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PERFORMANCE ANALYSIS OF PWM ALGORITHMS FOR REDUCED COMMON MODE VOLTAGE IN DIRECT TORQUE CONTROLLED INDUCTION MOTOR DRIVES

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ABSTRACT

This paper presents a novel near state PWM (NSPWM) algorithm for reduced common mode voltage (CMV) in direct torque controlled induction motor drives. In the proposed algorithm, active voltage vectors are used to program the output voltage 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. As the proposed NSPWM algorithm is 120 degrees bus-clamping PWM algorithm, it reduces the switching losses of the inverter. 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.*

INTRODUCTION

Dynamic performance of PWM inverter fed ac motor drives has been increased with the advent of fast-switching semi conductor switches like IGBTs, IGCTs, thereby increasing the switching frequency of the inverter. This development created several unexpected problems such as shaft voltages, bearing currents, conducted EMI. The direct cause of above mentioned problems presented is common mode voltage (CMV) which is generated in the inverter itself. Many studies for reducing the CMV have been progressed. These studies however focused on the design of common mode choke, 4-phase inverter 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.

DTC has proven to be a powerful method for controlling induction motors. Though DTC is simple, robust to parameter variations it has certain draw backs such as steady state ripple, generation of high common mode voltage variations and variable switching frequency [6-7]. To reduce steady state ripple and to get constant switching frequency operation, a space vector PWM technique has been proposed. 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 CMV variations due to the presence of zero voltage vectors [8-9]. To reduce the complexity involved in conventional SVPWM algorithm, a novel SVPWM technique has been proposed using the concept of imaginary switching times [10] but still it suffers from high CMV variations. In recent researches for reduction of the CMV using a PWM scheme came to the front .Though these methods reduce CMV; they employed conventional approach for calculation of switching times which increases the complexity of the PWM algorithm. Moreover, these methods employed open loop v/f control.Though these methods reduce CMV variations, switching losses and switching frequency of inverter is high for these methods [11-15].

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

I. Conventional DTC

The torque developed by an three phase induction motor can be expressed as given in (1).

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

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 [6].

A. Common Mode Voltage(CMV)

For a 3-φ, two-level Voltage Source Inverter (VSI) there are three switching variables a, b, c one per phase of the inverter. The three phases together can have 23 combinations of switching states .There are six active voltage vectors and two zero voltage vectors that a VSI can produce.

The n[th] voltage vector can be represented by space vectors as

$$V_n = \frac{2}{3}V_{dc}\, e^{\left[j(n-1)\frac{\pi}{3}\right]}; n = 1,2,..6. \quad (2)$$

CMV for a 3-φ two-level voltage source inverter can be expressed as

$$V_{no} = \frac{V_{ao} + V_{bo} + V_{co}}{3} \quad (3)$$

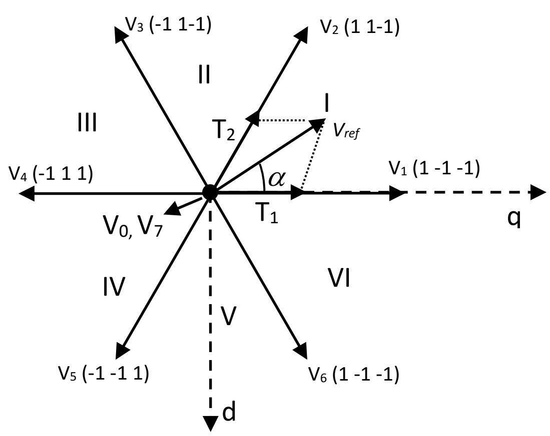

Fig 1 Construction of reference voltage vector

Where V_{ao}, V_{bo}, V_{co} are the inverter pole voltages. CMV can be determined from (3) based on the switching states summarized in Table-I.

Table – I: CMV variations for different Inverter Switching States:

State	V_{ao}	V_{bo}	V_{co}	V_{com}
V_0	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
V_1	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_2	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/6$
V_3	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_4	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_5	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/6$
V_6	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_7	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$

From the Table-I it can be observed that, if a transition from an even (odd) voltage vector to odd (even) voltage vector occurs CMV variation of $V_{dc}/3$ is generated, if a transition from an even (odd) voltage vector to zero (seventh) voltage vector occurs CMV variation of $2V_{dc}/3$ is generated, if a transition from seventh voltage vector to zero voltage vector occurs, a CMV variation of V_{dc} is generated which is a worst case. So, in order to minimize the CMV variations of the drive, eliminate both zero and seventh voltage vectors.

