

Implementation of Novel PWM Algorithm for the Reduction of Torque Ripple and Common Mode Voltage in VSI fed Induction Motor Drives

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Abstract: -- This paper presents a high performance near state PWM (NSPWM) algorithm for the reduction of common mode voltage (CMV) in direct torque controlled induction motor drives. In the proposed algorithms, actual switching times are calculated using the concept of imaginary times. As the proposed method did not use sector identification and angle information, it reduces the complexity involved in conventional methods. To reduce CMV, in the proposed method active voltage vectors are used to program the output voltage. NSPWM algorithm utilizes three adjacent active voltage vectors for the composition of reference voltage vector. To validate the proposed algorithm, simulation studies have been carried out using MATLAB-Simulink and results have been presented.

Keywords:— Common mode Voltage, Imaginary Switching Times, SVPWM

I. INTRODUCTION

Recent development of fast switching semiconductor devices like IGBT, has brought high frequency switching operations to power electronic equipments thereby improving the dynamic performance of PWM inverter fed ac motor drives. Moreover, this development created several unexpected problems such as conducted EMI, shaft voltages and breakdown of motor insulation. Many studies for reducing the CMV have been progressed. These studies however focused on the design of common mode choke and various types of active filters [1]-[4]. Since these methods require additional hardware and has drawbacks of increase in inverter weight and volume which are unavoidable.

Direct Torque Control (DTC) is an emerging technique for controlling the PWM inverter-fed induction motor drives when compared with vector controlled induction motor. In spite of its simplicity, DTC has certain draw backs such as steady state ripple and generation of high level common mode voltage (CMV) variations [5-7]. To reduce steady state ripple and to get constant switching frequency operation,

several PWM techniques have been developed. PWM techniques can be classified as Continuous PWM (CPWM) and Discontinuous PWM (DPWM). One of such CPWM technique is conventional space vector PWM technique (SVPWM).

In this approach, two active voltage vectors and two zero voltage vectors are utilized to match the reference volt-seconds. This technique also generates high level common mode voltage variations due to the presence of zero voltage vectors [8-9]. DPWM method such as DPWM1 popularly known to reduce switching losses of inverter also suffers from high CMV variations due to presence of zero voltage vectors [10]. Various PWM methods for the reduction of CMV have been developed for inverter control. In Active Zero State PWM (AZPWM) algorithm division of active voltage vectors is same as SVPWM method whereas instead of zero voltage vectors two active opposite voltage vectors are used to program the output voltage. In Remote State PWM (RSPWM) method three active voltage vectors which are 120° apart are utilized to synthesize the output voltage. These methods are considered with standard PWM methods employing open loop v/f control algorithm for the reduction of CMV. Though these methods reduce CMV variations,

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switching losses and switching frequency of inverter is high for these methods [12-15].

This paper presents a novel near state PWM algorithm (NSPWM) for reduced CMV variations and reduced switching losses for DTC fed induction motor drive. In the proposed NSPWM method, three adjacent voltage vectors are utilized to match the reference volt-sec.

II. CONVENTIONAL DTC

The electromagnetic torque produced by the induction motor in stationary reference frame can be expressed as given in (1).

$$T_e = \frac{3}{2} \frac{P}{\sigma L_s L_r} \lambda_r \lambda_s \sin \delta \quad (1)$$

Where δ is the angle between the stator flux linkage space vector λ_s and rotor flux linkage space vector λ_r .

During steady state as both stator and rotor fluxes move with same angular velocity, the angle determines the electromagnetic torque developed. But during transient state both fluxes do not move with same velocity. As the rotor time constant of an induction motor is large, rotor flux change slowly with respect to stator flux. Therefore, any change in torque can be produced by rotating stator flux in the required direction. Neglecting the rotor resistance drop, for a short time interval Δt , when the voltage vector is applied, $\Delta \lambda_s = V_s \Delta t$. Thus, the stator flux linkage space vector moves by $\Delta \lambda_s$ in the direction of the stator voltage space vector at a speed proportional to magnitude of voltage space vector. By selecting step-by-step the appropriate stator voltage vector, it is then possible to change the stator flux in the required direction [6].

