A Novel Seven-Level Inverter System for DTC Induction Motor Drive

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Abstract–This paper presents the novel multilevel inverter fed control structure for induction motor based Direct Torque Control (DTC) strategy using a seven-level Multi Point Clamped (MPC) Voltage Source Inverter (VSI) is presented. It is shown that the multilevel topology presents enough degrees of freedom to control both electromagnetic torque and stator flux with very low ripple and high dynamics on other side. Simulation results, obtained with conventional or two-level, three-level inverter, five-level and seven-level inverter fed DTC induction motor (IM) drive, are presented and compared. This analysis shows that feeding electrical drive with multi level inverter can greatly improves the drive performance. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package, MATLAB/SIMULINK.

Keywords–DTC, seven-level MPC VSI, induction motor, MATLAB/SIMLINK.

I. Introduction

Electrical vehicle applications require frequent torque control to adjust the speed of a vehicle. This has resulted in the need for a control scheme with high performance, fast transient, and accurate control of torque for an induction motor drive. The two most popular schemes for this are the vector control and the direct torque control (DTC) [1], [2]. The DTC schemes proposed by [3], and [4] (as a direct self-control) have several variations to the original structure, such as to overcome the inherent disadvantages in any hysteresis-based controller with variable switching frequency, high sampling requirement for digital implementation, and high torque ripple [5]–[11] Recently, predictive control strategy [12]–[14], dithering technique [15], sliding mode control [16], fuzzy logic control [17], and support vector machine (SVM) [10], [18]–[20] have found applications in motor drives. Furthermore, the use of these control schemes during a large step change in torque command does not guarantee the fastest torque response.

Multilevel power conversion technology is a very rapid growing area of power electronics with good potential for further development. The most attractive application of this technology are in the medium to high voltage range (2-13kv), and include induction motor drives, power distribution, power quality and power conditioning applications.

In general multilevel power converters can be viewed as voltage synthesizers, in which the high output voltage is synthesized from many discrete small voltage levels. The main advantages of this approach is ,The voltage capacity of the existing devices can be increased many times without the complications of static and dynamic voltage sharing that occurring series connected device. It is possible to obtain refine voltage wave forms and reduced THD in voltage with increased number of voltage levels. It is possible to reduce the electromagnetic interference problem by reducing the switching dv/dt stress. Multilevel wave forms naturally limit the problems of large voltage transients that occur due to the reflections on cables, which can damage the motor windings and cause other problems.

The diode-clamped multilevel converter employs clamping diodes and series DC capacitors to produce AC Voltage waveforms with multiple levels. The converter can be generally configured as a multilevel topology, but only the three-level converter, also referred as Multi Point Clamped (MPC) converter, has found wide application in medium-voltage high-power applications. The main features of the MPC converter include reduced *dv/dt* and Total Harmonic Distortion (THD) in its AC output voltages in comparison to the conventional two level converters. As in any multilevel converter it can be used in the medium-voltage applications to reach a certain voltage level without series connection of power semiconductors.
In principle, DTC method is based on instantaneous space vector theory. By optimal selection of the space voltage vectors in each sampling period, DTC achieves effective control of the electromagnetic torque and the stator flux on the basis of the errors between theirs references and estimated values. It is possible to directly control the inverter states through a switching table, in order to reduce the torque and flux errors within the desired bands limits[8][9]. The present work is based on the study of the application of DTC to the seven-level MPC VSI.

II. Multi Level Direct Torque Control (MDTC)

Fig.1 shows a simple structure of the Proposed Block diagram of 7-level MPC inverter DTC IM drive. In DTC the reference to be applied is directly calculated from the equation of the load, usually an Induction Motor (IM). In the following, a short description of DTC is presented, just to introduce to its extension to multilevel VSI. Considering Park transform of IM equations, it is possible to write in equation (1), where φ_S is the stator flux, u_s, i_s and r_s are the stator voltage, current and resistance respectively.

