Three Level Modified SVPWM Inverter Fed DTC Induction Motor Drive

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Abstract - ***In this paper, a modified space vector Pulse width modulation (MSVPWM) algorithm has been developed for 3-level inverter fed direct torque control(DTC) induction motor (IMD). MSVPWM algorithm simplifies conventional space vector pulse width modulation (CSVPWM) algorithm, whose complexity lies in sector identification and will proportionalty increase with multilevel inverter output. In the proposed algorithm sectors and subsectors are identified through shifting of the modulating wave to the first sector, there by eliminating the need of reference vector position. Switching state/sequence selection is also very criticalin dealing with SVPWM fed multilevel(MLI). This is for the reason of redundancy in switching states. In the proposed algorithm out of 27 available switching states opt switching state is selected based on sectoe and subsector number, such that voltage ripple is considerably less. Dwell time of each inverter state in a given sample is also calculated using their respective modulating waves. The validate of the proposed algorithm is tested over a three level inverter fed DTC-IMD.***

Key Words: *DTC, MSVPWM*

1. INTRODUCTION

In many industrial applications AC drives play a vital role. In recent years, many studies have been developed to find out different solutions for the control of induction motor like pulse width modulation voltage source inverter(PWM-VSI),Field oriented control(FOC),and V/f control. In this FOC became popular in the field of high performance drives. Control of induction motor is similar to that of separately excited DC motor using FOC algorithm [1], but in this linear transformation is involved and therefore mathematically intense. To evade this and to achieve decoupled nature, DTC strategy is proposed [2]. Contrast flanked by the FOC and DTC has been presented in [3] and finally concluded that DTC gives a good dynamic response. Conventional DTC (CDTC) employs flux and torque hysteresis controllers and so variable inverter switching frequency, ripples in flux and torque particularly in steady state will manifest. To reduce total harmonic distortion (THD) and to attain constant switching frequency different PWM algorithms have been developed, among which SVPWM gained prominence due to its constant switching frequency operation , maximum DC bus utilisation, ease in digital implementation etc. With the advent of the high frequency power semiconductor devices THD in the inverter output voltage can further be reduced with MLI's. Recently multilevel inverters brought renaissance and so neutral point clamped (NPC) three-level inverter [5] is considered in this paper. The pulses generated through MSVPWM algorithm are fed to a three level NPC inverter based DTC-IMD.

Increasing the number of levels in multilevel inverter increases the complexity involved in SVPWM. for two level inverter there will be maximum of 8 eight switching states and 6 sectors, for three level it increases to 27 states and each sector inturn has 6 subsectors, with five level the number of states raise to 125 and each subsector inturn will have 6 sub-subsectors. In general with n level inverter, number of states is n^3, number of sectors/subsector/sub-subsectors and so on are n^3-n, where n is the number of levels. Reference voltage using CSVPWM algorithm is synthesised based on the magnitude (length) and position(subsector in which the tip) of the reference vector is present. Estimating the position of the reference vector needs angle information which leads to computational overhead. Firstly , the novelty of the paper deals in eliminating the thorough iterative processes involved in estimating the position through three phase modulating signals instead of reference vector , $\overline{V_{ref}}$. Also appropriate switching state selection for a given $\overline{V_{ref}}$ is done based on the same logic that is used for sector/subsector selection, i.e.with modulating signals. The concept of the proposed MSVPWM algorithm can be extended to an n-level inverter, as well as for any switching sequence.

To validate the functionality of the proposed algorithm the pulses obtained are fed to a three-level inverter and THD in line voltage is compared with two-level inverter output line voltage. To validate the functionality of the proposed algorithm, three-level inverter fed DTC-IMD is tested under various operating modes like transient, steadystate, speed reversal and variable load conditions.

2. CDTC

In every sampling time of inverter stator voltages and currents are sampled. Using these sampled inputs stator flux,speed,torque and flux angle are predicted in the adaptive motor model. Predicted torque and flux are compared with their respective reference values through hysteresis comparators based on Torque,flux errors and flux angle apt switching state is generated by the optimal switching table.