2.1. Common Mode Voltage

In a standard three phase two-level voltage source inverter the common mode voltage can be expressed as

$$V_{cm} = \frac{V_{ao} + V_{bo} + V_{co}}{3} \quad (2)$$

Where V_{ao} , V_{bo} , V_{co} are the inverter pole voltages.

Common mode voltage is different from zero, when the drive is fed from an inverter employing PWM technique and its instantaneous values can be determined from (2) based on the switching states summarized in [16, 18].

2.2. Conventional SVPWM

In conventional SVPWM, the reference voltage space vector (V_{ref}) is obtained by substituting the various sampled voltage vectors at each time interval, T_s , referred to as sub cycle in the average sense. The six non zero voltage vectors and two zero voltage vectors can be represented by space vectors as shown in Fig. 1(a). Given a sample V_{ref} at angle α in sector-1 as shown in Fig.1(a), two adjacent active voltage vectors V_1 and V_2 in combination with two zero voltage vectors V_0 and V_7 must be applied for time durations T_1 , T_2 and T_z respectively within the sampling time period T_s to generate a sample.

$$T_1 = \frac{3}{\pi} * M * \frac{\sin(60^\circ - \alpha)}{\sin(60^\circ)} * T_s \quad (3)$$

$$T_2 = \frac{3}{\pi} * M * \frac{\sin \alpha}{\sin 60^\circ} * T_s \quad (4)$$

$$T_z = \frac{\pi * V_{ref}}{2 * V_{dc}}$$

Where M is the modulation index and given by $M = \frac{V_{ref}}{V_{dc}}$. To keep the switching frequency constant, the remainder of the time is spent on the zero states, that is

$$T_z = T_s - (T_1 + T_2) \quad (5)$$

Thus SVPWM uses 0127-7210 in sector-I and 0327-7230 in sector-2 and so on.

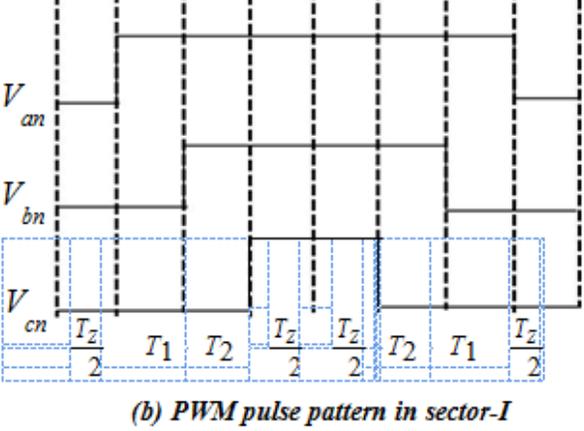
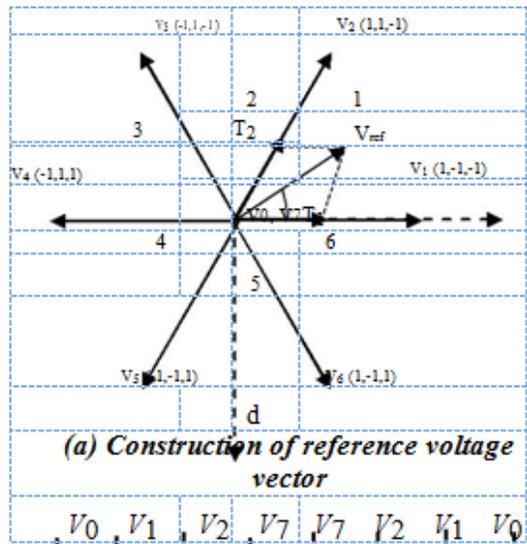


Figure.1 Construction of reference voltage vector and pulse pattern of SVPWM in sector-I

2.3. Existing NSPWM algorithm

As SVPWM uses zero voltage vectors in each sector CMV variations are very high. To reduce CMV variations in NSPWM algorithm three adjacent voltage vectors are utilized to match the reference volt – seconds. These voltage vectors are selected in such away that voltage vector closest to the reference voltage vector and its two neighbors are utilized to program the output in each sector. Thus NSPWM uses 216-612 in sector-I and 321-123 in sector-2 and so on. Moreover the modulating waveform of NSPWM is similar to DPWM1 waveform. From Fig. 2(b) it can be observed

that a-phase is clamped to positive dc bus. Hence the switching losses associated with the inverter are reduced. As all the sectors are symmetric this paper is limited to first sector only. For the required reference voltage vector, the active voltage vectors times can be calculated as given in (6), (7) and (8)