$$\frac{d\varphi_S}{dt} = \vec{U}_S - r_S \vec{i}_S \quad (1)$$

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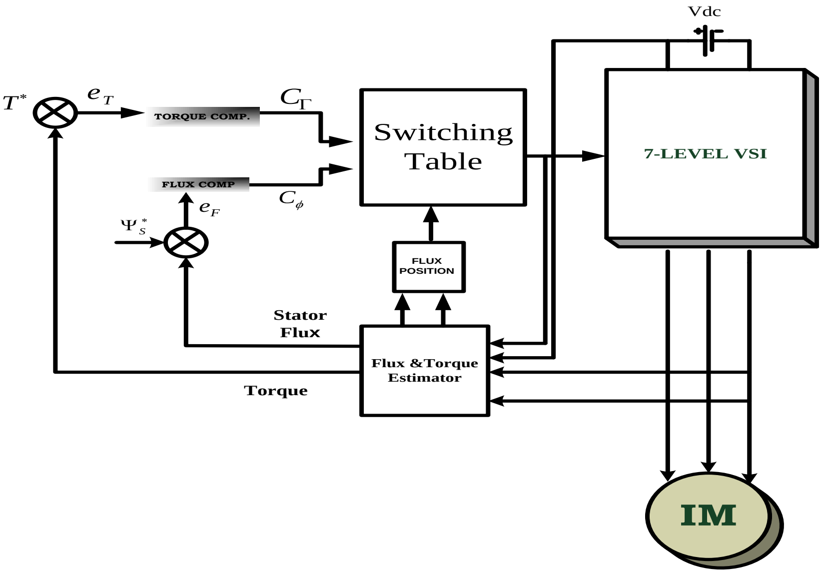


Fig.1: Proposed Block diagram of 7-level MPC inverter DTC IM drive

Ignoring the contribution of the current, which can be considered small in the respect of the stator voltage, the variation of stator flux can be ascribed all to the voltage applied. So, a proportional relationship between flux variation and voltage in a given cycle T_c can be found by discretizing (1).

$$\Delta\vec{\varphi}_S \cong T_c\,\vec{i}_S \tag{2}$$

Analyzing the equation binding the stator and rotor fluxes (φ_S and φ_r) to the torque (T_e), it is possible to find that an augmentation of the angle between fluxes (ϑ_{sr}) means an augmentation of torque, as equation (3) shows, where M, σ, Ls and p are the mutual inductance, the leakage inductance and number of poles respectively.

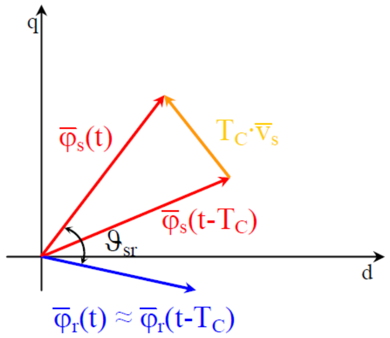


Fig.2: DTC Principles: vector representation of the stator a rotor fluxes during a sample interval T_C.

$$T_e = \frac{3}{2}\frac{p}{2}\frac{M}{\sigma L_S}\varphi_S\varphi_r \sin\nu_{sr} \tag{3}$$

The relationship between stator and rotor fluxes it can be assumed that a fast variation of the stator flux angular speed will reflect in an increment of the angle V_{sr} as Fig.2. Schematically shows. So, imposing a particular stator voltage, it is possible to control either the stator flux amplitude or the torque. The vector $\Delta\vec{\varphi}_S \cong T_C\,\vec{U}_S$ can be decomposed in the component parallel and perpendicular

to the stator flux; the parallel component modifies the stator flux amplitude while the perpendicular component controls the torque.

III. Seven-Level MPC VSI and Related Output Voltage Vectors

A seven-level MPC converter topology typically consists of six capacitors on the DC bus and seven levels of the phase voltage. Fig.3 shows a seven–level MPC inverter topology in which the dc bus consists of six capacitors C_1, C_2, C_3, C_4, C_5 and C_6. For a dc bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/6$, and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/6$, through clamping diodes. Each phase consists of eight switches, each one with its freewheeling diode in series and two other in parallel and two clamping diodes that allow the connection of the phases outputs to the middle point *o*. Table 1 illustrates the switching states of this inverter for one phase.

