Generalized PWM algorithm for Direct Torque Controlled Induction Motor Drives using the only Sampled Voltages

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***Abstract*—**This paper presents a simple generalized pulse width modulation (GPWM) algorithm for 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. But, as the SVPWM algorithm requires angle and sector information the complexity involved is more. Also, it gives more switching losses of the inverter. 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.

Index Terms—DPWM, DTC, GPWM, Induction motor drive, SVPWM.

I. 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 pulsewidth modulation (PWM) algorithms. A large variety of PWM algorithms have been discussed in [4]. But, the most popular PWM algorithms as sinusoidal PWM (SPWM) and space vector PWM (SVPWM) algorithms. The SVPWM algorithm offers more degrees of freedom when compared with the SPWM algorithms. Hence, it is attracting many researchers. The SVPWM algorithm is explained in detailed in [5]. Though the SVPWM and SPWM algorithms give good performance, these give more switching losses of the inverter due to the continuous modulating signals. Hence, to reduce the switching losses of the inverter, the discontinuous PWM (DPWM) algorithms are becoming popular. Also, the classical SVPWM algorithm requires angle and sector information to generate the actual gating times of the inverter. Hence, the complexity involved is more. To reduce the complexity involved in the algorithms and for easier implementation, nowadays, the carrier based PWM algorithms are attracting many researchers.

The magnitude tests based approach is presented to generate the carrier based SVPWM and various DPWM algorithms with reduced complexity in [6]-[7]. Also, by distributing the zero state time unequally, various PWM algorithms have been generated in [9]. The detailed explanation regarding to the correlation between carrier comparison and space vector approaches is given in [10]. However, the [6]-[10] gives the explanation under the linear modulation region only.

To reduce the complexity in the classical SVPWM algorithms and to extend the operation up to overmodulation region, various PWM algorithms have been generated in [11]-[12] by using the concept of offset time. By adding the suitable offset time to the imaginary switching times, which are proportional to the instantaneous phase voltages, various PWM algorithms have been generated under both linear and overmodulation regions. Similarly, various approaches have been presented in [13]-[14] for the generation of various carrier based PWM algorithms.

This paper presents carrier based generalized PWM (GPWM) algorithm for 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. 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]:

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

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 (V_n).

$$V_n^* = k_1 + \frac{V_n + V_z}{V_{dc}} \qquad (3)$$

where $V_z = k_2[\min(V_n) - \max(V_n)] - \min(V_n) \qquad (4)$

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 δ = π/6, 0, - π/6 and - π/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.

The overmodulation range is of remarkable importance, particularly in the adjustable speed drive applications, in order to well exploit the dc-link voltage, thus obtaining the rated voltage of the motor without using a large dc voltage. It is easy to realize that a good over modulation strategy should manage the transition beyond the linear range, going toward the six-step behavior and thus avoiding any abrupt change of the fundamental voltage components that is applied to the load. There are so many approaches to extend the operation in to the overmodulation region. However, to reduce the complexity burden, this paper presents a simplified approach to extend the operation in to the overmodulation region. In the overmodulation region the difference between the maximum and minimum voltages in a sampling time period, which is also known as effective voltage is greater than the V_{dc}. The effective voltage can be defined as follows:

$$V_{eff} = \max(V_n) - \min(V_n) \qquad (6)$$

Hence, in the overmodulation region the modulating signal can be calculated as follows:

$$V_n^* = \frac{1}{2} + \frac{V_n + V_z}{V_{eff}} \qquad (7)$$

In overmodulation region, the zero state time partition parameter value (k_2) is fixed at 0.5. However, k_2 is clearly no longer present in the duty-cycle expression because now the null states are not applied.

III. PROPOSED GPWM ALGORITHM BASED DTC

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. The block diagram of the proposed GPWM based DTC is as shown in Fig. 1. From Fig. 1, 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.

In the proposed method, the position of the reference stator flux vector $\overline{\psi}_s^{\,*}$ is derived by the addition of slip speed and actual rotor speed. The actual synchronous speed of the stator flux vector $\overline{\psi}_s$ is calculated from the adaptive motor model.

