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Generalized PWM Algorithm for 3-level Diode Clamped Inverter fed Direct Torque Controlled Induction Motor Drive

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ABSTRACT: This paper presents a simple generalized pulse width modulation (GPWM) algorithm for three-level diode clamped inverter fed direct torque controlled induction motor drives. Though the classical direct torque control (DTC) algorithm gives fast dynamic response, it gives large steady state ripples and variable switching frequency operation of the inverter. To overcome these problems, space vector pulse width modulation (SVPWM) algorithm is used for DTC drives. In order to meet the requirements of high power applications, nowadays multilevel inverter fed drives are becoming popular. But, the complexity involved in the classical SVPWM algorithm based three-level inverter is more. Hence, to reduce the complexity involved, the proposed algorithm uses the instantaneous phase voltages only. Moreover, the proposed approach gives the realization of various carrier based PWM algorithms that include both SVPWM and various discontinuous PWM (DPWM) algorithms by using a generalized control algorithm and is obtained via unequal sharing of zero states. In the proposed approach, by varying a constant □k □ value from zero to one, various DPWM algorithms can be generated along with the SVPWM algorithm. To validate the proposed GPWM algorithm based DTC drive, several numerical simulation studies have been carried out and the results have been presented. The simulation results show the effectiveness of the proposed algorithm.

KEYWORDS: DPWM, DTC, GPWM, Induction motor drive, SVPWM, three-level inverter.

1.INTRODUCTION

The variable speed drives (VSDs) are becoming popular in many industrial applications. The invention of field oriented control (FOC) algorithm has been made a renaissance in the high-performance variable speed drive applications. The FOC algorithm gives the decoupling control of torque and flux of an induction motor drive and control the induction motor similar to a separately excited dc motor [1]. But, the complexity involved in the FOC algorithm is more due to reference frame transformations. To reduce the complexity involved, a new control strategy called as direct torque control (DTC) has been proposed in [2]. A detailed comparison between FOC and DTC is presented in [3] and concluded that DTC gives fast torque response when compared with the FOC. Though, FOC and DTC give fast transient and decoupled control, these operate the inverter at variable switching frequency due to hysteresis controllers. Moreover, the steady state ripples in torque, flux and currents are high in DTC.

To reduce the harmonic distortion and to obtain the constant switching frequency operation of the inverter, nowadays many researchers have focused their interest on pulse width modulation (PWM) algorithms. A detailed survey of the various PWM algorithms is given in [4]. Nowadays, there are two popular approaches for the implementation of PWM algorithms, namely triangular comparison (TC) approach and space vector (SV) approach [5]. For the implementation point of view, TC approach is simple when compared to SV approach. However, the SV approach provides more degrees of freedom in the implementation when compared to TC approach. Due to the development of digital signal processors, space vector PWM

(SVPWM) has become one of the most popular PWM methods for three-phase inverters [5]. It uses the SV approach to compute the duty cycle of the switches. The main features of this PWM algorithm are easy digital implementation and wide linear modulation range for output line-to-line voltages. Though, the SVPWM gives superior performance, it gives more switching losses of the inverter as it has continuous modulating signal. Hence, to reduce the switching losses of the inverter, nowadays discontinuous PWM (DPWM) algorithms are becoming popular. The generation of these DPWM algorithms is given in detail in [6]-[10].

The two-level voltage source inverters are not suitable for medium and high power applications due to large dv/dt stresses and more harmonic distortion. In order to reduce these problems three-level inverters are introduced in 1980s [11]. The detailed survey on multilevel inverter topologies is given in [12]. In order to obtain controllable three phase power from a multilevel inverter, various PWM algorithms can be generated by using both SV and TC approaches. However, in SV approach the complexity will be increased due to the more number of voltage vectors. Hence, in most number of applications the carrier based PWM algorithms are popular for multilevel inverters. Few simplified approaches by using duty cycle and offset times have been proposed for carrier based SVPWM algorithm based multilevel inverters [13], [14].

This paper presents carrier based generalized PWM (GPWM) algorithm for 3-level inverter fed direct torque controlled induction motor drives. In the proposed GPWM algorithm by changing a constant value between 0 and 1, various PWM algorithms have been generated. Moreover, the proposed algorithm uses instantaneous phase voltages only. Thus, the proposed GPWM algorithm will bring all modulators under a common roof with reduced complexity.