II. Conventional SVPWM

In conventional SVPWM, the reference voltage space vector (V_{ref}) at angle α in sector-1 as shown in Fig.1, two adjacent active voltage vectors V_1 and V_2 in combination with two zero voltage vectorsV_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 [17] .

Existing NSPWM algorithm

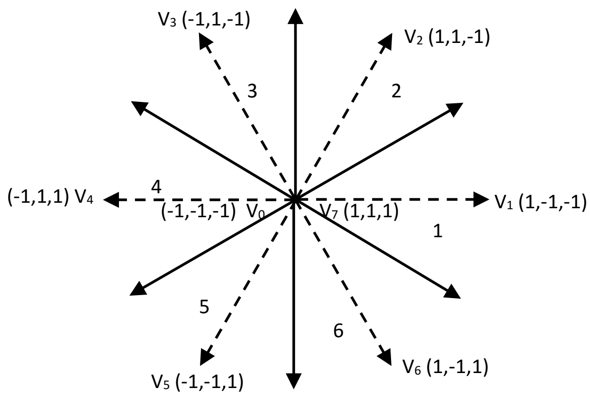

Fig. 2 Sector division in NSPWM

CMV is very high in SVPWM as it uses zero voltage vectors in each sector. To reduce CMV, in NSPWM three active voltage vectors are composed to maintain volt-sec. These voltage vectors are selected in such away that voltage vector closest to the V_{ref} 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-II and so on. Moreover the modulating waveform of NSPWM is similar to DPWM1 waveform. As all the sectors are symmetric this paper is limited to first sector only. For the required V_{ref}, the active voltage vectors times can be calculated as given in (6), (7) and (8)

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

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

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

III. 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 more. 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 [17]. 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:

$$\begin{aligned} T_{ga} &= T_{as} + T_{offset} \\ T_{gb} &= T_{bs} + T_{offset} \\ T_{gc} &= T_{cs} + T_{offset} \end{aligned} \quad (13)$$

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 of NSPWM algorithm, the procedure is as follows:

If the a-phase instantaneous reference voltage is 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,

$$\text{If } T_{Max} + T_{Min,} < 0 \text{ then } T_{Max} + T_{offset} = T_s \qquad (14)$$

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

Therefore, the time shifting value T_{offset} is given as in (15)

$$\text{If } T_{Max} + T_{Min,} < 0 \text{ then } T_{offset} = -T_{Min} \qquad (15)$$

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

Then, the modulating waveforms of NSPWM algorithm can be synthesized using the calculated gating times by using (16)

$$V_{in} = \frac{V_{dc}}{2}\left(\frac{2 * T_{gi}}{T_s} - 1\right) \quad \text{i=a,b,c} \qquad (16)$$