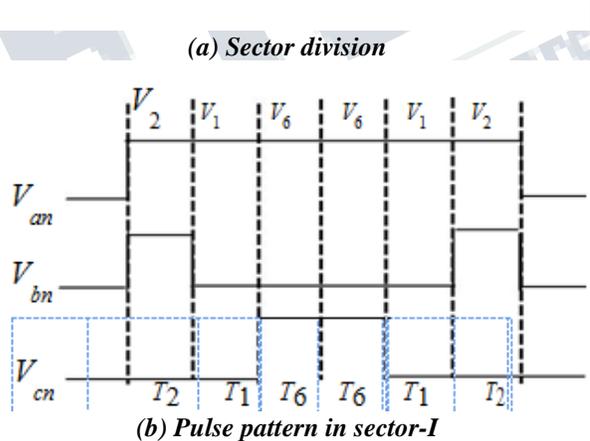
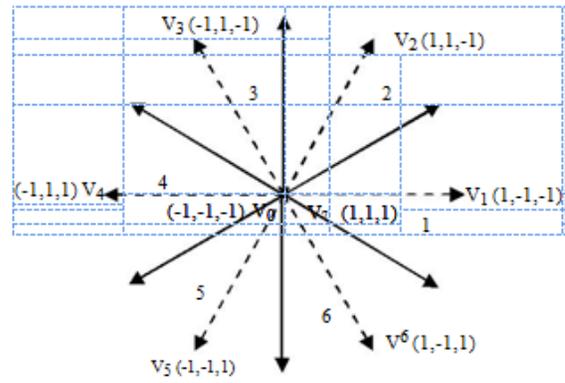


Figure. 2 Sector division and PWM pulse pattern in NSPWM

$$T_1 = \left\{ -1 + \frac{3}{\pi} M \cos\left(\alpha + \frac{\pi}{3}\right) + \frac{3}{\pi} \frac{3}{3} M \sin\left(\alpha + \frac{\pi}{3}\right) \right\} T_s \quad (6)$$

$$T_2 = \left\{ 1 - \frac{3}{\pi} M \cos\left(\alpha + \frac{\pi}{3}\right) - \frac{3}{\pi} M \sin\left(\alpha + \frac{\pi}{3}\right) \right\} T_s \quad (7)$$

$$T_6 = T_s - T_1 - T_2 \quad (8)$$

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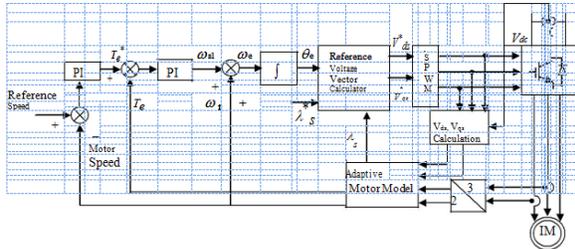


Figure 3 Block diagram of proposed DTC

2.4. NSPWM Algorithm using Imaginary Switching Times Concept

As the existing NSPWM algorithm approach is similar to the conventional space vector approach, the complexity involved in the algorithm is definitely more because of the conventional approach. In order to simplify the existing NSPWM algorithm, the proposed NSPWM algorithm has been developed by using the notion of imaginary switching times. By using the concept of imaginary switching times, the modulating waveform can be generated as given below:

The imaginary switching time periods proportional to the instantaneous values of the reference phase voltages are calculated as given in (9)

$$T = \frac{V_{as}}{V_{dc}} T_s, T = \frac{V_{bs}}{V_{dc}} T_s, \text{ and } T = \frac{V_{cs}}{V_{dc}} T_s \quad (9)$$

The maximum and minimum values of imaginary switching times are calculated in every sampling time as given in (10)-(11).