II.THREE LEVEL DIODE CLAMPED INVERTER

The three-level diode clamped inverter is also known as neutral point clamped (NPC) inverter. The NPC configuration was first proposed by Nabae, *et.al* in 1981. Fig. 1 shows the power circuit of a 3-phase, three-level NPC inverter. Node '*o*' indicates the negative bus and '*m*' is the midpoint of the dc bus. Switches (S_{a1} , $S_{a'2}$) of phase *a*, (S_{b1} , $S_{b'2}$) of phase *b* and (S_{c1} , $S_{c'2}$) of phase *c* are the main devices operating as modulating switches for the PWM. S_{a2} , $S_{a'1}$, S_{b2} ,$S_{b'1}$, S_{c2} and $S_{c'1}$ are the auxiliary switches to clamp the output voltage to the midpoint together with the diodes D_{a1}, D_{a2}, D_{b1}, D_{b2}, D_{c1}, and D_{c2}.

Assume the dc rail *o* is the reference point of the output phase voltage. For an output voltage level $/2$, turn on all upper-half switches S_{a1} S_{a2} . For an output voltage level $V_{ao} = 0$,turn on the middle switches $S_{a'1}$ and S_{a2} . For an output voltage level $V_{ao} = -V_{dc}/2$, turn on the lower half switches $S_{a'1}$ and $S_{a'2}$.

Thus a NPC-PWM inverter composed of main switching devices which operate as switches for PWM and auxiliary switching devices to clamp the output terminal voltage to the neutral point potential.

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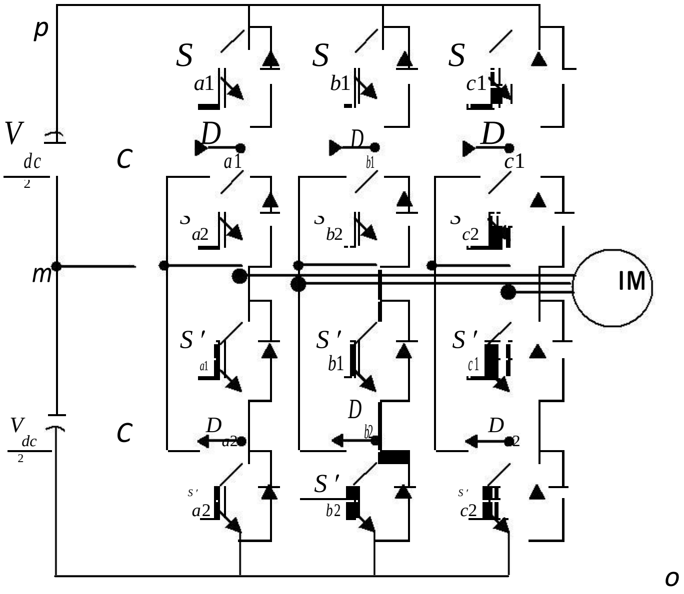

Fig. 1 Topology of 3-phase, 3-level diode clamped inverter

III. PROPOSED GPWM ALGORITHM

The proposed GPWM algorithm may be pursued by the definition of a duty cycle or modulating signal for phase *n* (with *n* = a, b and c), which is given as the ratio between pulsewidth and modulation period.

$$V_n^* = \frac{Pulsewidth}{Modualtionperiod} \qquad (1)$$

Once the modulating signal V_n^* is calculated, the ON and OFF times of the inverter-leg devices can be via digital counters and comparators. For example, the duty cycle or modulating signal of SPWM algorithm can be obtained as follows [9]-[10].

$$V_n^* = \frac{1}{2} + \frac{V_n}{V_{dc}}, \quad n = a, \text{b and c} \qquad (2)$$

Where V_n is the instantaneous reference voltage of phase *n* and V_{dc} is the dc-link voltage. In the similar way, the modulating signals of the various DPWM algorithms and SVPWM algorithms can be obtained by adding a suitable zero sequence voltage (V_z) to the instantaneous phase voltages (Vz).

$${}_n. \quad V_n^* = k_1 + \frac{V_n + V_z}{V} \qquad (3)$$

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where $V_z \square k_2[\min(V_n) \square \max(V_n)] \square \min(V_n)$ (4)

where k_2 is the parameter that takes into account the unequal null-state sharing, can be defined as follows:

