expression is derived. By varying a constant between 0 and 1 in offset expressions, various PWM methods such as continuous and discontinuous PWM techniques are derived. Thus, the all PWM techniques brought under one umbrella. Moreover, the same generalized PWM approach can be easily extended to multilevel inverters by increasing the number of carrier signals. To evaluate the performance of proposed PWM technique, numerical simulation studies have been carried out on multilevel inverter fed vector controlled drive in MATLAB environment. From the results, it is observed that when compared with continuous modulating PWM technique discontinuous modulating signal based PWM techniques give reduced switching losses for same switching frequency. Moreover, the quality of waveforms is increased as the number of level increases.

Keywords: *generalized PWM, multilevel inverter, scalar PWM, vector control*

1. INTRODUCTION

Nowadays, the vector controlled drives are becoming popular for high-performance industry applications, vehicle applications, etc. With the help of vector control technique, the induction motor will be operated as a separately excited dc motor by achieving the decoupled control. However, the classical vector control gives variable switching frequency operation due to the hysteresis controllers. Moreover, the 2-level inverter based vector controlled drive applications are limited to low power applications [1-6]. Hence, to overcome these drawbacks, the PWM techniques based multilevel inverter fed drives became popular.

The multilevel inverter topologies are gaining importance in medium and high power applications. Different multilevel inverter configurations like diode clamped multi level inverter, capacitor clamped multilevel inverter and cascaded H-bridge multilevel inverter topologies were proposed in literature [7-9]. Though the cascaded multilevel inverter topology [10] has many advantages when compared with diode clamped multilevel inverter [11], the cascaded H-bridge topology requires separate voltage sources for its operation. So, in applications where separate DC-sources are not available, diode clamped multilevel inverter is gaining importance [11].
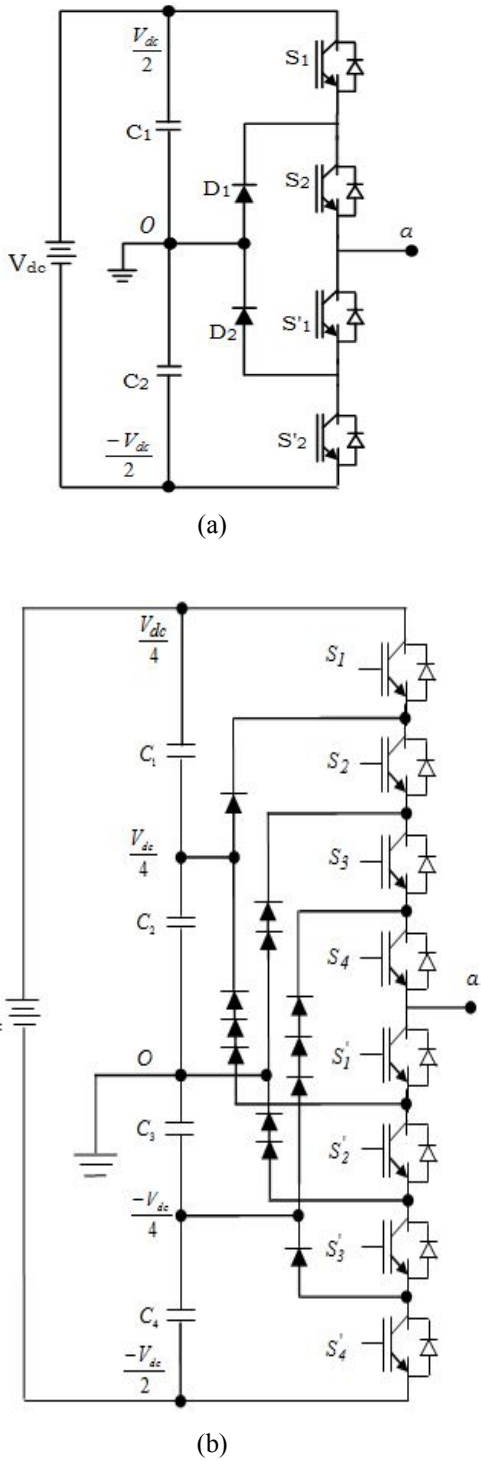
In literature, different PWM techniques based on carrier comparison approach [12-13] and space vector approaches [14-15] were proposed for multilevel inverter for the control of output voltage and frequency. The PWM techniques discussed in [12] could able to control the output parameters but generate low quality output voltage. In order to improve the output voltage quality space vector based PWM technique is presented [14-15]. In [16] authors proposed hybrid PWM technique using current ripple analysis for the improvement of quality of output voltage and reduced current ripple. These space vector based PWM techniques are complex for real time implementation. Because, this approach requires reference voltage vector calculation and sector information. Moreover, the complexity increases as number of levels increases due to the increment in number of voltage space vectors.

To reduce the complexity involved in space vector based PWM techniques simple scalar based implementation of PWM techniques for conventional two-level inverter configuration are presented in [17-20]. These PWM techniques do not require sector identification. In paper [20] different continuous and discontinuous modulating signal based PWM techniques were presented for conventional two-level inverter topology for the improvement in quality of output voltage, reduce current ripple and reduce switching losses. In this paper the scalar based continuous and discontinuous PWM techniques are employed for the three-level and five-level diode clamped multilevel inverter configuration for the improvement in quality of output voltage and reduce the switching losses.

2. SCALAR PWM TECHNIQUE FOR N-LEVEL DIODE CLAMPED MULTILEVEL INVERTER

The circuit topologies of a phase or leg in three and five-level diode clamped multilevel inverters are shown in Fig. 1. From which, it is observed that for an N level inverter 2(N-1) switches are present in one leg. In Fig. 1(a), the dc-bus voltage is split into three levels by two series-connected bulk capacitors, C_1, C_2. The key components that distinguish this circuit from a conventional two-level inverter are D_1 and D'_1. The potential across V_{ao} is called as pole voltage, V_{an} is called as the phase voltage (n is the neutral point of star connected load of induction motor) and V_{ab} is called as line voltage. The output pole voltages with different switching combinations are given in Table 1 and Table 2.