$$T_{Max} = \text{Max}(T_{as}, T_{bs}, T_{cs}) \quad (10)$$

$$T_{Min} = \text{Min}(T_{as}, T_{bs}, T_{cs}) \quad (11)$$

The effective time during which the induction motor is effectively connected to the source can be calculated as given in (12).

$$T_{eff} = T_{Max} - T_{Min} \quad (12)$$

When the computed gating signals for power devices in the inverter circuit are generated in the PWM algorithm, there is a choice by which the effective time can be repositioned anywhere within the sampling time period. Therefore, the actual switching times for each inverter leg can be obtained by the time shifting operation this can be done by simply adding the offset time period to the computed imaginary

switching times this illustration as follows:

$$I_{ga} = I_{as} + I_{offset} \quad (13)$$

$$I_{gb} = I_{bs} + I_{offset} \quad (14)$$

$$I_{gc} = I_{cs} + I_{offset} \quad (15)$$

V_{dc} of the inverter can be fully utilized, if the actual

switching times are restricted to a value from 0 to T_s. The procedure to generate the modulating waveforms NSPWM algorithm, the procedure is as follows: If the a-phase instantaneous reference voltage positive (or negative) and has maximum magnitude, the a-phase switch should be fixed to the ON (or OFF) state. In mathematical computations that is to say,

$$\text{If } T_{Max} + T_{Min, offset} < 0 \text{ then } T_{Max} + T_{offset} = T_s \quad (16)$$

$$\text{If } T_{Max} + T_{Min, offset} \geq 0 \text{ then } T_{Min} + T_{offset} = 0 \quad (17)$$

Therefore, the time shifting value T_{offset} is given as in (18) [17].

$$\text{If } T_{Max} + T_{Min, offset} < 0 \text{ then } T_{offset} = -T_{Min} \quad (18)$$

$$\text{If } T_{Max} + T_{Min, offset} \geq 0 \text{ then } T_{offset} = T_{Max} - T_s$$

Then, the modulating waveforms of NSPWM algorithm can be synthesized using the calculated gating times by using (19).

$$V_{in} = \frac{V}{2} \begin{pmatrix} 2 * T_{gi} \\ T_s \\ -1 \end{pmatrix} \quad (19)$$

Where T_{gi} (for i=a,b,c) is actual gating signals.

The generated modulating waveforms of both NSPWM and DPWM1 algorithm are exactly the same [14] and Fig 4 shows the waveform of generated modulating signal of NSPWM algorithm. From the modulating waveform of NSPWM algorithm, it has been observed that at a particular time period in any one of the three phases is clamped either to the positive or negative DC bus for a total of 1200 over a fundamental cycle. Hence, the switching losses of the accompanying inverter leg have been eliminated.

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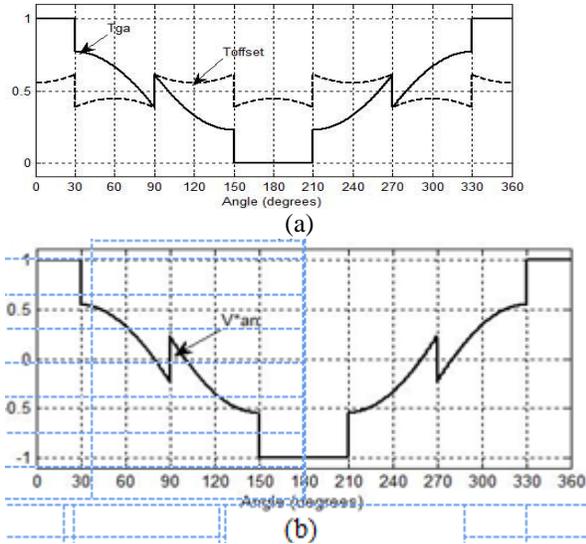


Fig 4 (a) actual gating time (T_{ga}) and offset time (T_{offset}) (b) Modulating wave of NSPWM

In order to keep switching frequency constant for each PWM method equal number of commutations (N_c) per PWM cycle must be considered. Table-I indicates the number of commutations (N_c) per PWM cycle of NSPWM method along with SVPWM. In order to obtain the same N_c in each method, the switching frequency of each method must be divided by K_f factor.