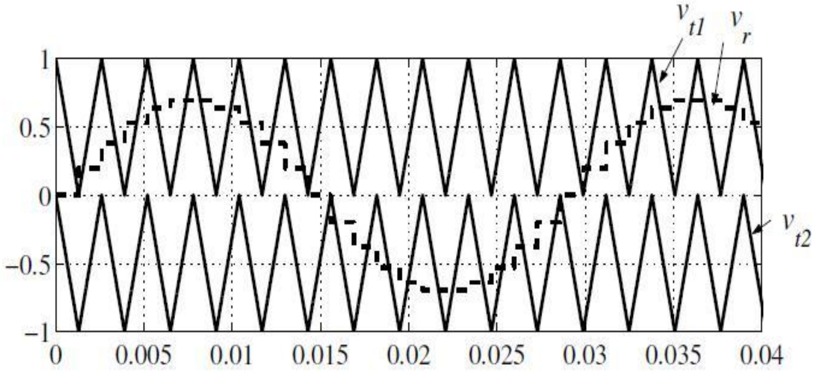
$$k_2 = 0.5(1 + \mathrm{sgn}(\cos(3\omega t + \delta))) \qquad (5)$$

where sgn(X) is 1, 0 and –1 when X is positive, zero, and negative, respectively. As previously discussed, and k_1 is an additional parameter whose value may be equal to the value of k_2 or be fixed at 0.5. Thus, the proposed approach eliminates the calculation of both the hexagon sector, in which the reference-voltage space vector is located, and the related phase.

In all the other carrier-based techniques, it must be taken that $k_1 = k_2$. The standard SVPWM algorithm can be obtained by fixing the k_2 value at 0.5. Similarly, by fixing the k_2 value at 0 and 1, the DPWMMIN and DPWMMAX algorithms can be obtained. By varying the modulation angle δ in (5), various DPWM algorithms can be generated. The DPWM0, DPWM1, DPWM2 and DPWM3 can be obtained for $\delta = \pi/6, 0, -\pi/6$ and $-\pi/3$ respectively.

In conclusion, it is worth noticing that a mathematical expression of the modulating signal in SVPWM was, in effect, already known, but it was referred only to classical SVPWM operating in linear modulation range. Here, the use of the modulating signal in the synthesis of the switching pattern has been put in evidence, and as a novelty, it has been extended to the over modulation range and in generalized modulation by defining the new k_1 and k_2 parameters.

After the generation of the modulating waves of various PWM algorithms, two triangular carrier signals have been generated in-phase as shown in Fig. 2. Then the modulating waves and carrier waves have been compared and the switching signals have been generated as shown in Table-1.



The reference voltage space vector can be constructed in many ways. But, to reduce the complexity of the algorithm, in this thesis, the required reference voltage vector, to control the torque and flux cycle-by-cycle basis is constructed by using the errors between the reference d-axis and q-axis stator fluxes and d-axis and q-axis estimated stator fluxes sampled from the previous cycle.

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Table-1: Generation of switching logic of the devices

Condition	**Switch Status**	**State**
$v_r > v_{t1}$ and $v_r > v_{t2}$	$S_{a1} = ON$, $S_{a2} = ON$ $S'_{a1} = OFF$, $S'_{a2} = OFF$	$S_a = +1$
$v_r < v_{t1}$ and $v_r > v_{t2}$	$S_{a1} = OFF$, $S_{a2} = ON$ $S'_{a1} = ON$, $S'_{a2} = OFF$	$S_a = 0$
$v_r < v_{t1}$ and $v_r < v_{t2}$	$S_{a1} = OFF$, $S_{a2} = OFF$ $S'_{a1} = ON$, $S'_{a2} = ON$	$S_a = -1$

The block diagram of the proposed GPWM based DTC is as shown in Fig. 3. From Fig. 3, it is seen that the proposed GPWM based DTC scheme retains all the advantages of the DTC, such as no co-ordinate transformation, robust to motor parameters, etc. However a space vector modulator is used to generate the pulses for the inverter, therefore the complexity is increased in comparison with the DTC method.

IV. PROPOSED GPWM ALGORITHM BASED DTC

In the proposed method, the position of the reference stator flux vector ψ_s^* is derived by the addition of slip speed and actual rotor speed. The actual synchronous speed of the stator flux vector ψ_s is calculated from the adaptive motor model.After each sampling interval, actual stator flux vector ψ_s is corrected by the error and it tries to attain the reference flux space vector ψ_s^* . Thus the flux error is minimized in each sampling interval. The d-axis and q-axis components of the reference voltage vector can be obtained as follows:
Reference values of the d-axis and q- axis stator fluxes and actual values of the d-axis and q-axis stator fluxes are compared in the reference voltage vector calculator block and hence the errors in the d-axis and q-axis stator flux vectors are obtained as in (6)-(7).

$$\Delta\Psi_{ds} = \Psi_{ds}^* - \Psi_{ds} \qquad (6)$$

$$\Delta\Psi_{qs} = \Psi_{qs}^* - \Psi_{qs} \qquad (7)$$

The appropriate reference voltage space vectors due to flux error and stator ohmic drop are given as

$$v_{ds}^* = R_s i_{ds} + \frac{\Delta\psi_{ds}}{T_s} \qquad (8)$$

$$v_{qs}^* = R_s i_{qs} + \frac{\Delta\psi_{qs}}{T_s} \qquad (9)$$

Where, T_s is the duration of sub cycle or sampling period and it is a half of period of the switching frequency. This implies that the torque and flux are controlled twice per switching cycle. Further, these d-q components of the reference voltage vector are fed to the SVPWM block from which, the actual switching times for each inverter leg are calculated.