Where Tgi (for i=a,b,c) is actual gating signals

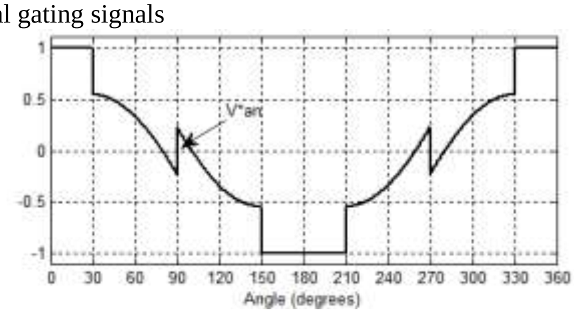

Fig 3 Modulating wave of NSPWM

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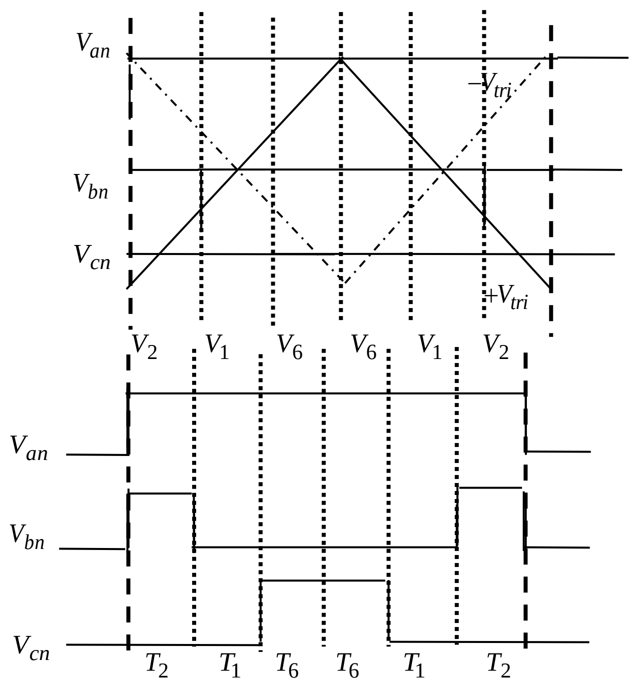

Fig 4 Scalar Implementation of NSPWM Algorithm (in first sector)

The generated modulating waveforms of both NSPWM and DPWM1 algorithm are exactly the same [14] and Fig 3 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 120^0 over a fundamental cycle. Hence, the switching losses of the accompanying inverter leg have been eliminated.

Instead of utilizing 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. Therefore, from Fig.4, 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. 4.

In order to keep switching frequency constant for each PWM method equal number of commutations (Nc) per PWM cycle must be considered. In order to obtain the same Nc in each method, the switching frequency of NSPWM method must be divided by 2/3.

A. NSPWM Algorithm based DTC

In NSPWM based DTC of Induction motor method, the reference values of d-axis and q-axis stator fluxes are compared with the actual values of d-axis and q-axis stator fluxes are obtained from adaptive motor model. An error in flux is obtained which when divided by the sampling Time period gives a reference voltage vector used for direct control of torque and flux.

These are then fed to the NSPWM block. The NSPWM block first converts these two-phase reference voltages into three-phase reference voltages. Then by using above NSPWM algorithm procedure, the actual gating pulses can be generated by using the instantaneous phase voltages. The generated pulses are then fed to the inverter.

IV. Simulation Results and Discussions

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, 4 kW, 4-pole, 50 Hz, 1470 rpm induction motor has considered. The parameters of the given induction motor are as follows: *Rs*=1.57ohm, *Rr*=1.21ohm, *Lm*= 0.165H, *Ls*= 0.17H, *Lr*= 0.17 H and J= 0.089 Kg - m^2. The results for conventional DTC based induction motor drive are shown in Fig. 6-Fig. 8.