Table -I: Number of Commutations per Sub cycle and K_f

S.No	PWM METHOD	NUMBER OF COMMUTATIONS(N_c)	OF (K_f)
1	SVPWM	3	1
2	NSPWM	2	2/3

Instead of utilising one carrier wave in NSPWM algorithm, two carrier waves must be employed. The choice of the triangle to be compared with the modulation signals is dependent on the region. When the slope of the instantaneous reference phase voltage is positive then the corresponding phase modulating waveform is compared with V_{tri} and the

modulating waveform of corresponding phase is compared with $-V_{tri}$ if slope of the instantaneous reference phase voltage is negative. As a general switching rule, if the modulating waveform is larger than that of the carrier signal, the upper switch is set on with the specific phase. The reference phase voltages are as shown in Fig 5 in all the six sectors. It has been observed from Fig 5, in the first sector that is from zero degrees to 60 degrees period the slope of a- and b-phase voltages is positive, whereas the slope of c-phase voltage is negative. Therefore, from Fig.6, it is evident that the modulating waveforms of a-phase and b-phase are compared with V_{tri} and modulating wave of c-phase is compared with $-V_{tri}$ in the first sector. The possible pulse pattern for the first sector is also shown in Fig 6.

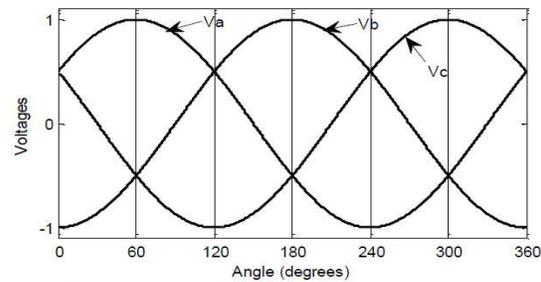


Fig 5 Reference phase voltages in all sectors in NSPWM algorithm

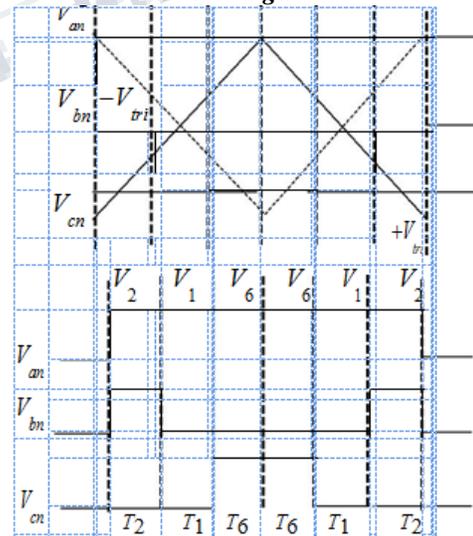


Fig 6 Scalar Implementation of NSPWM Algorithm (in first sector)

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2.5. Proposed NSPWM based DTC

The block diagram of proposed NSPWM algorithm based DTC is shown in Fig.3. In this method, actual values of d-axis and q-axis stator fluxes which are obtained from adaptive motor model are compared with that of the reference values of d-axis and q-axis stator fluxes in reference voltage vector block and an error in flux is obtained which when divided by the sampling time period gives a reference voltage. These d-axis and q-axis reference voltage vectors are then fed to the NSPWM block where these reference voltages are converted into three-phase reference voltages by d-q transformation theory. By the use of the instantaneous phase voltages, actual gating pulses can be generated. After the generation, the pulses are then fed to the inverter.

2.6. Simulation Results and Discussion

To validate the proposed PWM algorithms, numerical simulation studies have been carried out by using Matlab /Simulink. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 45 N-m. For the simulation studies, a 3-phase, 400V, 5 kW, 4-pole, 50 Hz, 1470 rpm induction motor has considered. The parameters of the given induction motor are as follows: $R_s=1.60\text{ohm}$, $R_r=1.30\text{ohm}$, $L_m=0.175\text{H}$, $L_s=0.18\text{H}$, $L_r=0.18\text{H}$ and $J=0.089\text{Kg-m}^2$.

The results for conventional DTC based induction motor drive are shown in Fig. 7- Fig. 10. The results for SVPWM based DTC are shown in Fig. 11- Fig. 14.