3.EXISTING SVPWM ALGORITHM

Among these six vectors,V_1 – V_6 are active voltage vectors or active states remaining two vectors, V_0 and V_7 are zero voltage vectors or null vectors. The reference vector $\overline{V_{ref}}$ Is shown in Fig-1, $\overline{V_{ref}}$ is a set of balanced three-phase voltages that are represented in the stationary frame by a space vector of constant magnitude and rotating with the angular speed $\omega=2\pi f_{ref}$.

Time period of each switching cycle is Ts. Reference vector in each switching cycle is achieved by switch over between two active states and two null states. Zero vector time (Tz) is equally divided between V_0 and V_7.

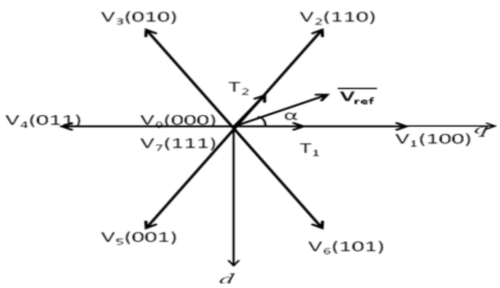

Fig-1: Vector diagram of 2-level inverter

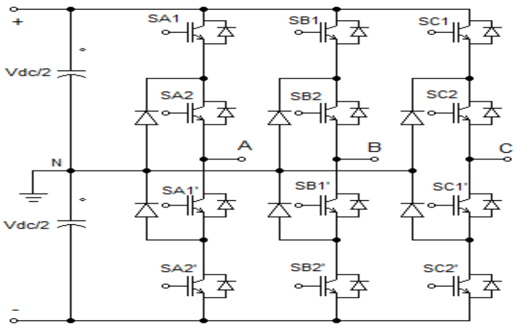

Fig-2: Three-level NPC inverter

Table-1: Switch Status, State and Pole Voltage

Switch status	State	Pole voltage ,V_{A0}
SA1=ON, SA2=ON	+	+Vdc/2
SA1=OFF,SA2= ON	0	0
SA1=OFF,SA2= OFF	-	-Vdc/2

All the six active voltage vectors are divided symmetrically. Active and zero voltage vectors dwell Times are calculated by
Eqn. (1), (2) and (3).

$$T_1 = \frac{2\sqrt{3}}{\pi} Mi \sin(60-\alpha) T_s \quad (1)$$

$$T_2 = \frac{2\sqrt{3}}{\pi} Mi \sin(\alpha) T_s \quad (2)$$

Here *Mi* is modulation index

$$Mi = \frac{3}{2}\frac{V_{ref}}{V_{dc}}$$

$$Tz = Ts - T_1 - T_2 \quad (3)$$

$$\overline{V_{ref}}\, Ts = V_1T_1 + V_2T_2 + V_zT_z \quad (4)$$

SVPWM uses sequence 0127-7210 in sector-I, 0327-7230 in sector-II and so on.

4.PROPOSED MODIFIED SVPWM ALGORITHM FOR 3-LEVEL INVERTER

A Three level NPC inverter is shown in Fig-2. Space vector diagram of three level inverter is shown in Fig-3. Switch status, state and pole voltages are shown in table-1. Step by step procedure is developed for a modified SVPWM algorithm for three level inverter. In MSVPWM algorithm three phase sinusoidal modulating Signals (ma, mb and mc) are used in the place of reference Vector $\overline{V_{ref}}$. These three modulating signals are presented at any instant of reference vector.

In SVPWM, the sector in which the reference vector presented is identified based on its angle, but in MSVPWM algorithm the sector identification is based upon the comparison between the absolute values of modulating signals (|ma|, |mb| and |mc|). sector identification as indicated in Table-2.

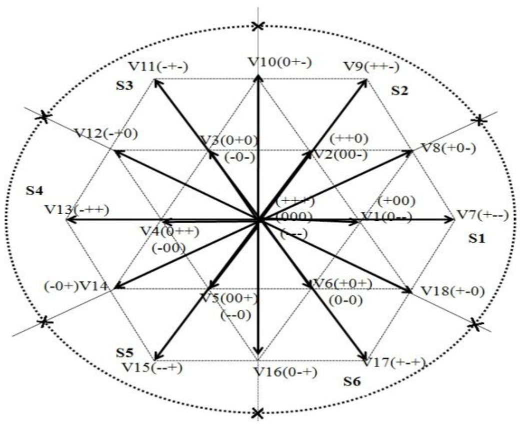

Fig-3: Space vector diagram of 3-level inverter

Table-2: Indetification of Sector

Condition	Sector
$\lvert m_a\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_a>0$	1
$\lvert m_a\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_a<0$	4
$\lvert m_b\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_b>0$	3
$\lvert m_b\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_b<0$	6
$\lvert m_c\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_c>0$	5
$\lvert m_c\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_c<0$	2