After each sampling interval, actual stator flux vector $\overline{\psi}_s$ is corrected by the error and it tries to attain the reference flux space vector $\overline{\psi}_s^{\,*}$. 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

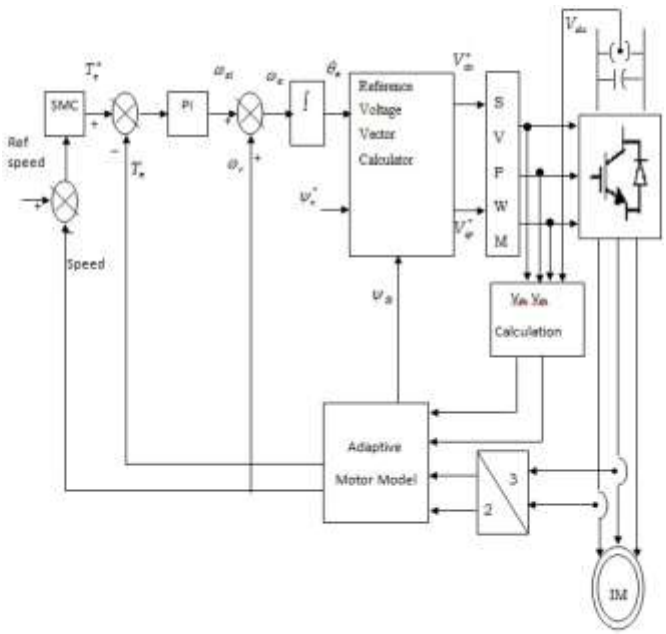


Fig.1 Block diagram of proposed SVPWM based DTC

errors in the d-axis and q-axis stator flux vectors are obtained as in (8)-(9).

$$\Delta\Psi_{ds} = \Psi_{ds}^{*} - \Psi_{ds} \quad (8)$$

$$\Delta\Psi_{qs} = \Psi_{qs}^{*} - \Psi_{qs} \quad (9)$$

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

$$v_{ds}^{*} = R_s i_{ds} + \frac{\Delta\psi_{ds}}{T_s} \quad (10)$$

$$v_{qs}^{*} = R_s i_{qs} + \frac{\Delta\psi_{qs}}{T_s} \quad (11)$$

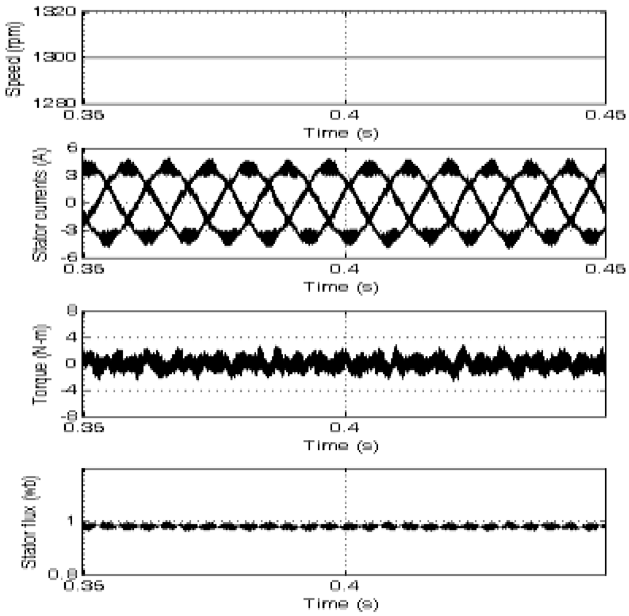
IV. Simulation Results And Discussion

To validate the proposed generalized PWM algorithm based 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, 1200rpm induction motor with parameters as follows:

R_s = 1.57Ω, R_r = 1.21Ω, L_s = L_r = 0.17H, L_m = 0.165H and J = 0.089Kg.m^2.

The steady state simulation results for various PWM algorithms based DTC are shown from Fig. 2 to Fig. 8. From the simulation results it can be observed that at higher modulation indices (motor is running at 1300 rpm, which pertains to the higher modulation region), the DPWM algorithms give reduced harmonic distortion when compared with the SVPWM algorithm. Moreover, it can be concluded that among the various DPWM algorithms, DPWM3 gives reduced harmonic distortion. 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.