To show the effectiveness in the proposed PWM technique here the steady state conditions are considered. From Fig. 7 it can be observed that the ripple in torque varies from -12 N-m to 12 N-m in Conventional DTC which is very high, this torque ripple is reduced using conventional SVPWM based DTC as shown in Fig .11, where torque ripple is reduced to -2 N-m to +2 N-m. with the proposed PWM technique the steady state operation period is shown in Fig.15 and it is visualised as the torque waveform is appearing as thick line. The ripple content in the waveform is observed as -0.4 N-m to +0.4 N-m.

From Fig. 7 it can be observed that, the ripple in current varies from -5A to +5A which can be reduced as shown in Fig.11 a considerable reduction in the current

waveform can be observed. This current harmonics are further reduced with the proposed PWM technique. The total harmonic distortion is calculated for the proposed technique and observed as 3.15% shown in Fig.17, which is less than the CSVPWM technique. From Fig.7 and Fig.11 it can be observed that the ripple in Stator flux is reduced with conventional SVPWM based DTC as compared to that of Conventional DTC algorithm. To mitigate the CMV variations NSPWM method is proposed for DTC fed induction motor drive in which only active vectors are used in each sector.

The steady state results of proposed PWM algorithm based DTC are given in Fig.15 - Fig. 18 along with their CMV variations, line voltage and THD. Fig. 15 it can be observed that, the ripple in torque, stator flux and current is less in steady state. From Fig. 8, Fig. 12 the CMV changes from +Vdc/2 to -Vdc/2 in conventional DTC and SVPWM based DTC algorithms due to the presence of zero voltage vectors. In the proposed method as shown in Fig. 16, it can be observed that, the CMV changes from +Vdc/6 to -Vdc/6 due to usage of active voltage vectors which is less when compared with conventional methods. From Fig.9, Fig.13 and Fig.17 it can be observed that the THD of proposed PWM algorithm based DTC is less when compared with conventional methods. Any well-designed PWM strategy must ensure that the line-line voltages do not have negative pulses in the positive half-cycle and vice versa. From Fig. 10, Fig.14 and Fig.18 it can be observed that the proposed algorithm has pulses of opposite polarity when compared with the SVPWM algorithm.

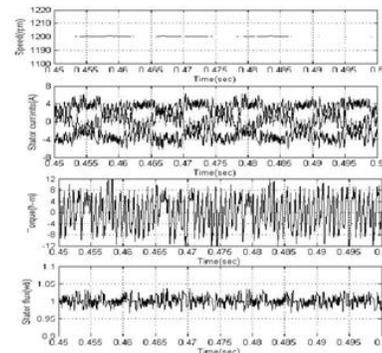


Figure 7 Steady state plots in conventional DTC Algorithm

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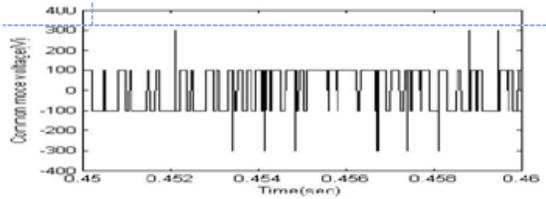
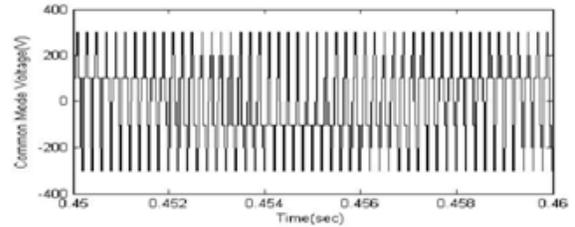