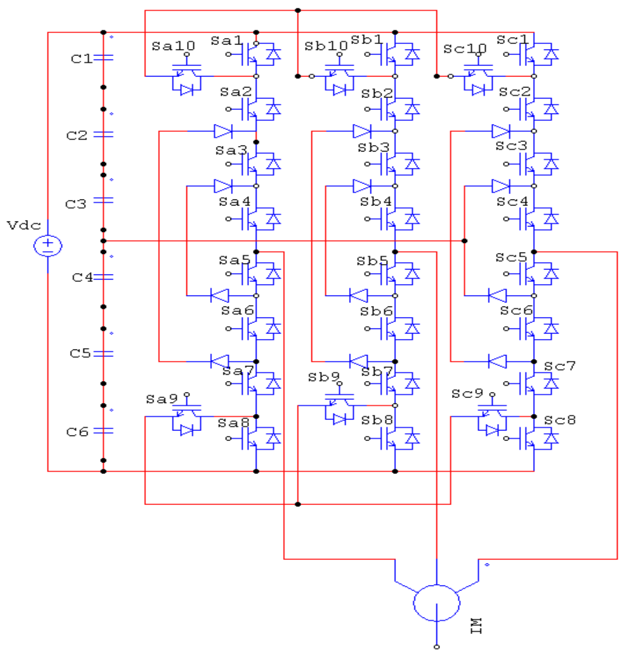


Fig.3: Seven-level MPC VSI topology

As shown in Fig.4, the number of discrete voltage vectors has increased if compared with a three-phase three-level inverter. Keeping in mind the simplicity of DTC, the same principle, as explained in [10],[11],[12] can be applied when a three-phase multilevel inverter feeds the induction machine. Having voltage vectors with different magnitudes means that different speeds of the stator-flux-linkage vector can be obtained.

Therefore, by changing the speed of the stator flux vector, the rate of change of the produced electromagnetic torque can be changed. This extra flexibility in selecting an optimal space voltage means that a more precise control of both torque and flux can be obtained. As in the three-level DTC strategy [8], [9], the α -β plane will be divided into several sectors. In a multilevel inverter the number of available discrete voltage vectors is more important than those obtained with a two or three-level inverter. Thus, the α -β plane will be divided into 12 sectors rather than six.

Table 2: Seven-level inverter output magnitudes of space voltages vectors

Group	Magnitude of Voltage Vectors
1	[V_o]
2	[V_1, V_2, V_3, V_4, V_5, V_6]
3	[V_{44}, V_{45}, V_{46}, V_{47}, V_{48}, V_{49}]
4	[V_{63}, V_{64}, V_{65}, V_{66}, V_{67}, V_{68}]
5	[V_{75}, V_{77}, V_{79}, V_{81}, V_{83}, V_{85}]
6	[V_{100}, V_{101}, V_{102}, V_{103}, V_{104}, V_{105}, V_{106}, V_{108}, V_{110}, V_{112}, V_{113}, V_{114}, V_{115}, V_{116}, V_{117}, V_{118}, V_{125}]
7	[V_{205}, V_{206}, V_{207}, V_{208}, V_{209}, V_{210}]
8	[V_{218}, V_{219}, V_{220}, V_{221}, V_{222}, V_{223}, V_{224}, V_{225}, V_{226}, V_{228}, V_{230}, V_{232}, V_{234}, V_{236}, V_{237}]
9	[V_{296}, V_{297}, V_{298}, V_{299}, V_{300}, V_{301}, V_{302}, V_{303}, V_{304}, V_{305}, V_{306}, V_{308}, V_{310}, V_{312}, V_{314}, V_{316}]

A seven-level inverter has 343 switching states and there are 78 effective vectors. According to the magnitude of the voltage vectors, we divide them into nine groups as shown in table2.