After identification of sectors, in SVPWM algorithm reference vector is shifted to first sector by using Eqn.(5). where high computational efforts are involved.

$$\overline{V_r} = V_{ref}\, e^{j*(sector-1)\pi/3} \qquad (5)$$

For reducing these computational efforts, the alternative method is carried out in MSVPWM using Table-3. Here Ma, Mb and Mc represent shifted modulating signals and also represent a shifted reference vector $\overline{V_r}$.

Table-3: Shifting the Modulating Signals to First sector

Sector	*Ma*	*Mb*	*Mc*
1	ma	mb	Mc
2	-1*mc	-1*ma	-1*mb
3	mb	mc	Ma
4	-1*ma	-1*mb	-1*mc
5	mc	ma	Mb
6	-1*mb	-1*mc	-1*ma

Now the modulating signals are in the first sector. In SVPWM the pivot vector of first sector V_1 is subtracted from the $\overline{V_r}$ Such that we get an equivalent reference vector, $\overline{V_r'}$. For the conceptual two level inverter in sector1 is shown in fig-4. In MSVPWM, vector is in the form of signals (*Ma, Mb and Mc*). The equivalent reference modulating signals (*Ma′, Mb′ and Mc′)* are obtained by using Eqn. (6) (7) and (8).

$$Ma' = Ma - \frac{Vp}{3}; \qquad (6)$$

$$Mb' = Mb - \frac{-Vp}{6}; \qquad (7)$$

$$Mc' = Mc - \frac{-Vp}{6} \qquad (8)$$

Table-4: Identification of Subsector

Condition 1	Condition 2	Subsector
$M_a' \geq 0$ and $(M_b' - M_c') \geq 0$	$(M_b' - M_c') \geq 3*M_a'$	2
	$(M_b' - M_c') < 3*M_a'$	1
$M_a' \leq 0$ and $(M_b' - M_c') \leq 0$	$(M_b' - M_c') \geq 3*M_a'$	4
	$(M_b' - M_c') < 3*M_a'$	5
$M_a' \geq 0$ and $(M_b' - M_c') \leq 0$	$(M_c' - M_b') \geq 3*M_a'$	5
	$(M_c' - M_b') < 3*M_a'$	6
$M_a' \leq 0$ and $(M_b' - M_c') \geq 0$	$(M_c' - M_b') \leq 3*M_a'$	2
	$(M_c' - M_b') > 3*M_a'$	3

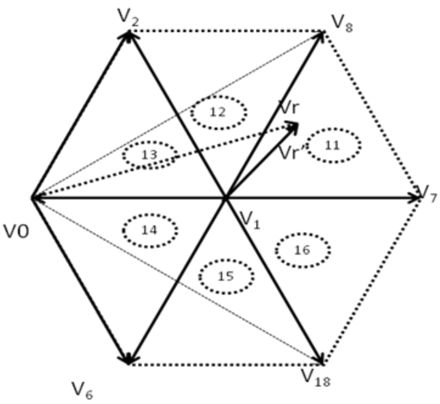

Fig-4: Revised Reference Vector In Sector1

In SVPWM, subsector identification of equivalent two-level inverter is based on angle of $\overline{V_r'}$. In proposing algorithm this is done using equivalent reference modulating signals as indicated in table-4.

In SVPWM computation of dwell times using $\overline{V_r'}$ is having more trigonometric functions, so it consumes more computation time.

In MSVPWM dwell time is nothing but simple differences between equivalent reference modulating signals, that are directly available as Ma′, Mb′ and Mc′. Computation of dwell time as indicated in Table-5.