Figure 8 CMV variations in conventional DTC algorithm



SVPWM based DTC

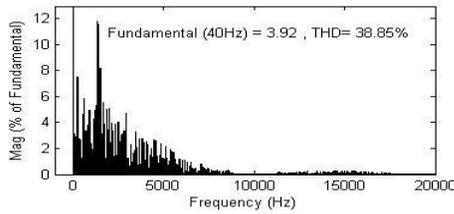


Figure 9 Total Harmonic Distortion in conventional DTC algorithm

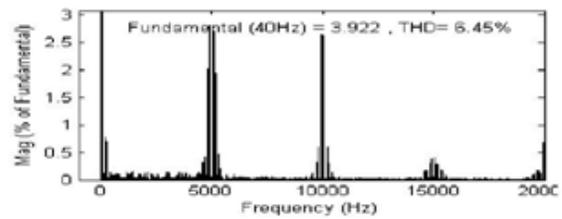


Figure 13 Total Harmonic Distortion in SVPWM based DTC algorithm

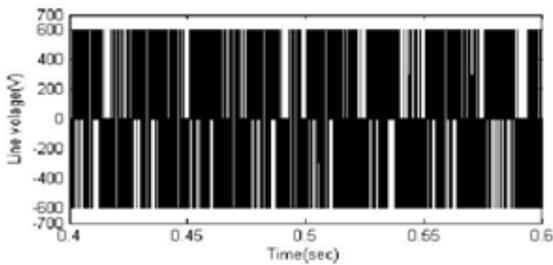


Figure 10 Line voltages in conventional DTC algorithm

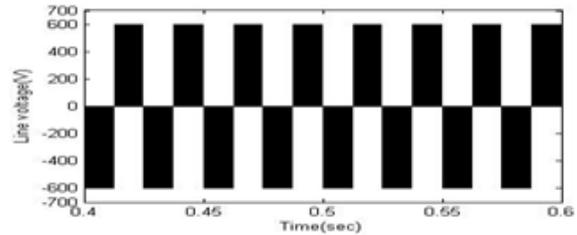


Figure 14 Line voltage in SVPWM based DTC algorithm

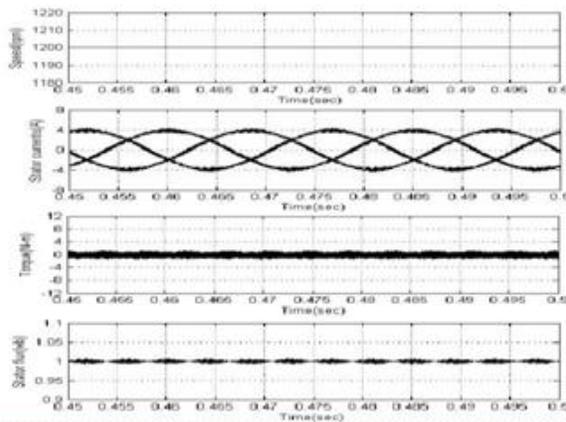


Figure 11 Steady state plots in SVPWM based DTC algorithm

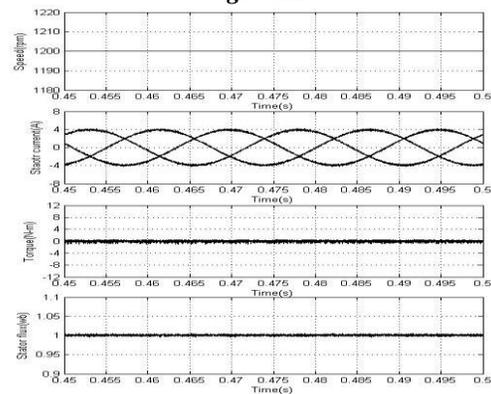


Figure 15 Steady state plots in proposed NSPWM based DTC algorithm

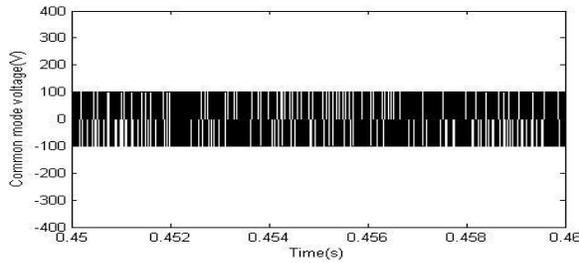


Figure 16 Common mode voltage variations in NSPWM based DTC algorithm

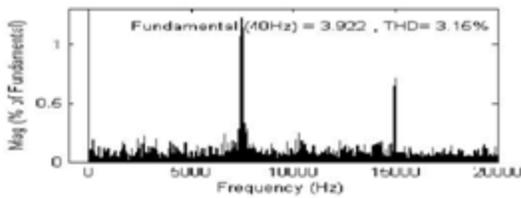


Figure 17 Total Harmonic Distortion in NSPWM based DTC algorithm

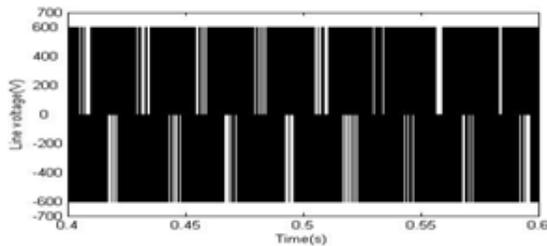


Figure 18 Line voltage in NSPWM based DTC algorithm

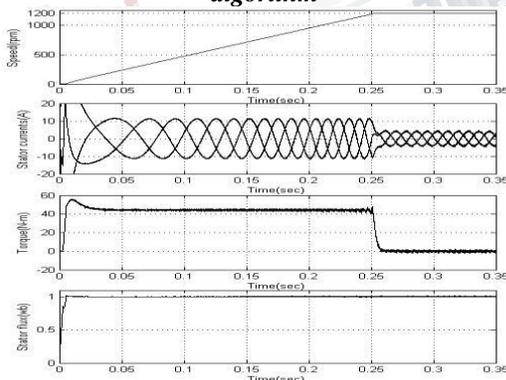


Figure 19 Starting transients in NSPWM based DTC algorithm

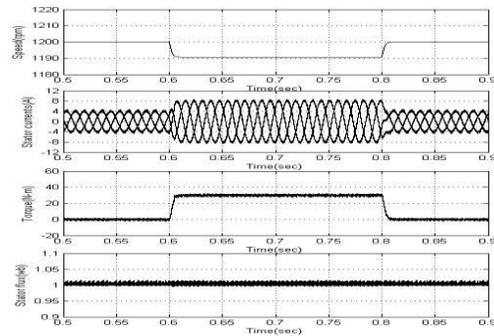


Figure 20 Transients during the step change in load in NSPWM based DTC (a load of 30 N-m is applied at 0.6 sec and removed at 0.8 sec)