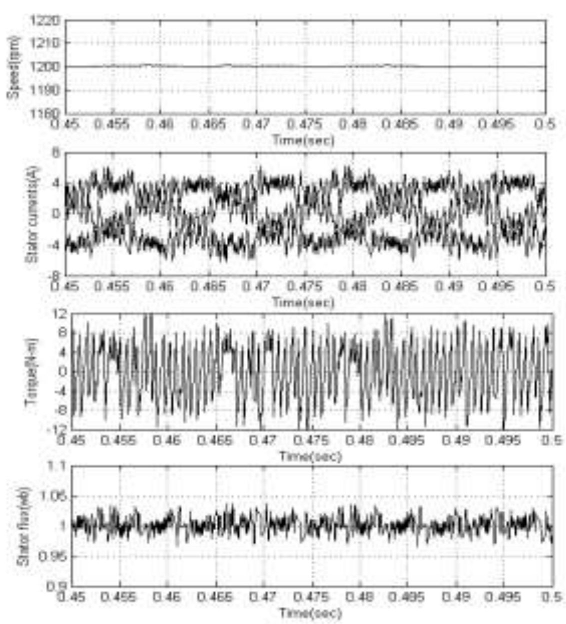

Fig. 6 Steady state plots in conventional DTC algorithm

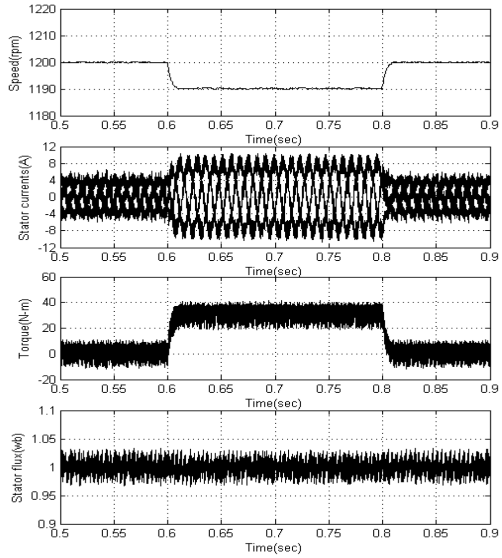

Fig.7 Transients during the step change in load (a load of 30 N-m is applied at 0.6 sec and removed at 0.8 sec in conventional DTC

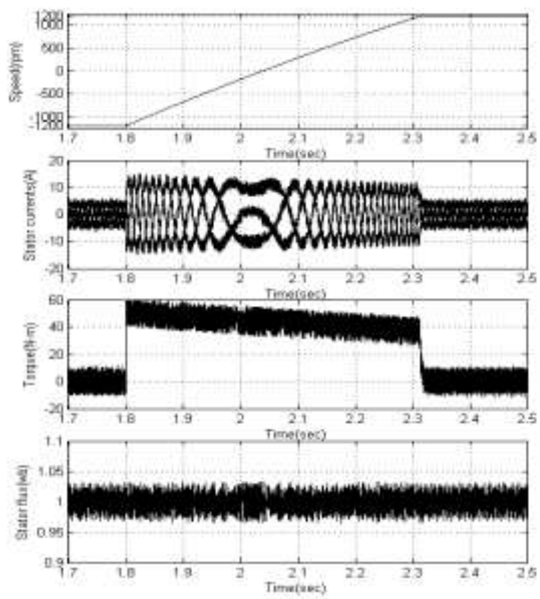

Fig.8: Transients in speed, currents, torque and flux during the speed reversal (Speed is changed from -1200 rpm to +1200 rpm at 1.8 sec)in conventional DTC

The results for SVPWM based DTC are shown in Fig. 9- Fig. 11. From Fig. 6 and Fig. 9, it can be observed that, the ripple in torque, stator flux and current can be reduced with conventional SVPWM based DTC 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.12 - Fig. 14 along with their CMV variations, line voltage and THD. Fig. 12 it can be observed that, the ripple in torque, stator flux and current is less in steady state. From Fig. 7, Fig. 10 and Fig. 13, it can be observed that, the CMV changes from +Vdc/6 to -Vdc/6 in proposed PWM method instead of +Vdc/2 to -Vdc/2 as in conventional DTC algorithm and SVPWM based DTC algorithm due to elimination of zero voltage vectors. From Fig.8, Fig.11 and Fig.14 it can be observed that the THD of proposed PWM algorithm based DTC is less when compared with conventional methods.