Table-5: Dwell Time Computation in each of Subsector

Subsector	Time-x	Time-y	Time-z
1	*2(Ma'- Mb')Ts*	*2(Mb'- Mc')Ts*	*Ts-Tx-Ty*
2	*2(Ma'- Mc')Ts*	*2(Mb'- Ma')Ts*	*Ts-Tx-Ty*
3	*2(Mb'- Mc')Ts*	*2(Mc'- Ma')Ts*	*Ts-Tx-Ty*
4	*2(Mb'- Ma')Ts*	*2(Mc'- Mb')Ts*	*Ts-Tx-Ty*
5	*2(Mc'- Ma')Ts*	*2(Ma'- Mb')Ts*	*Ts-Tx-Ty*
6	*2(Mc'- Mb')Ts*	*2(Ma'- Mc')Ts*	*Ts-Tx-Ty*

Based on the above procedure, sector, Subsector and dwell times are computed. But here subsectors and dwell times correspond to sector1 only.

Choose the proper switching states based on subsectors and they have to dwelt with their respective dwell times as indicated in Table-6. These switching states belong to sector1 because all the modulated signals are in sector1. Switching states are shifted to original sectors as indicated in Table-7.

Table-6: Switching States of Sector 1

Sector	Subsector	State0	State1	State2	State7
1	1	0--	+--	+0-	+00
	2		00-	+0-	
	3		00-	000	
	4		0-0	000	
	5		0-0	+-0	
	6		+--	+-0	

Table-7: Shifting Switching States to all Sectors

Sector No	State of A leg (SA)	State of B leg (SB)	State of C leg (SC)
1	SA1	SB1	SC1
2	-SB1	-SC1	-SA1
3	SC1	SA1	SB1
4	-SA1	-SB1	-SC1
5	SB1	SC1	SA1
6	-SC1	-SA1	-SB1

Here SA, SB and SC represent the state of legs A, B and C respectively where as SA1, SB1 and SC1 represent the state of legs before shifting to all sectors.

Pulses generated by using state of leg as indicated in TABLE I.

5. PROPOSED MSVPWM ALGORITHM FOR 3-LEVEL INVERTER FED DTC IM DRIVE

The proposed DTC block diagram is shown in Fig-5. In every sampling period, actual speed ω_r, torque Te and flux Ψ_s are determined by using the adaptive motor model. The flux error is to be minimized, that might be caused by actual flux $\overline{\Psi_s}$ And reference flux $\overline{\Psi_s *}$. Actual speed, torque and flux are compare with their respective reference quantities, and summation of actual speed ω_r and additional slip speed ω_{sl} will produce the speed of flux$\overline{\Psi_s *}$. The appropriate reference vectors are produced by using reference voltage vector calculator block.

$$V_{ds}^{*} = R_s i_{ds} + \frac{\Delta\Psi_{ds}}{T_s} \qquad (9)$$

$$V_{qs}^{*} = R_s i_{qs} + \frac{\Delta\Psi_{qs}}{T_s} \qquad (10)$$

We are obtaining three phase modulating waves Va, Vb and Vc from the reference voltage vectors by using two phases to three phase transformations.

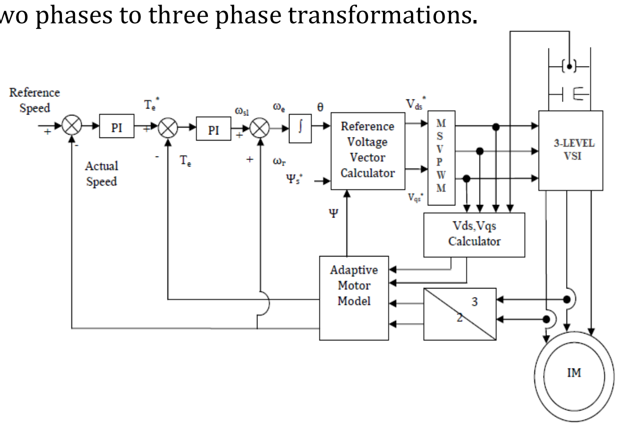

Fig-5: Block diagram of the proposed DTC IM drive

6. SIMULATION RESULTS AND DISCUSSIONS

By using Matlab/Simulink, the reward of SVPWM application as a mathematical simulation has been carried out with fixed step size of 1μs in ode4 (Runge-Kutta) solver. A three phase, 4 pole, 1300 rpm induction motor having parameters R_s=7.83Ω, R_r=7.55Ω, L_s=0.4751H, L_r=0.4751H, L_m=0.4535H and J=0.06Kg.m^2, are considered. CDTC gives large steady state ripple.