(a)

Table 1 Switching combination in three-level diode clamped inverter

Switching combinations	Pole voltage
S_1 and S_2 are ON S_1' and S_2' are OFF	$V_{dc}/2$
S_1 and S_2 are OFF S_1' and S_2' are ON	$-V_{dc}/2$
S_1' and S_2 are ON S_1 and S_2' are OFF	0
S_1' and S_2 are OFF S_1 and S_2' are ON	0

Table 2 Switching combination in five-level diode clamped inverter

Switching combinations	Pole voltage
S_1, S_2, S_3 and S_4 are ON S_1', S_2', S_3' and S_4' are OFF	$V_{dc}/2$
S_1', S_2, S_3 and S_4 are ON S_1, S_2', S_3' and S_4' are OFF	$V_{dc}/4$
S_1', S_2', S_3 and S_4 are ON S_1, S_2, S_3' and S_4' are OFF	0
S_1', S_2', S_3' and S_4 are ON S_1, S_2, S_3 and S_4' are OFF	$-V_{dc}/4$
S_1', S_2', S_3' and S_4' are ON S_1, S_2, S_3 and S_4 are OFF	$-V_{dc}/2$

(b)

Fig. 1 Diode-clamped multilevel inverter circuit topologies (a) three-level (b) five-level

For the control of output voltage and frequency, different PWM techniques are employed for multilevel inverters. In carrier comparison approach to generate control signals for two level inverter one carrier signal is used. Similarly, to generate control signals for N-level inverter N-1 level shifting carrier signal are required. Hence, the three-level inverter requires two level shifting carrier signals and five-level inverter requires four level shifting carrier signals. The intersection point of carrier signals with reference signals gives the switching instants. The realization of carrier comparison approach for the generation of control signals to all top switches for three and five level inverter configurations are shown in Fig. 2.

To generate control signals for 3-phase multilevel inverter configuration, three reference signals are considered as given in (1).

$$V_i = V_{ref} \cos(\theta - 2(r-1)\pi/3)$$
$$i = a, b, c \ and \ r = 1,2,3 \tag{1}$$

From these instantaneous reference signals (V_a, V_b, V_c) the imaginary switching times can be directly calculated as defined in (2) [20].

$$T_{in} = \frac{V_i}{V_{dc}} T_s \qquad i = a, b, c \tag{2}$$

The imaginary switching times may be positive or negative, which depend on reference signals. Hence, these switching times are called as imaginary switching times. From these imaginary switching times, the modulating signals can be generated using (3).
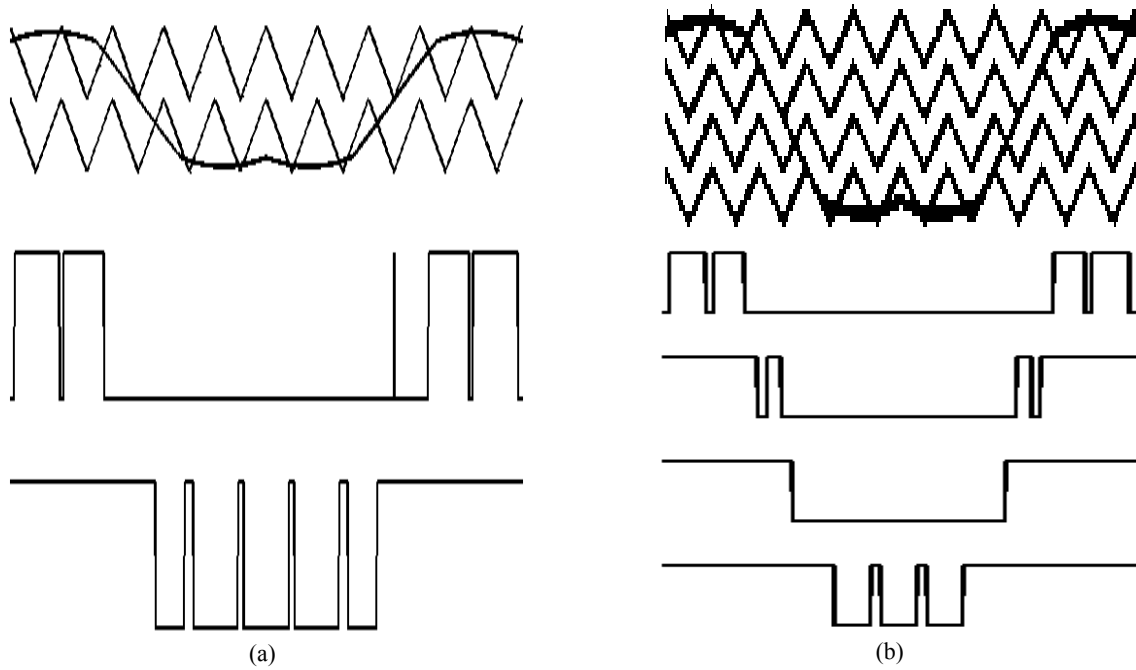
From the Table 1 and Table 2, it is observed that the circuit configuration shown in Fig. 1(a) generates three different voltage levels as $V_{dc}/2$, 0, $-V_{dc}/2$ in the pole voltage and the circuit configuration given in Fig. 1(b) generates five different levels as $V_{dc}/4, V_{dc}/2$, 0, $-V_{dc}/4$, $-V_{dc}/2$ in the output pole voltage. Hence, the circuit configuration shown in Fig. 1(a) and Fig. 1(b) are called as three- level and five- level inverter configurations. When the inverters are operated with switching states given in Table 1 and Table 2, an uncontrolled output voltage is generated.

Fig. 2 Realization of carrier comparison approach for (a) three-level inverter (b) five-level inverter

$$V_{in}^* = \frac{V_{dc}}{2}\left(\frac{T_{gi}}{T_s/2} - 1\right) \tag{3}$$

where

$$\begin{aligned}T_{gi} &= T_{in} + T_s(1 - k_o) + (k_o - 1)T_{max} - k_o T_{min} \\ &= T_{in} + T_{offset}\end{aligned}$$

$$T_{offset} = T_s(1 - k_o) + (k_o - 1)T_{max} - k_o T_{min} \tag{4}$$

Now by varying (k_0) between 0 and 1 in (4), various offset times (T_{offset}) can be generated. This gives various types of continuous and discontinuous modulating signals. The constant k_o value to generate different continuous and discontinuous PWM techniques are given in Table 3. The obtained new reference signals along with old reference signals for different values of k_o are shown in Fig. 3.