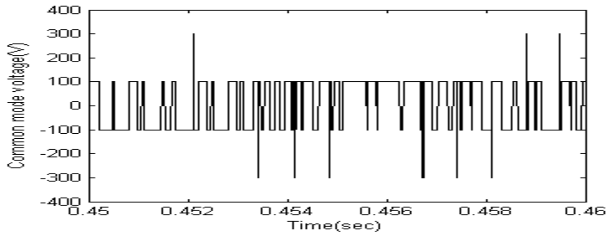

Fig 9 CMV variations in conventional DTC algorithm

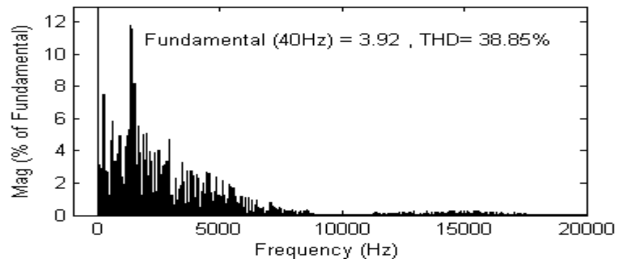

Fig 10 Total Harmonic Distortion (THD) in conventional DTC algorithm

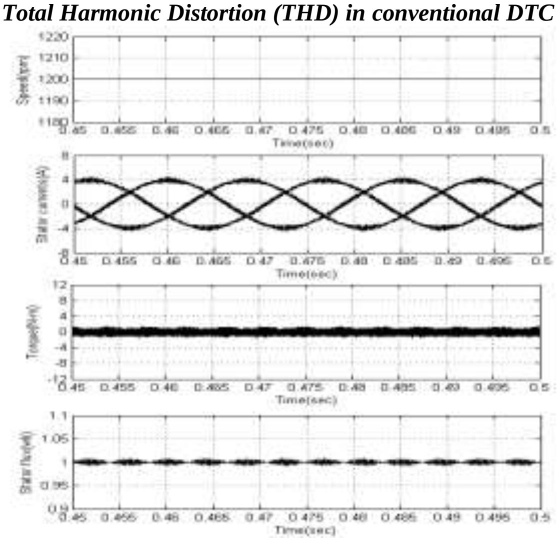

Fig 11 Steady state plots in SVPWM based DTC algorithm

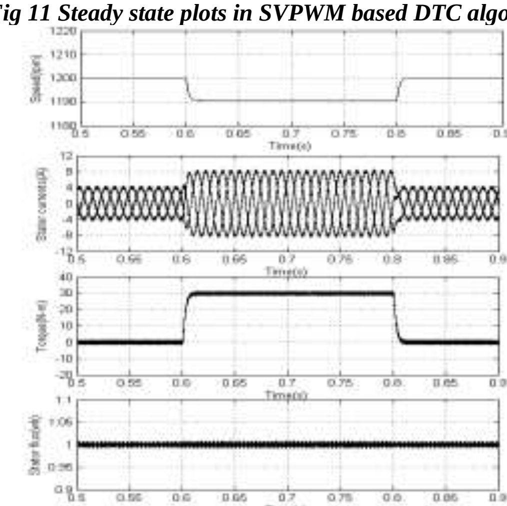

Fig.12 Transients during the step change in load in Conventional SVPWM based DTC

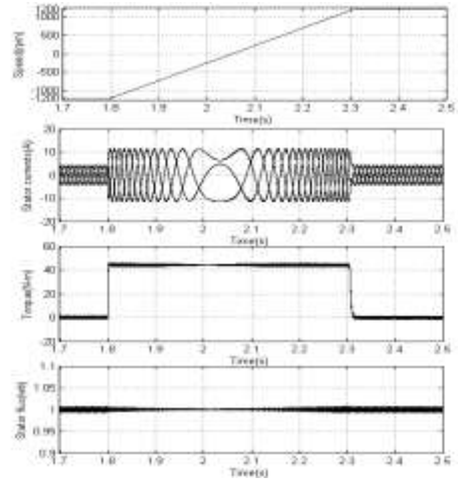

Fig.13 Transients in speed, currents, torque and flux during the speed reversal in Conventional SVPWM based DTC