To reduce the large ripple SVPWM is used for two level inverter and MSVPWM is used for three level inverter. Phase and line voltage plots of 2-level inverter are shown in Fig-6. Simulation results of SVPWM based two level inverter fed DTC Induction motor having speed, torque, stator current and stator flux for various states as steady state, starting transients, transients during speed reversal (+ve speed to –ve speed and vice versa) and THD of stator current are shown in Fig-7 to Fig-11. Phase and line voltages of 3-level inverter are shown in Fig-12. THD of stator current is shown in Fig.13 and simulation results of MSVPWM based three level inverter fed DTC Induction motor having speed, torque, stator current and stator flux for various states as steady state, starting transients, transients during load torque changes and speed reversal (+ve speed to –ve speed and vice versa) are shown in Fig-14 to Fig-18.

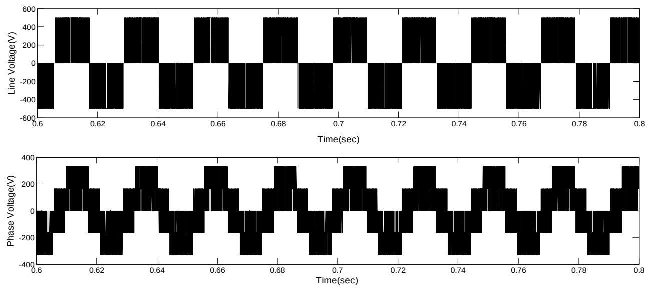

Fig-6: Line voltage and phase voltages of 2- level SVPWM inverter.

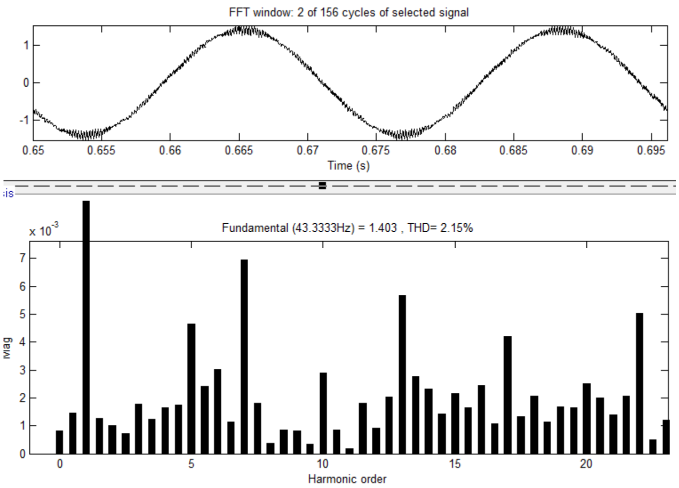

Fig-7: Harmonic Spectrum of stator current along with THD for 2-Level SVPWM based DTC-IM drive.

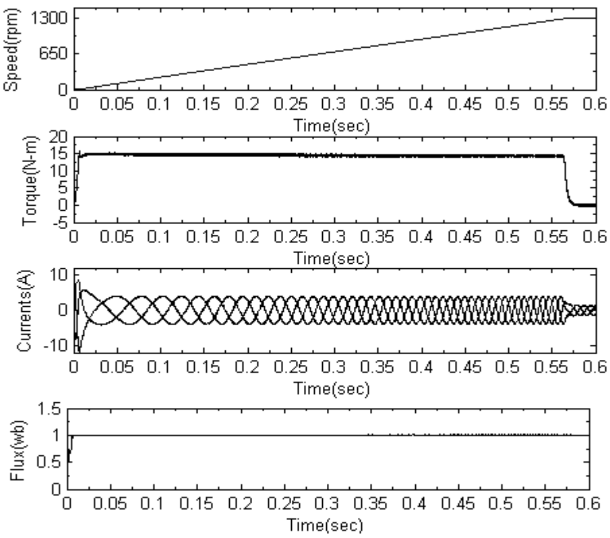

Fig-8: Starting transients for SVPWM algorithm based 2-level inverter fed DTC-IM.