Table 3 Generation of various PWM algorithms by varying k_0 value

PWM Algorithm	K_0 Value
SVPWM	0.5
DPWMMIN	1
DPWMMAX	0
DPWM0	if $T_{max,x} + T_{min,x} < 0 \Rightarrow k_o = 0$ if $T_{max,x} + T_{min,x} \geq 0 \Rightarrow k_o = 1$
DPWM1	if $T_{max} + T_{min,} < 0 \Rightarrow k_o = 1$ if $T_{max} + T_{min} \geq 0 \Rightarrow k_o = 0$

DPWM2	if $T_{max,x} + T_{min,x} < 0 \Rightarrow k_o = 1$ if $T_{max,x} + T_{min,x} \geq 0 \Rightarrow k_o = 0$
DPWM3	if $T_{max} + T_{min,} < 0 \Rightarrow k_o = 0$ if $T_{max} + T_{min} \geq 0 \Rightarrow k_o = 1$

These modulating signals in Fig. 3 are compared with common level shifting carrier signal as shown in Fig. 2 to generate control signals for three level and five level inverter configuration.
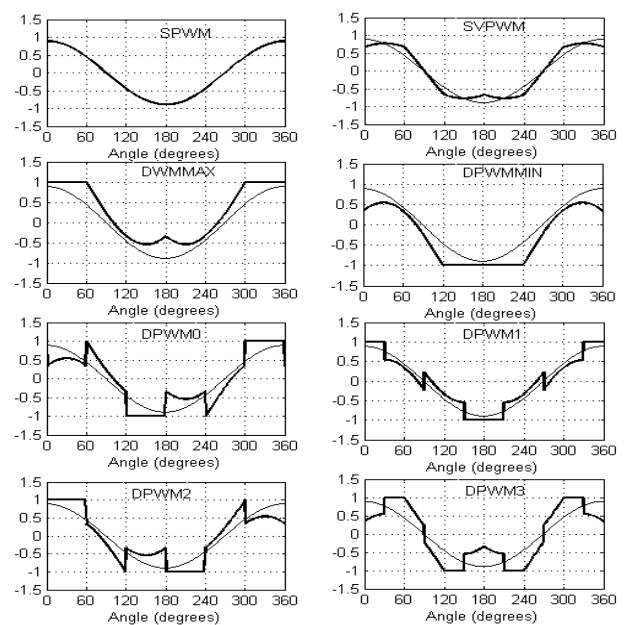

Fig. 3 Different types of continuous and discontinuous modulating signals

3. VECTOR CONTROLLED MULTILEVEL INVERTER FED INDUCTION MOTOR DRIVE

In vector controlled drive, to achieve decoupled control between torque and flux, the stator current vector is resolved into i_{qs} and i_{ds}. The general torque expression of induction motor drive in terms of d- and q-axes currents is expressed as in (5).

$$Te = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr}i_{qs} - \psi_{qr}i_{ds}) \qquad (5)$$

In order to get decoupled control, rotor flux is aligned along d-axis so that the q-axis flux component becomes zero. Hence, the torque equation given by (5) can be modified as in (6)

$$Te = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr}i_{qs}) \qquad (6)$$

The rotor flux linkages is given by (7)

$$\psi_{dr} = L_m i_{ds} \qquad (7)$$

From (6) and (7) it is observed that to control torque I_{qs} is varied and to control flux i_{ds} is varied. As the vector control uses the synchronous reference frame, the instant angle between the synchronous frame and stator frame needs to be calculated. This angle equals to the position angle of the rotor flux vector (θ_s). If the θ_s is calculated, then all quantities can be transformed on to the synchronously rotating reference frame, in which all quantities looks like dc quantities. The reference angle can be calculated using (8).

$$\theta_s = \theta_r + \theta_{sl} = \int (\omega_r + \omega_{sl})dt = \int \omega_s \qquad (8)$$

where ω_r is the rotor speed and ω_{sl} is the slip speed which can be calculated given as in (9).

$$\omega_{sl} = \frac{L_m R_r}{L_r \lambda_r}i_{qs} \qquad (9)$$

Using the above discussed concept and equations, the block diagram of vector controlled induction motor drive can be given as in Fig. 4.
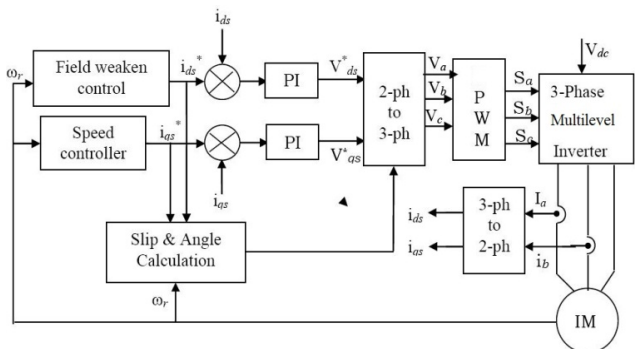
Fig. 4 Block diagram of vector controlled based multilevel inverter fed IM drive

In the block diagram of vector control shown in Fig. 4, from the 2-phase to 3-phase transformation block three reference signals V_a, V_b, V_c are derived and these are fed to PWM block to generate control signals for multilevel inverter. Various types of continuous and discontinuous modulating signal can be derived using these three reference signals. In the PWM block the obtained new reference signals are compared with carrier signals to generate control signals (S_a, S_b, S_c).