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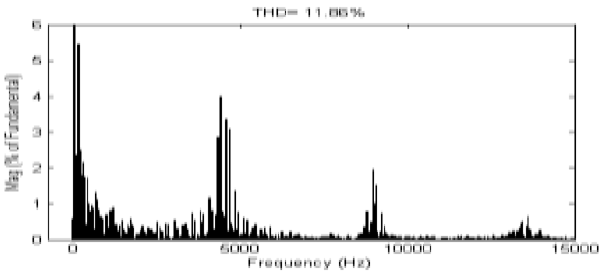

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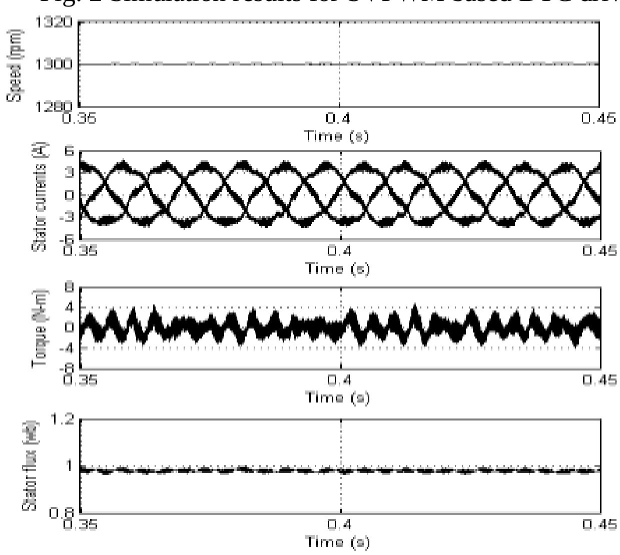
Fig. 2 Simulation results for SVPWM based DTC drive



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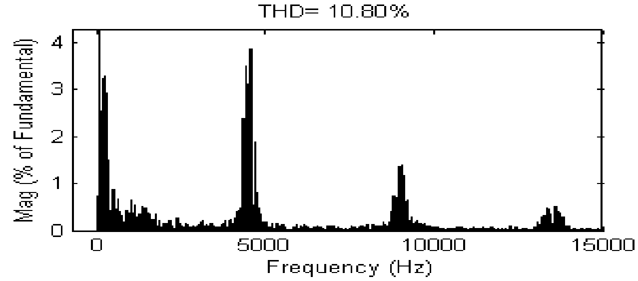

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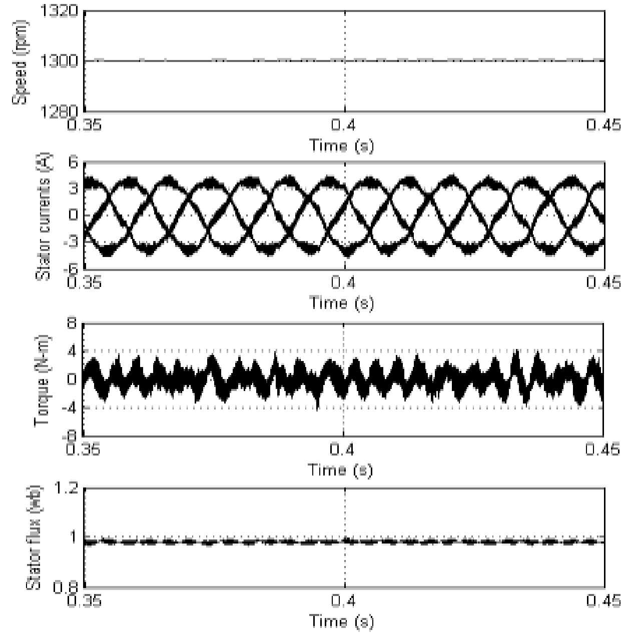
Fig. 3 Simulation results for DPWMMIN based DTC drive



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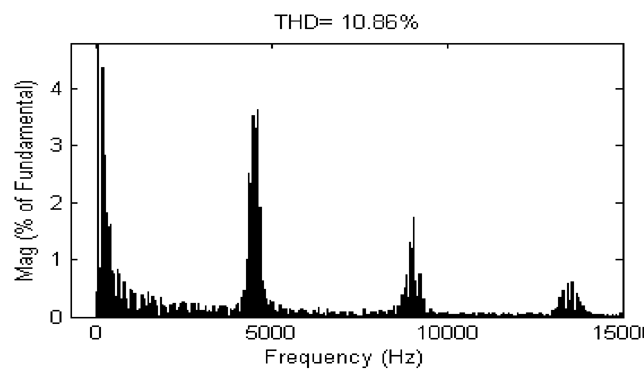