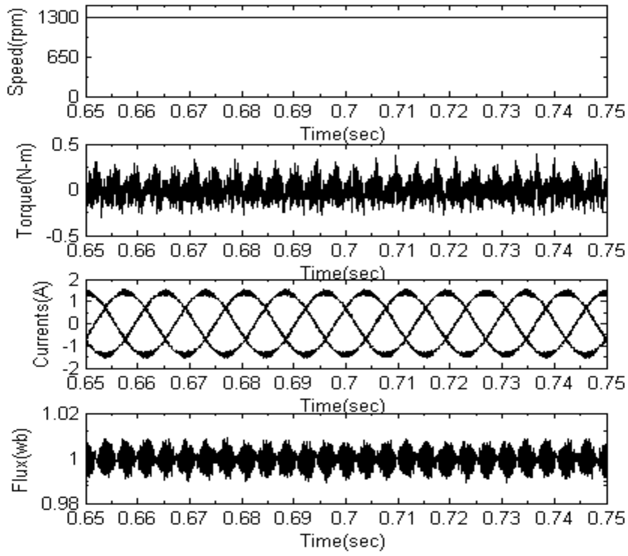

Fig-9: Steady state plots for 2-level SVPWM based DTC-IM drive.

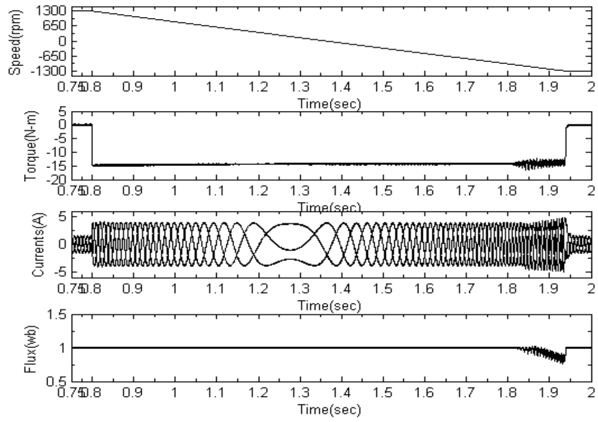

Fig-10: Transients during speed reversal for 2- level SVPWM based DTC-IM drive (Speed changed from1300 rpm to-1300 rpm).

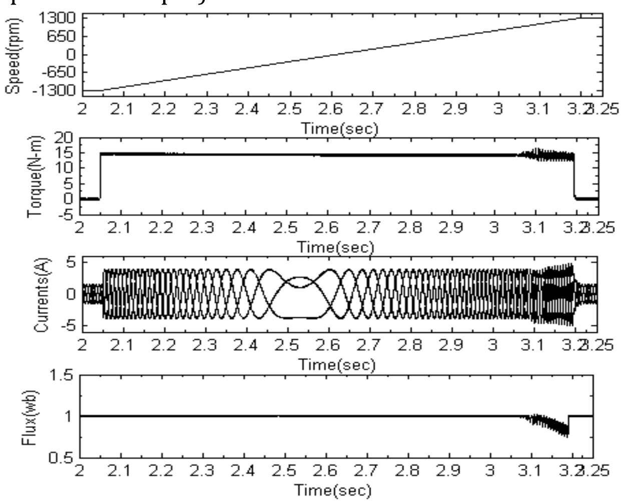

Fig-11: Transients during speed reversal for 2- level SVPWM base DTC-IM drive (Speed changed from-1300 rpm to 1300 rpm).