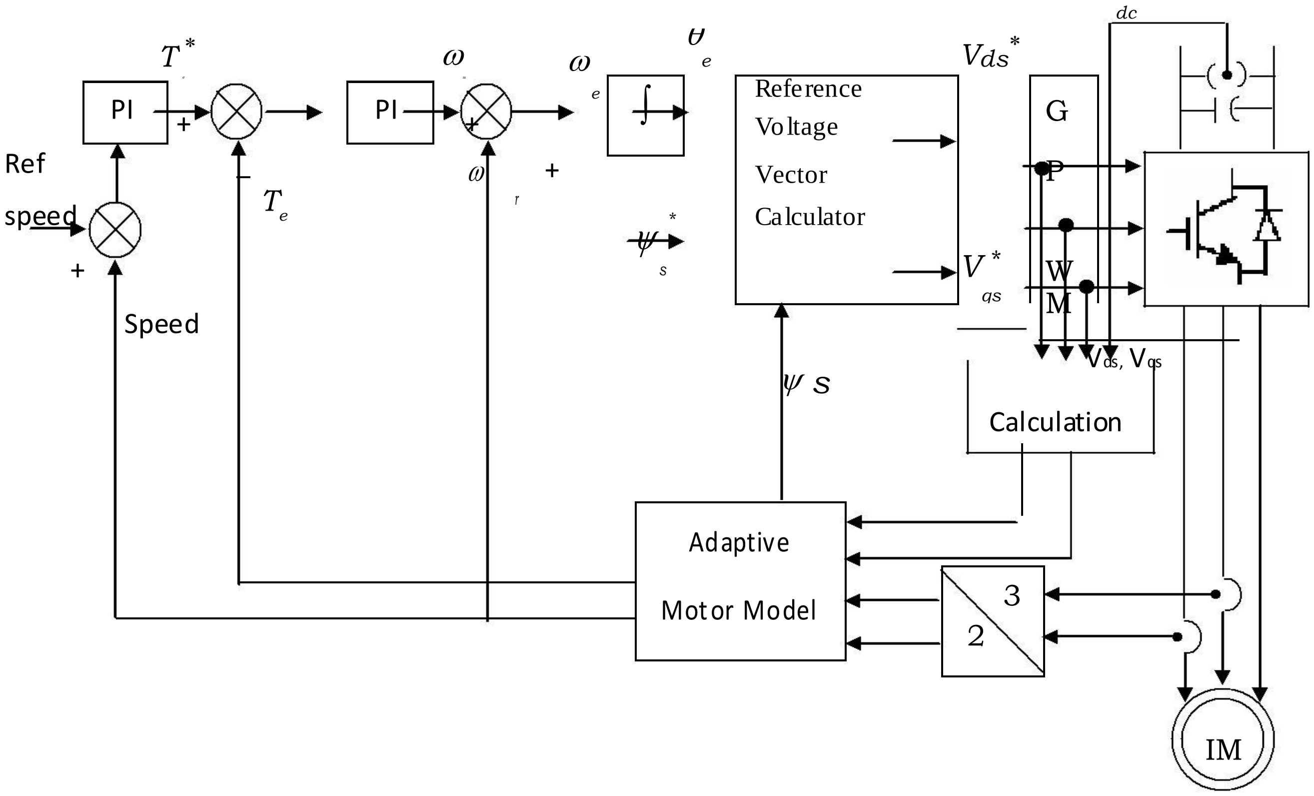


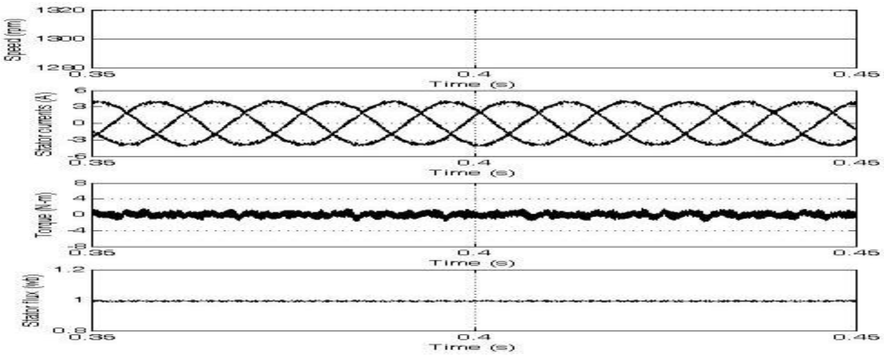
Fig.3 Block diagram of proposed SVPWM based DTC