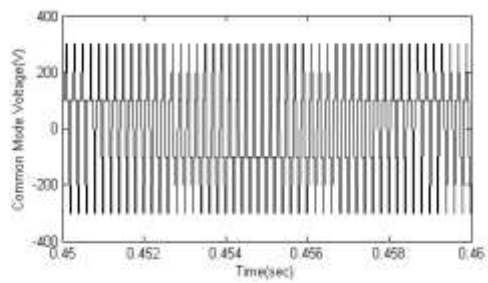

Fig. 14 CMV variations in SVPWM based DTC

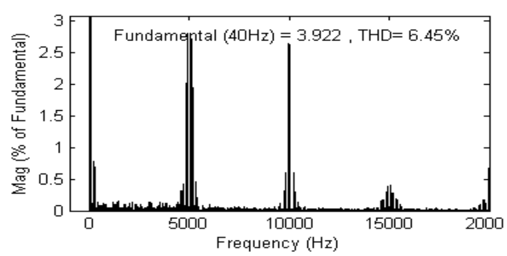

Fig. 15 Total Harmonic Distortion in SVPWM based DTC algorithm

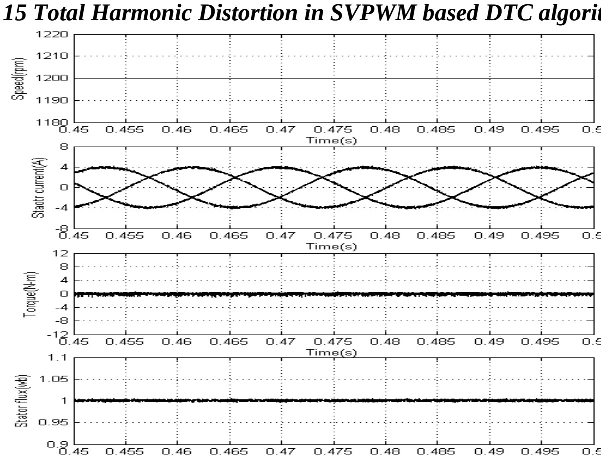

Fig.16 Steady state plots in proposed NSPWM based DTC algorithm

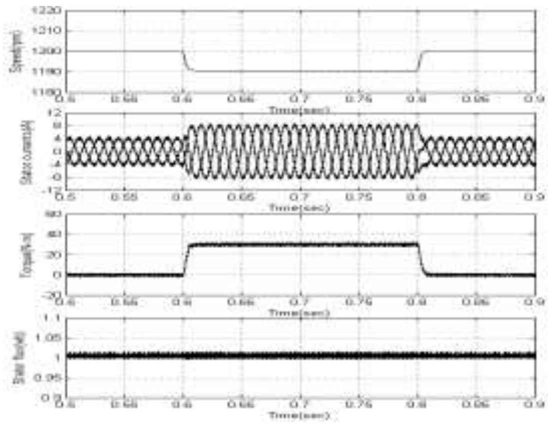

Fig.17 Transients during the step change in load in NSPWM based DTC (a load of 30 N-m is applied at 0.6 sec and removed at 0.8 sec)

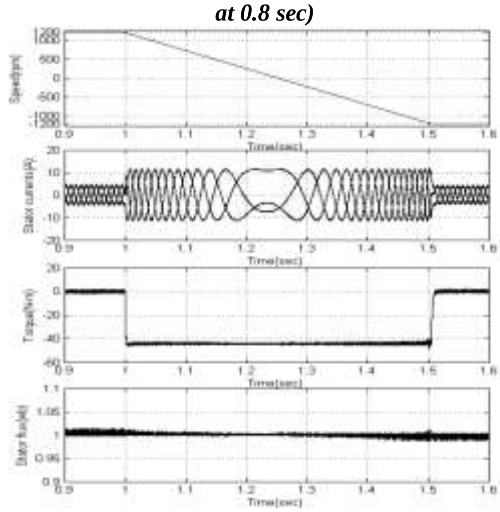

Fig.18 Transients in speed, currents, torque and flux during the speed reversal in NSPWM based DTC

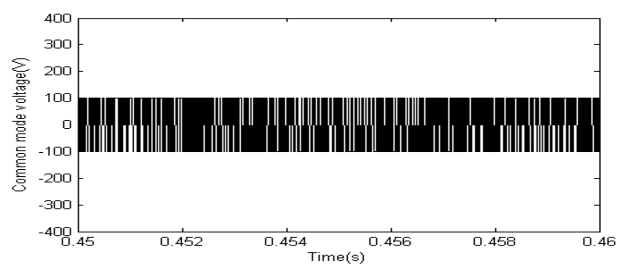

Fig.19 CMV variations in NSPWM based DTC algorithm

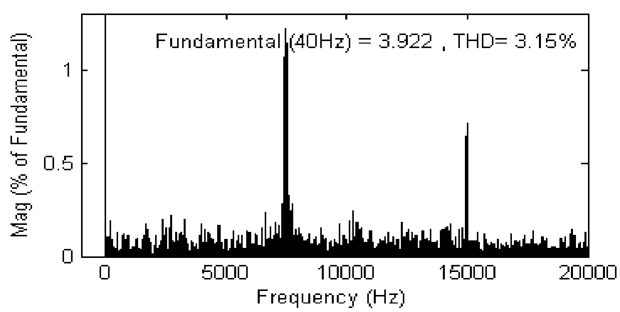

Fig. 20 Total Harmonic Distortion in NSPWM based DTC algorithm

CONCLUSIONS

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