4. RESULTS AND DISCUSSION

To verify the performance of these continuous and discontinuous modulating signals based PWM techniques MATLAB based simulation studies are carried on vector controlled multilevel inverter fed induction motor drive. For the simulation studies, the parameters of the induction motor are chosen as Rs=1.57 Ω, Rr=1.21 Ω, Lm= 165 mH, Ls= 170 mH, Lr= 170 mH and J= 0.089 Kg-m^2. The switching frequency is taken as 3 kHz. The steady state plots of modulating signal, line voltage, stator currents, speed and electromagnetic torque of three and five level inverter fed vector controlled induction motor drive are shown from Fig. 5 to Fig. 8. Along with these, the harmonic spectra of line current are also shown in Fig. 6 and Fig. 8. From the results it is observed that with discontinuous modulating signal based PWM techniques reduce the switching losses as modulating signal is clamped for duration of 120^0 either to positive or negative DC bus. It is observed that the magnitude of voltage levels are small and number of voltages levels are more in line voltages of five-level diode clamped multilevel inverter when compared with three-level diode clamped inverter. Hence, the harmonic content present in the line current of five-level diode clamped multilevel inverter is less and hence, the THDs of line current showed in Fig. 8 are low when compared with Fig. 6. The THD of line currents with various PWM techniques for three-level and five-level diode clamped multilevel inverters are tabulated in Table 4.

Table 4 THD of line currents

| Type of PWM technique	Three –level inverter	Five –level inverter
SVPWM	3.02	1.56
DPWMMIN	4.30	2.36
DPWMMAX	4.29	2.36
DPWM0	5.42	2.37
DPWM1	4.40	2.49
DPWM2	4.63	2.38
DPWM3	4.62	2.45