V.SIMULATION RESULTS AND DISCUSSION

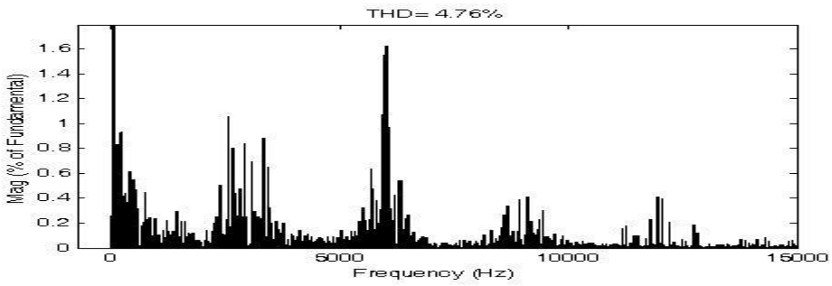
To validate the proposed generalized PWM algorithm based 3-level inverter fed DTC, several numerical simulation studies have been carried out and results are presented. The details of the induction motor, which is used for simulation studies are as follows:

A 3-phase, 4 pole, 4kW, 1440 rpm induction motor with parameters as follows:
$R_s = 1.57\Omega$, $R_r = 1.21\Omega$, $L_s = L_r = 0.17H$, $L_m = 0.165H$ and $J = 0.089 Kg.m^2$.

The steady state simulation results for various PWM algorithms based 3-level inverter fed DTC drive are shown from Fig. 4 to Fig. 10. From the simulation results, it can be observed that as the SVPWM algorithm is a continuous PWM algorithm, it gives continuous pulse pattern and more switching losses. Whereas, the DPWM algorithms clamp each phase to either positive or negative DC bus for 120 degrees over a fundamental cycle, these reduce the switching frequency and switching losses by 33.33% when compared with the SVPWM algorithm. Thus, the proposed GPWM algorithm generates a wide range of PWM algorithms at all modulation indices with reduced complexity by varying a parameter k_2 from 0 to 1.



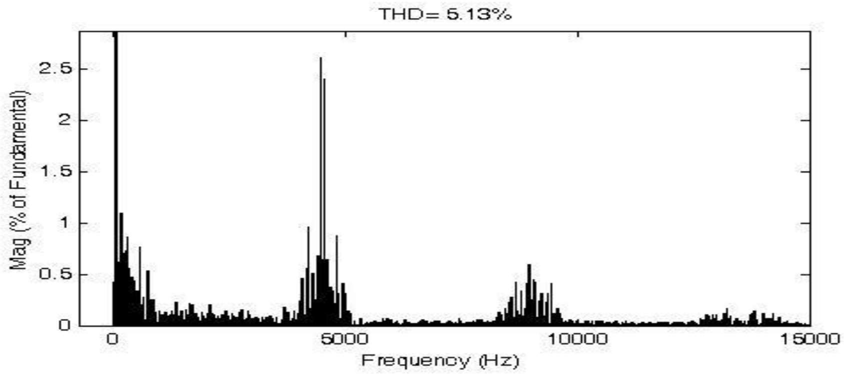
(a)



(b)

Fig. 4 Simulation results for SVPWM based DTC drive

The Results given in fig.4(a) & (b) are showing the Simulation results of speed, currents, torque ,flux for 3 level VSI fed SVPWM based DTC-IM drive and in fig.(b),the line current spectra with THD of 4.76% is shown .



(a)