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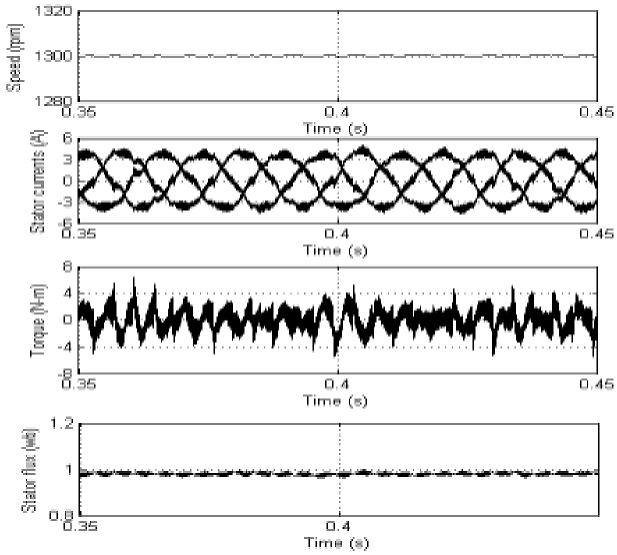
Fig. 4 Simulation results for DPWMMAX based DTC drive



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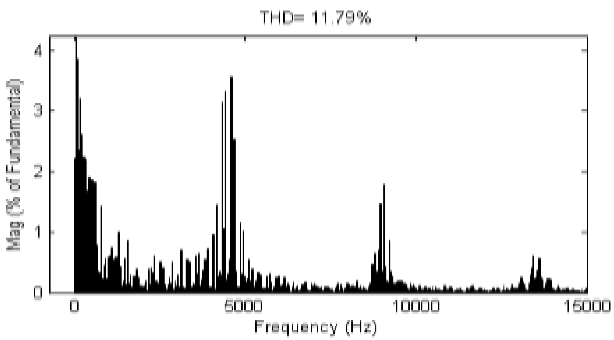

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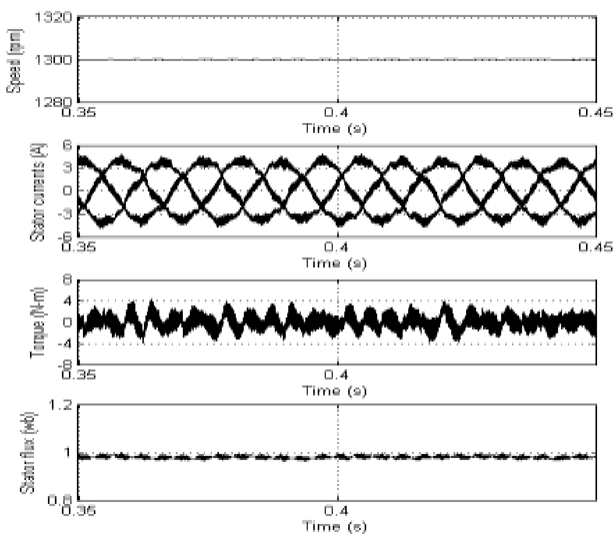
Fig. 5 Simulation results for DPWM0 based DTC drive



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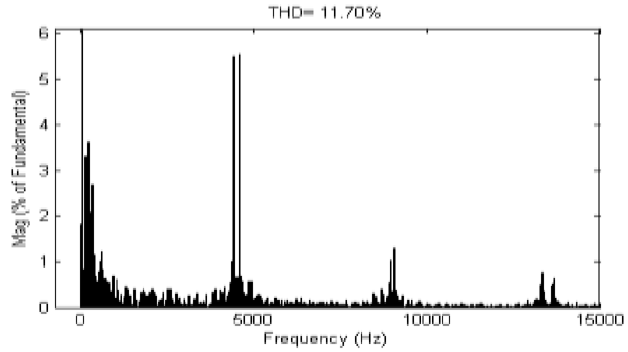