From the Table 4, it is observed that discontinuous modulating signal have high current ripple (i.e THD) when compared with continuous modulating signal based PWM techniques for both three and five level diode clamped inverters. Though the current ripple is high, the discontinuous modulating signal based PWM techniques show significant reduction in switching losses. From the Table it is observed that among the discontinue modulating signal based PWM techniques DPWMMIN shows superior performance in reducing current ripple.
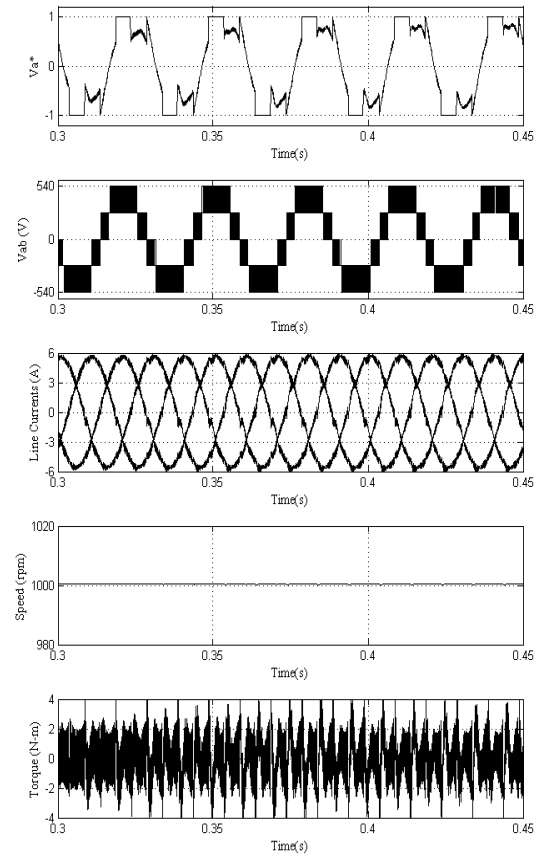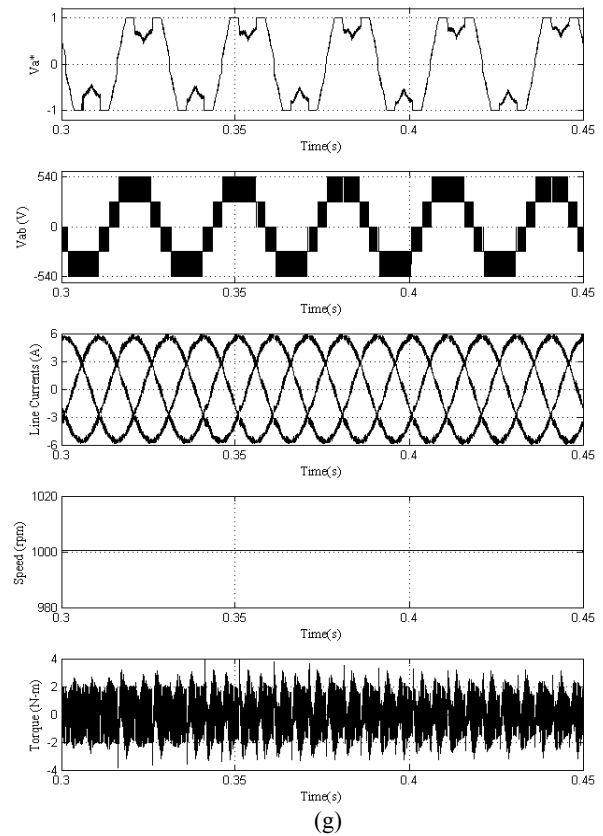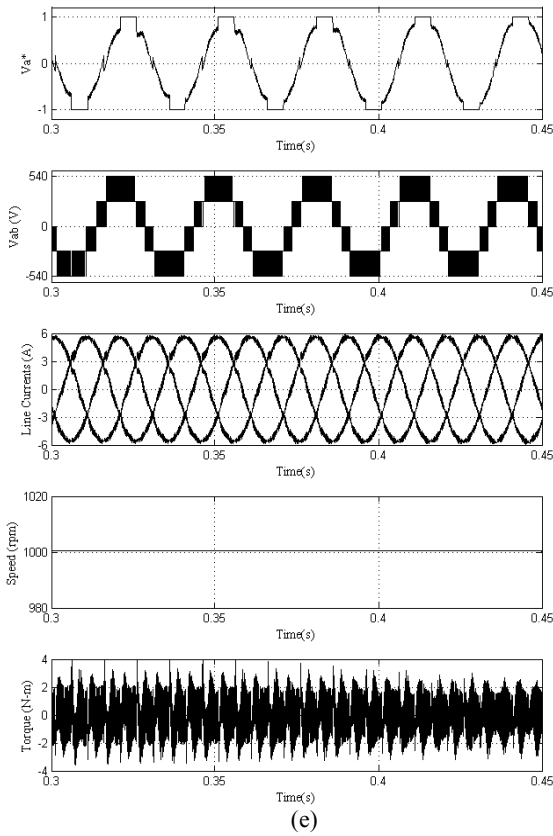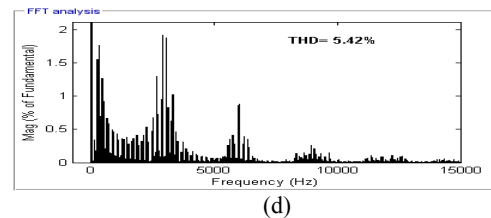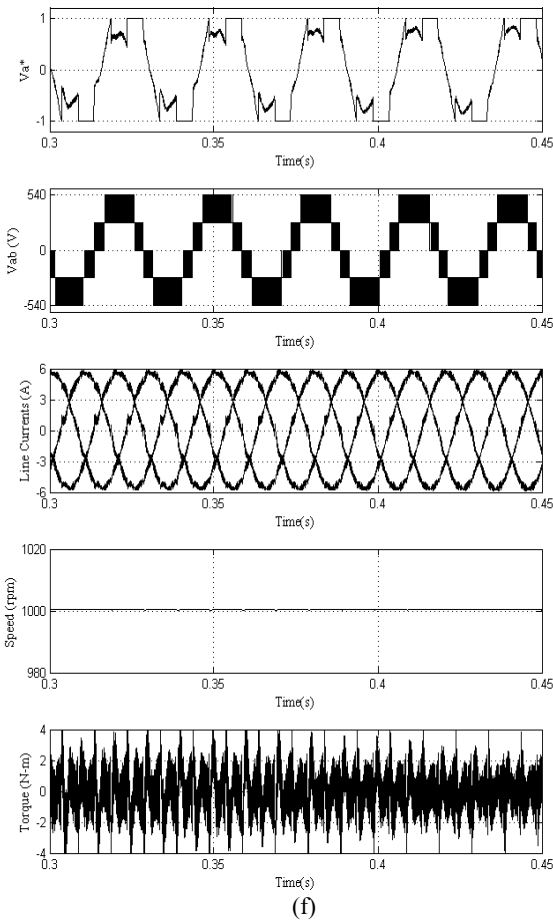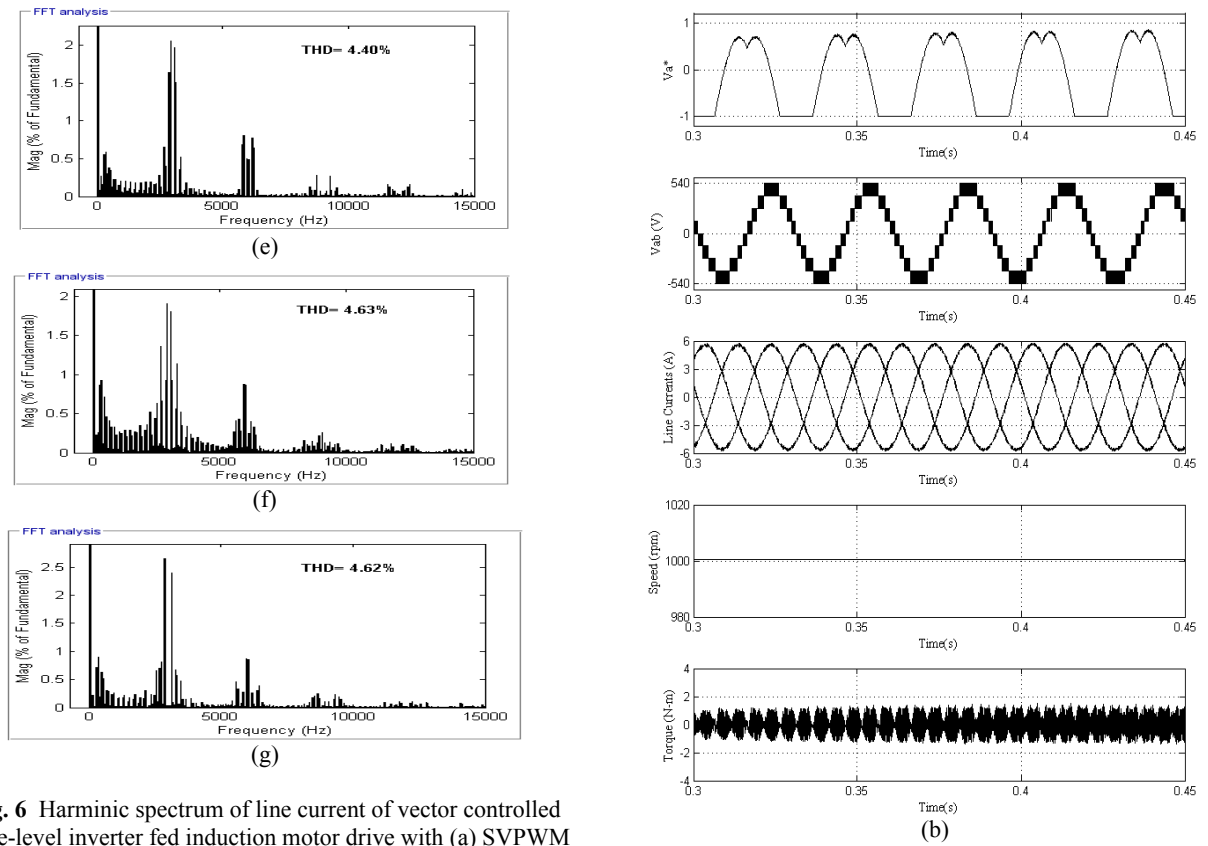
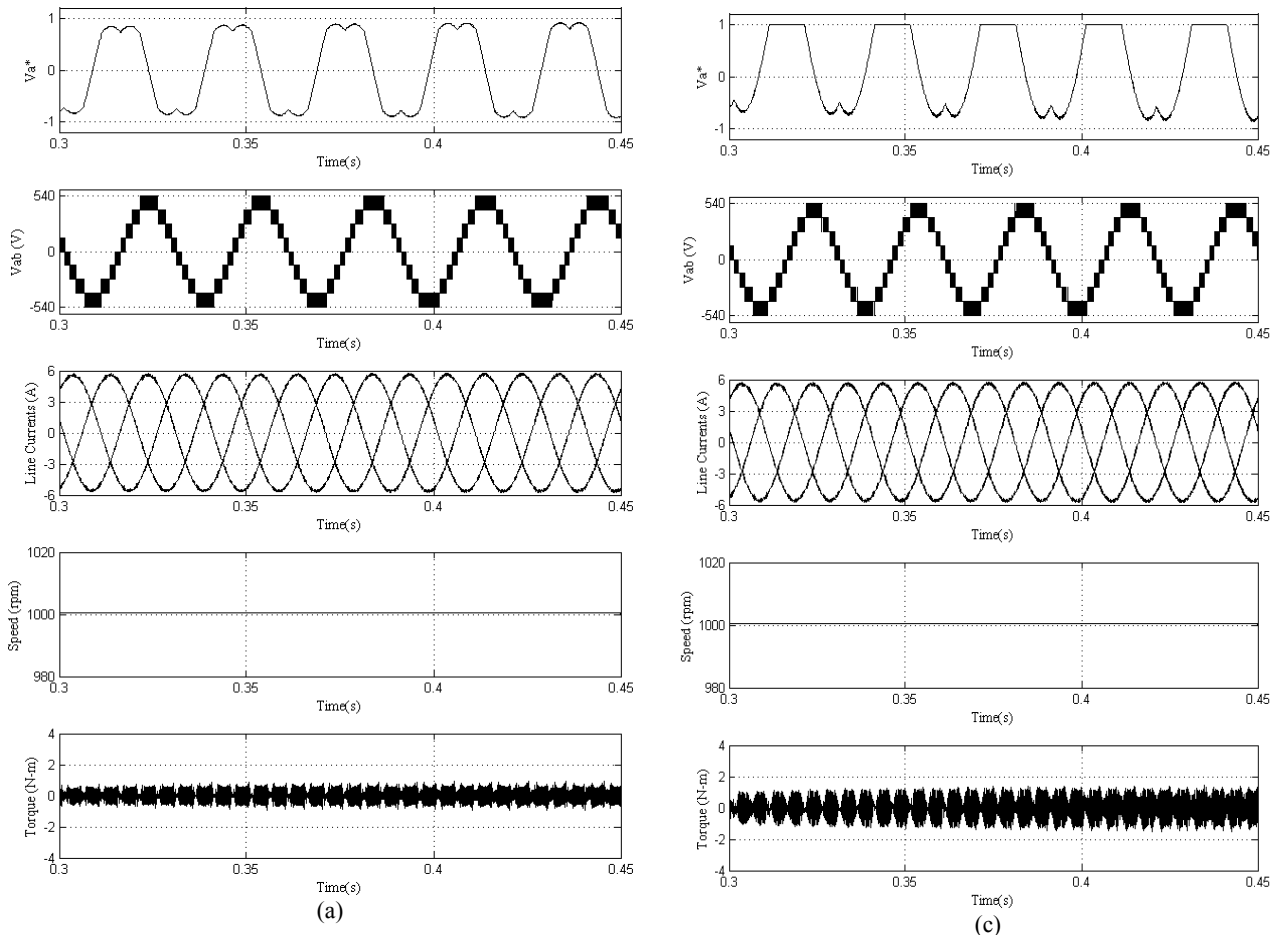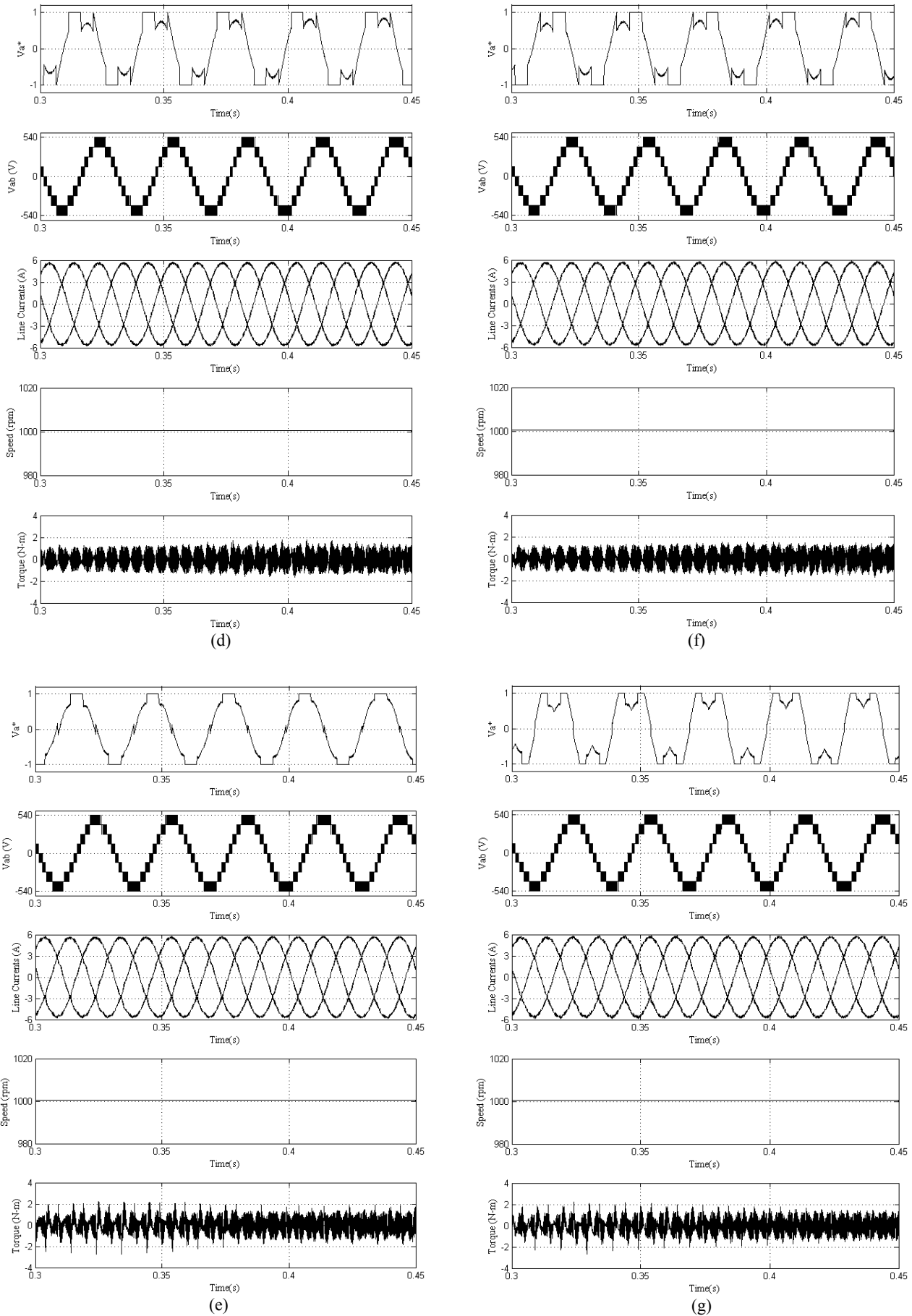(a)