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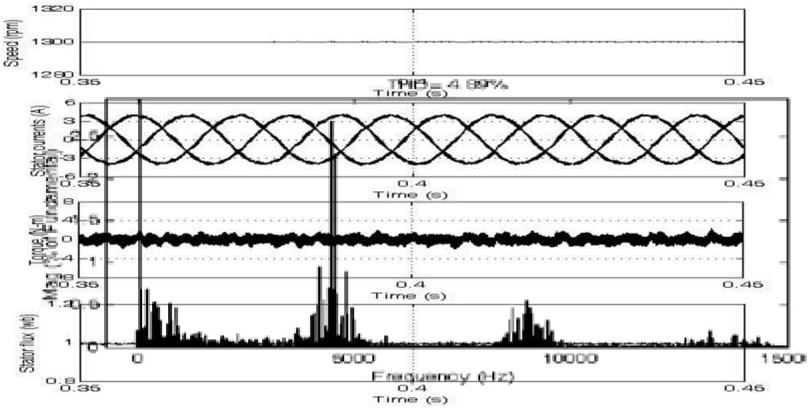
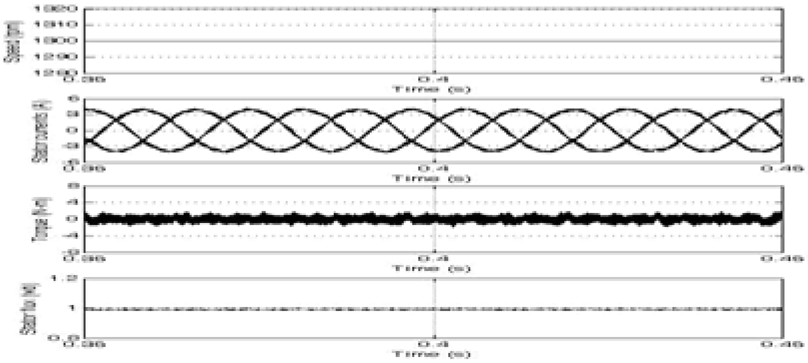


(b)

Fig. 5 Simulation results for DPWMMIN based DTC drive

The Results given in fig.5(a) showing the line current spectra with THD of 5.13 % and in fig.(b) ,Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWMMIN based DTC-IM drive are shown .

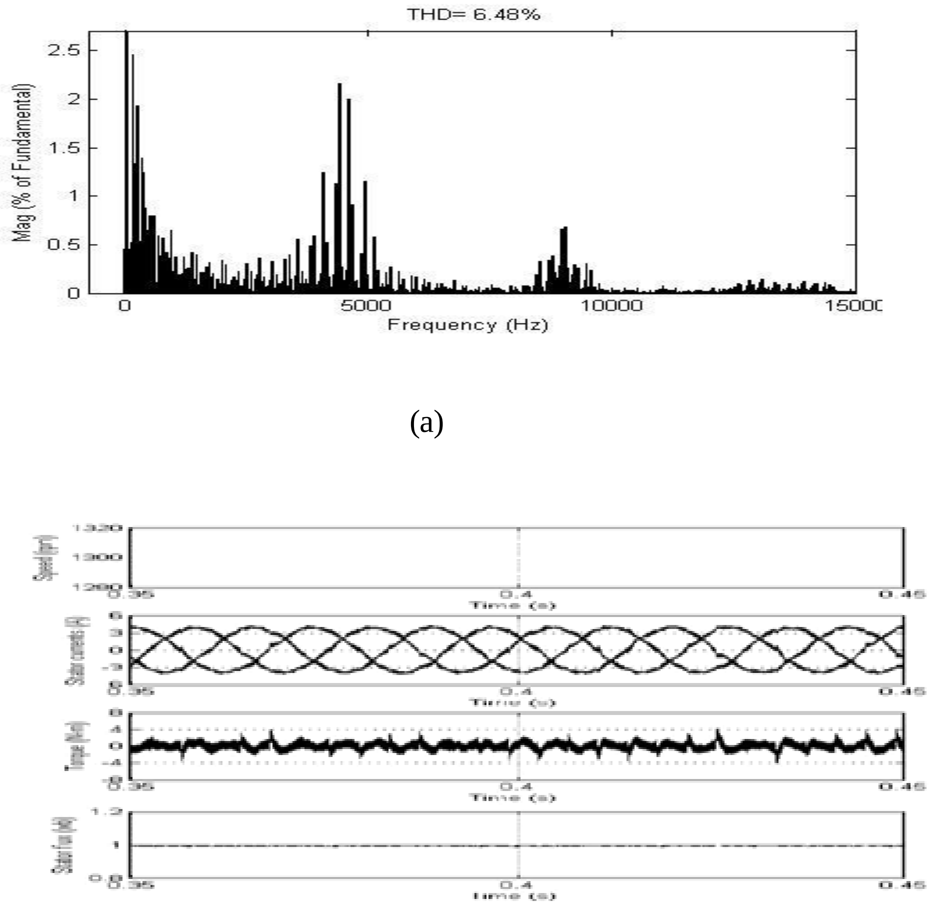
(a)



(b)

Fig. 6.Simulation results for DPWMMAX based DTC drive

The Results given in fig.6(a) showing the line current spectra with THD of 4.89% and in fig.(b) , Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWMAX based DTC-IM drive are show.