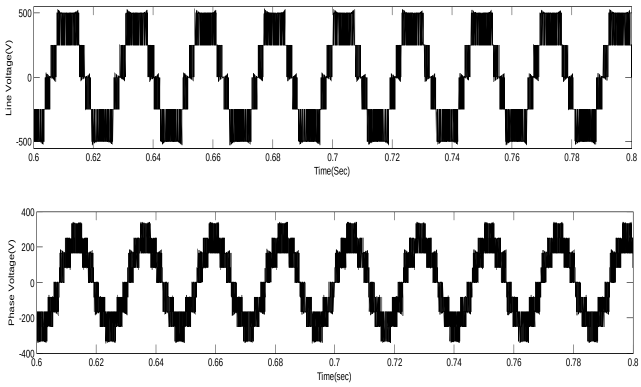

Fig-12: Line and phase voltage for 3-level MSVPWM based inverter

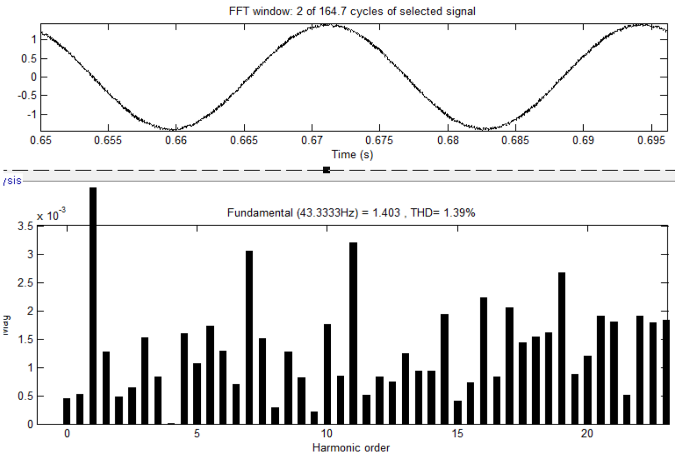

Fig-13: Harmonic Spectrum of stator current along with THD for 3-Level MSVPWM based DTC-IM drive

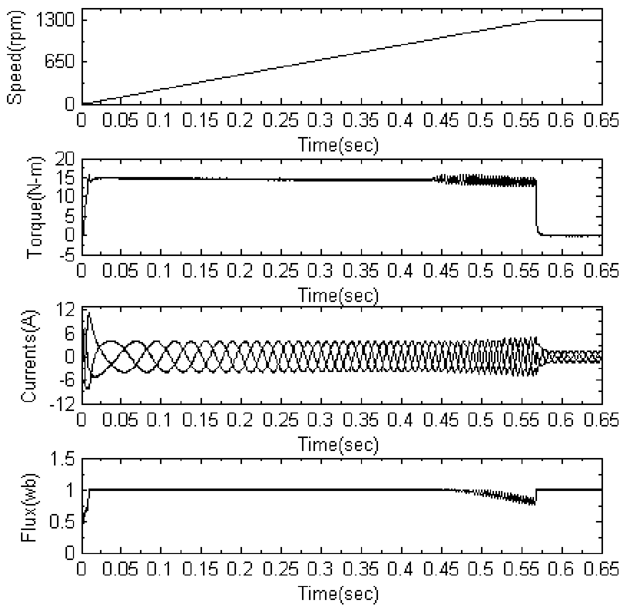

Fig-14: Starting transients for MSVPWM algorithm based 3-level inverter fed DTC-IM.

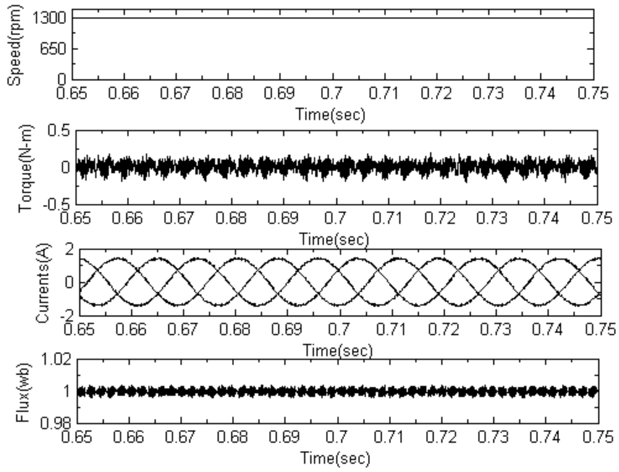

Fig-15: Steadystate plots for 3-level MSVPWM based DTC-IM drive

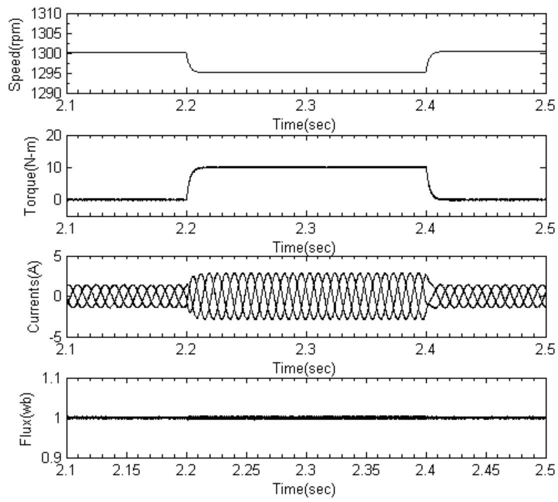

Fig-16: Three-level MSVPWM based DTC-IMD: Transients in speed, torque, stator currents and stator flux during step change in load (10N-m is applied from 2.2sec to2.4sec)