(c)

(b)

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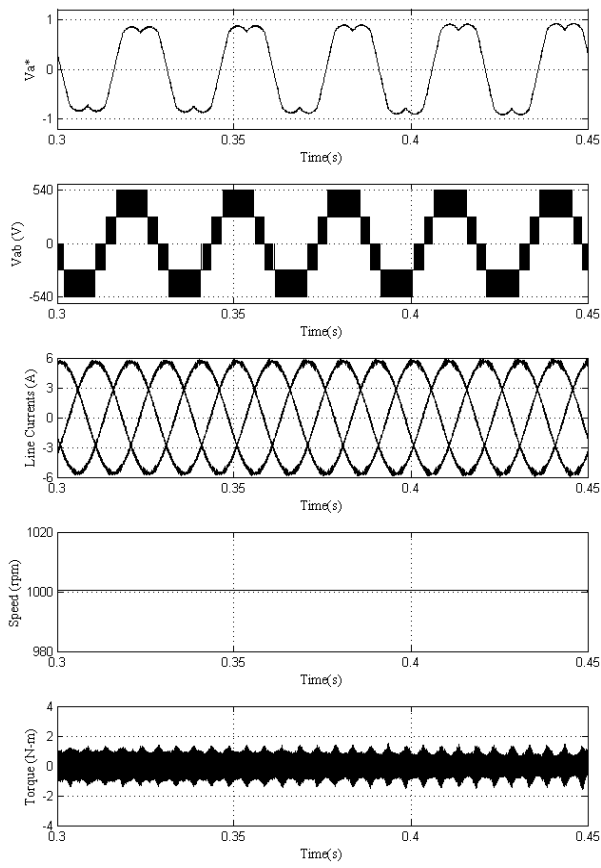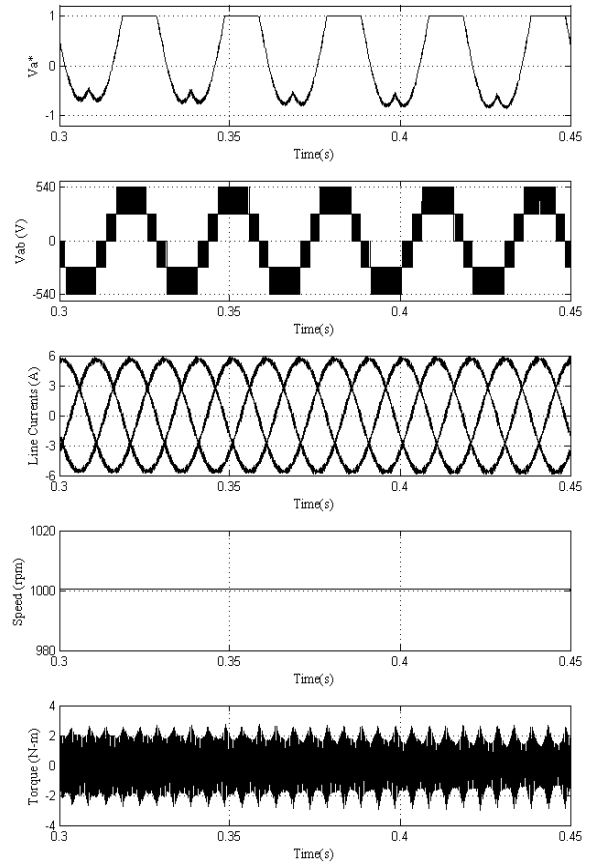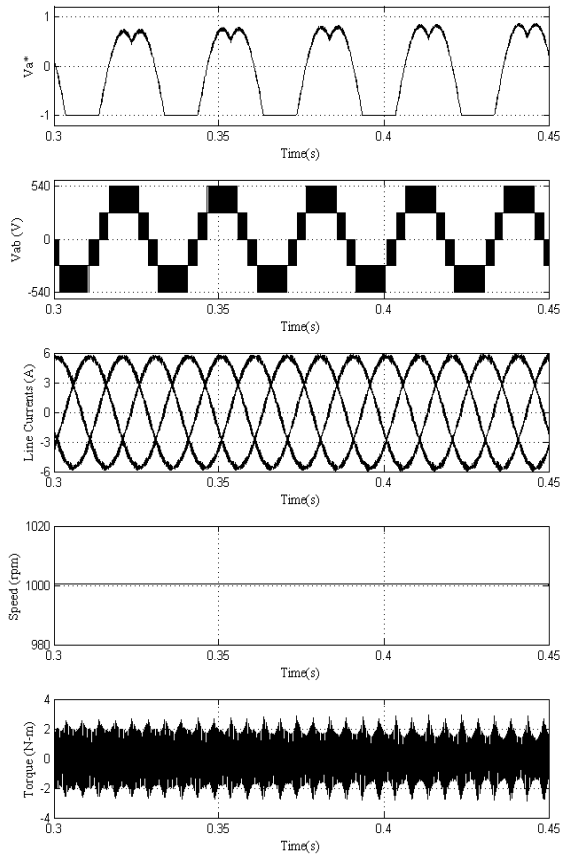
Fig. 5 Steady state response of various plots of vector controlled three-level inverter fed induction motor drive with (a) SVPWM (b) DPWMMIN (c) DPWMMAX (d) DPWM0 (e) DPWM1 (f) DPWM2 (g) DPWM3 techniques

(f)

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(b)