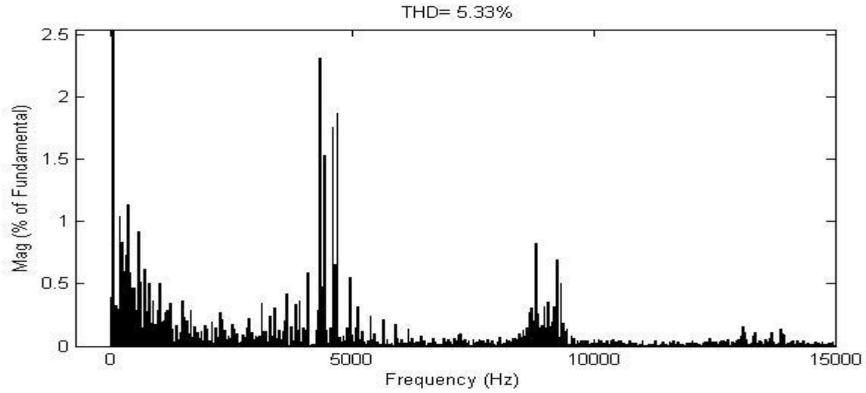


(a)

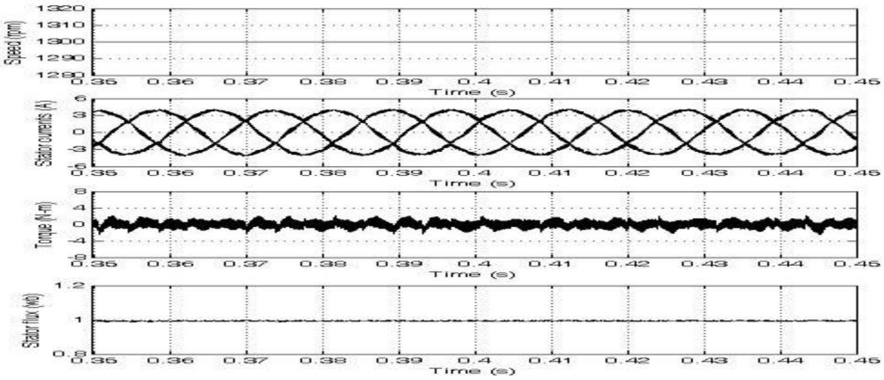
(b)

Fig.7. Simulation results for DPWM0 based DTC drive

The Results given in fig.7(a) showing the line current spectra with THD of 6.48% and in fig.(b) , Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWM0 based DTC-IM drive are shown.



(a)



(b)

Fig.8 Simulation results for DPWM1 based DTC drive

The Results given in fig.8(a) showing the line current spectra with THD of 5.33% and in fig.(b) , Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWM1 based DTC-IM drive are shown.

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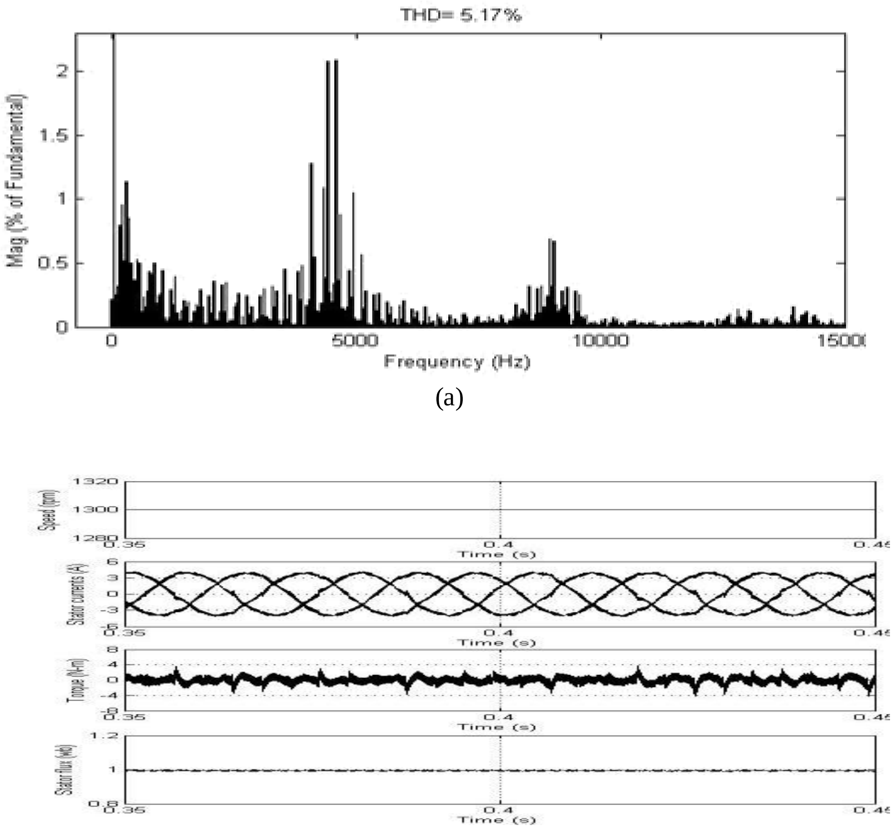