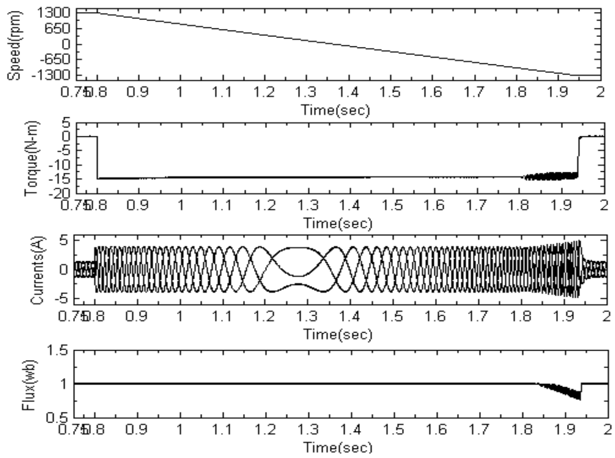

Fig-17: Transients during speed reversal for3-level MSVPWM base DTC-IM drive (Speed changed from1300 rpm to-1300 rpm)

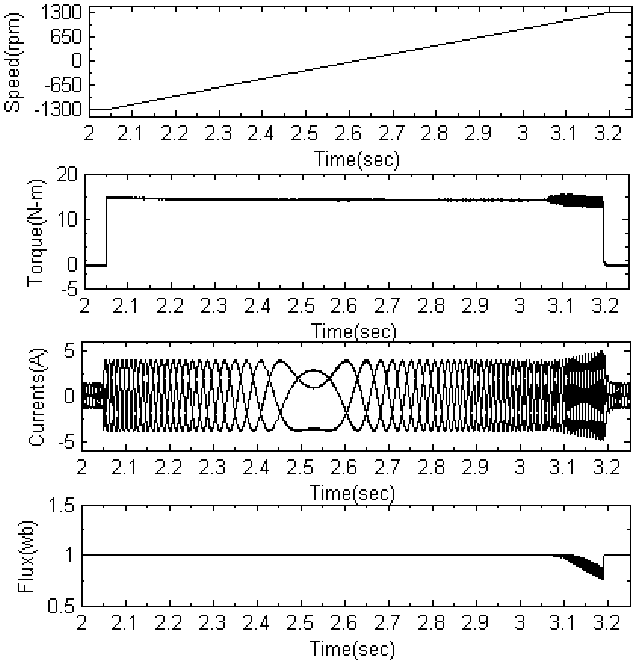

Fig-18: Transients during speed reversal for3-level MSVPWM base DTC-IM drive (Speed changed from-1300 rpm to 1300 rpm)

7. CONCLUSIONS

In this paper, a Modified SVPWM algorithm exists for three-phase three-level inverter fed DTC IM drive. The MSVPWM algorithm generates switching pulses for three-level inverter similar to that of a two-level inverter based SVPWM algorithm. Thus, the MSVPWM algorithm reduces the complexity involved in 3-level SVPWM algorithms. To validate the 2-level SVPWM inverter fed DTC IM drive, 3level MSVPWM inverter fed DTC IM drive, mathematical simulation studies have been carried out and the results are presented. From the simulation results, it can be concluded that the MSVPWM algorithm for three-level inverter fed DTC IM drive gives a good dynamic response, reduced steady state ripples and Total Harmonic Distortion.

Table-8: % REDUCTION IN THD

METHOD	%VTHD	% Reduction in VTHD	%ITHD	% Reduction in ITHD
2-level DTC-IMD	34.17	0	2.15	0
3-level DTC-IMD	19.29	43.54	1.39	35.34

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