Fig. 6 Harminic spectrum of line current of vector controlled three-level inverter fed induction motor drive with (a) SVPWM (b) DPWMMIN (c) DPWMMAX (d) DPWM0 (e) DPWM1 (f) DPWM2 (g) DPWM3 techniques
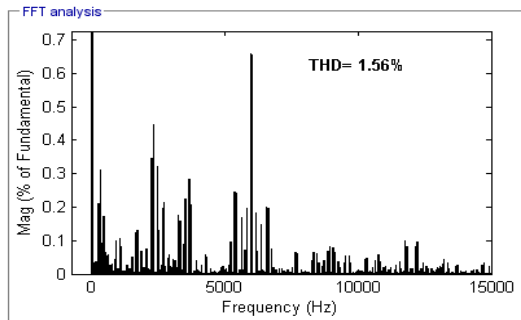

(a)
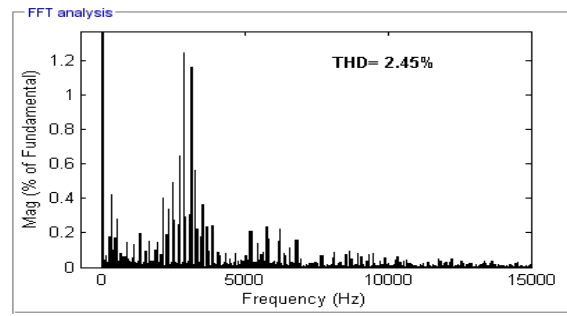

(c)

(d)

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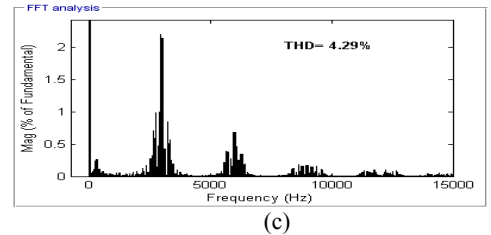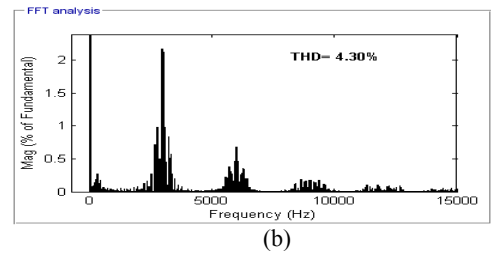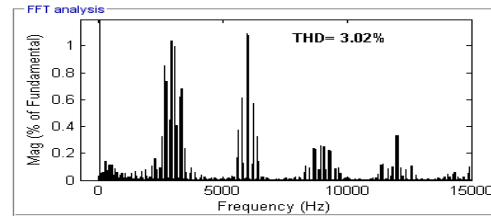
Fig. 7 Steady state response of various plots of vector controlled five-level inverter fed induction motor drive with (a) SVPWM (b) DPWMMIN (c) DPWMMAX (d) DPWM0 (e) DPWM1 (f) DPWM2 (g) DPWM3 techniques

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 8 Harminic spectrum of line current of vector controlled five-level inverter fed induction motor drive with (a) SVPWM (b) DPWMMIN (c) DPWMMAX (d) DPWM0 (e) DPWM1 (f) DPWM2 (g) DPWM3 techniques
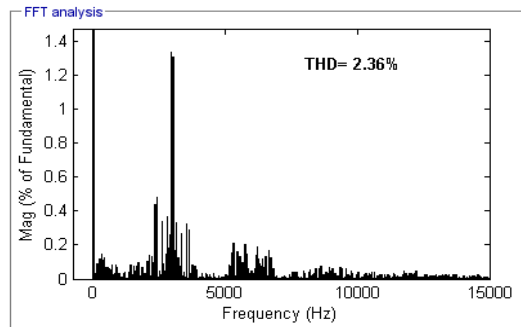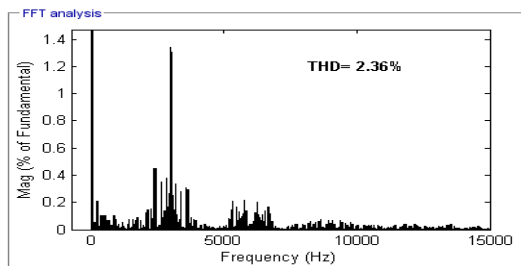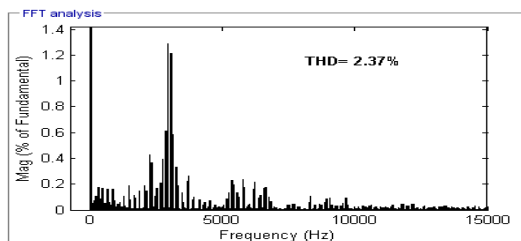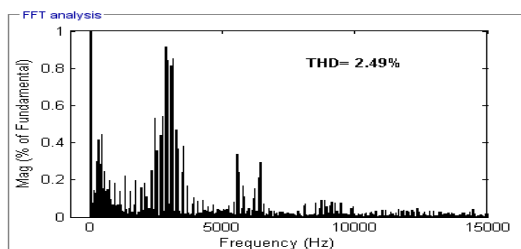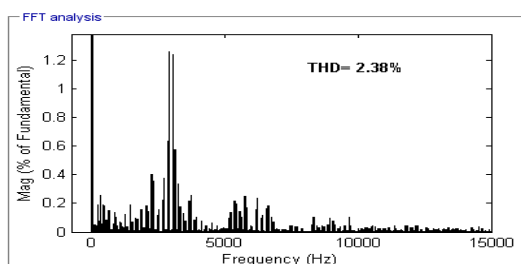
5. CONCLUSIONS

In this paper different types of continuous and discontinuous modulating signals based scalar PWM techniques were proposed for three and five-level diode clamped multilevel inverter topologies. The implementation of these PWM techniques were carried out based on scalar carrier comparison approach. Hence, the implementation of these PWM techniques do not require sector identification and reference voltage vector magnitude calculations. The proposed PWM techniques are validated through numerical simulations on vector controlled drives. From results, it is concluded that the THDs of line current reduces as the number of levels increases. Moreover, the DPWM techniques results in slightly increased current ripple with significant reduction in switching losses.

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