(a)

(b)

Fig.9 Simulation results for DPWM2 based DTC drive

The Results given in fig.9(a) showing the line current spectra with THD of 5.71% and in fig.(b) , Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWM2 based DTC-IM drive are shown

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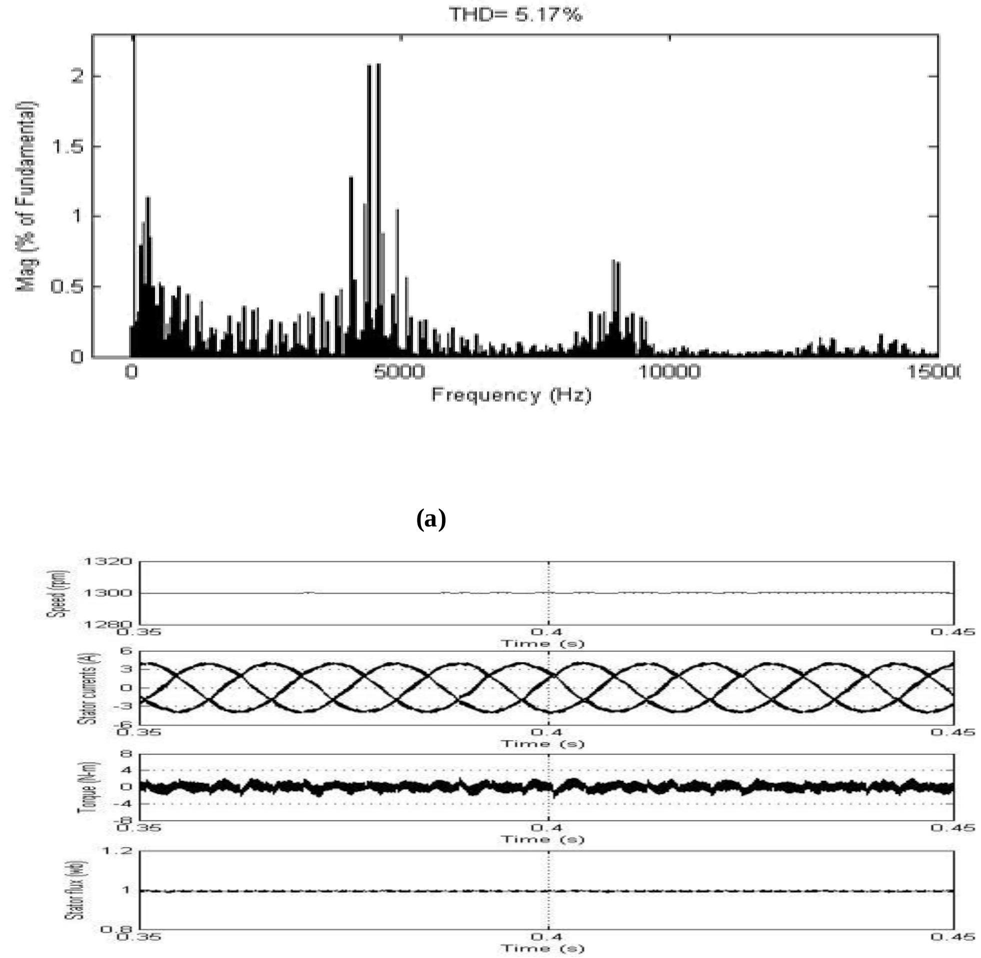

(a)

(b)

Fig.10. Simulation results for DPWM3 based DTC drive

The Results given in fig.10(a) showing the line current spectra with THD of 5.17% and in fig.(b) ,Simulation results of speed, currents, torque ,flux for 3 level VSI fed DPWM3 based DTC-IM drive are shown.

VI. CONCLUSION

A simple and novel GPWM algorithm for three level inverter fed direct torque controlled induction motor drives is presented in this paper. The proposed algorithm generates a wide range of DPWM algorithms along with SVPWM algorithm by using the instantaneous phase voltages only. From the simulation results it can be observed that the proposed GPWM algorithm gives all possible PWM modulators with reduced complexity.

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