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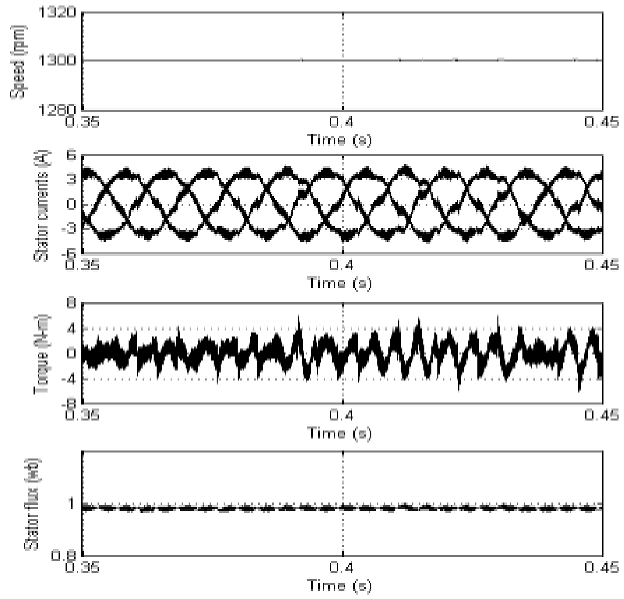
Fig. 6 Simulation results for DPWM1 based DTC drive



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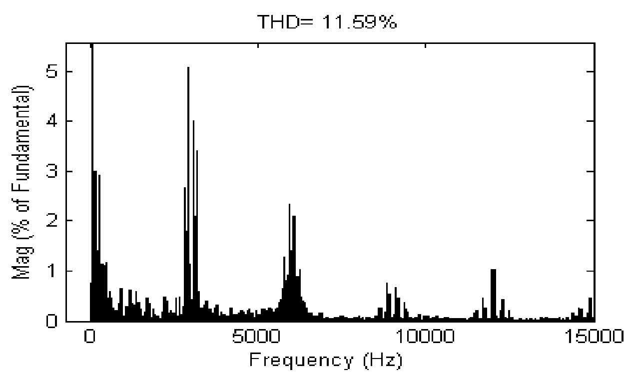

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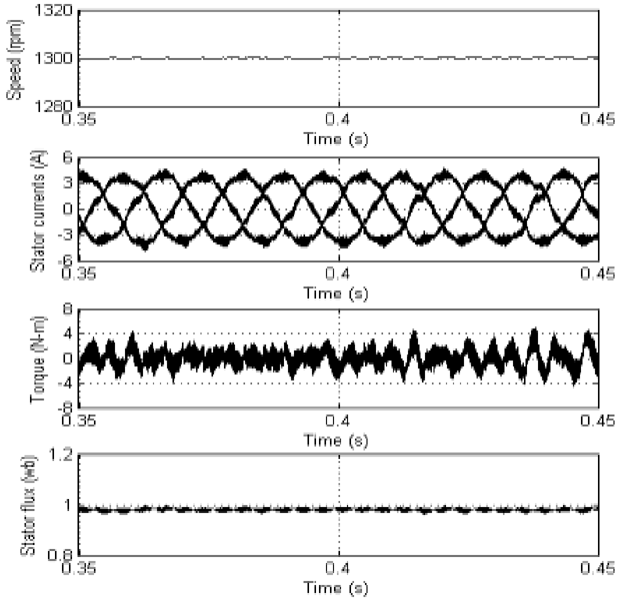
Fig. 7 Simulation results for DPWM2 based DTC drive



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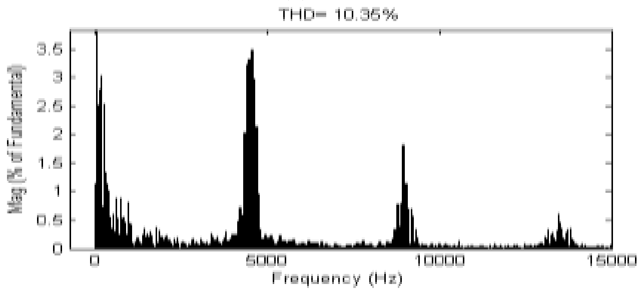

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Fig. 8 Simulation results for DPWM3 based DTC drive

V. Conclusion

A simple and novel GPWM algorithm for 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. Moreover, from the simulation results it can be observed that at higher modulation indices (motor is running at 1300 rpm, which pertains to the higher modulation region), the DPWM algorithms give reduced harmonic distortion when compared with the SVPWM algorithm. Moreover, it can be concluded that among the various DPWM algorithms, DPWM3 gives reduced harmonic distortion.

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