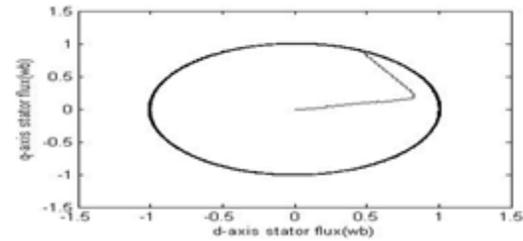


Figure 21 Locus in NSPWM based DTC algorithm

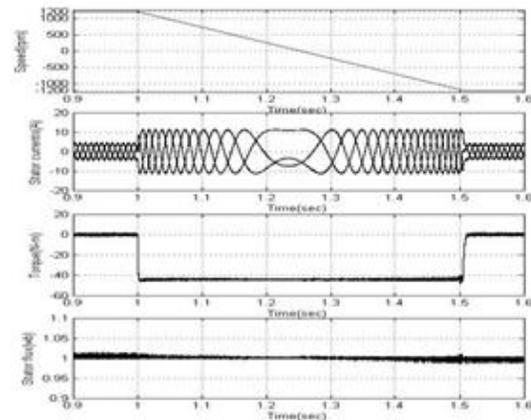


Figure 22 Transients in speed, currents, torque and flux during the speed reversal in NSPWM based DTC (Speed is changed from +1200 rpm to -1200 rpm at 1 sec)

III. CONCLUSIONS

Despite of its simplicity DTC generates high level CMV variations and large steady state ripple in

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torque and flux. To reduce steady state ripple and to get constant switching frequency operation, SVPWM technique has been proposed to DTC. Though this technique reduces steady state ripples it still suffers from CMV variations due to the usage of zero voltage vectors. To reduce the CMV variations, a simplified near state PWM algorithm (NSPWM) is proposed to DTC based induction motor drive. In the Proposed PWM algorithms instead of using zero voltage vectors, three adjacent active voltage vectors are utilized for composing the reference voltage vector. So, the proposed NSPWM method reduces the switching losses of the inverter and CMV variations.

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