The flux control is made by classical two-level hysteresis controller, so a high level performance torque control is required, and the torque is controlled by a hysteresis controller built with six lower bounds and six upper known

The closed-form mathematical model of the CSI-fed induction motor drive system has been considered the bounds. A combination of the controller's outputs and the sector is then applied to a new optimal switching table

Table 3 which will give the appropriate voltage vector to reduce the number of commutation and the level of steady state ripple.

IV. SIMULATION AND RESULTS

Simulation studies have been carried out for the proposed inverter scheme in DTC control with qualitative space vector pulse width modulation algorithm using SIMULINK software in MATLAB environment. The induction motor parameters are as follows: Rs=4.85Ω, Rr=3.805Ω, Ls=274mH, Lr=274mH, Lm=258mH, p=2, J=31g.m2, V=220V, power=1.5kW and speed=1420rpm. All simulations have a sample time for the control loop of 100μs; the voltage of the DC bus is 514V. To show the effectiveness of the DTC with seven-level inverter with SVPWM switching technique a simulation work has been carried out on induction motor.

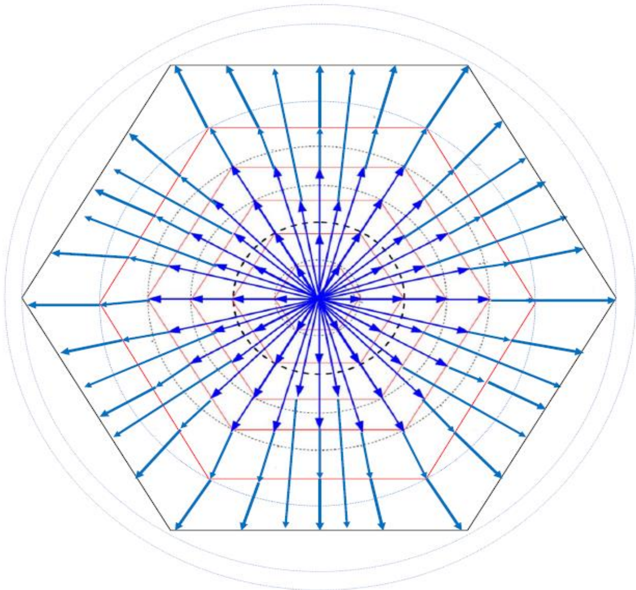
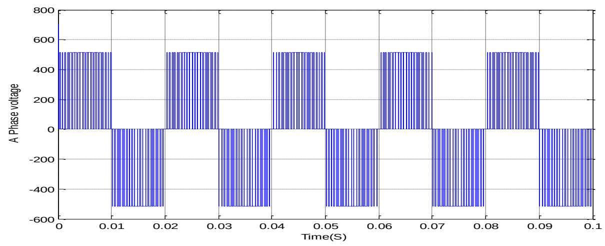


Fig.4: Space voltage vectors used in a seven-level inverter fed DTC scheme



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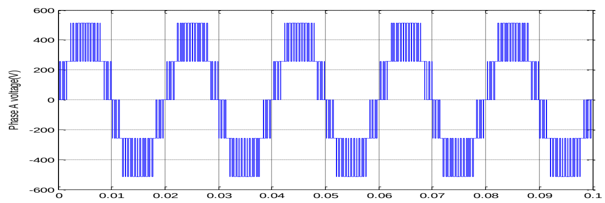

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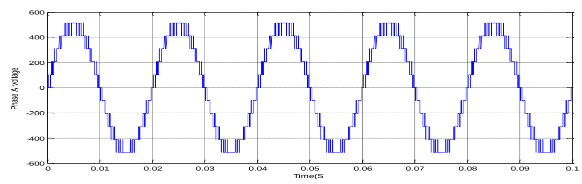

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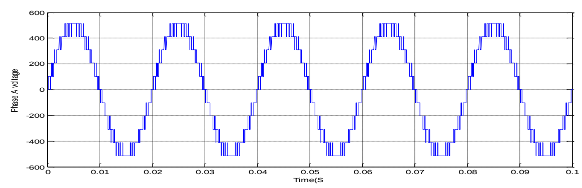

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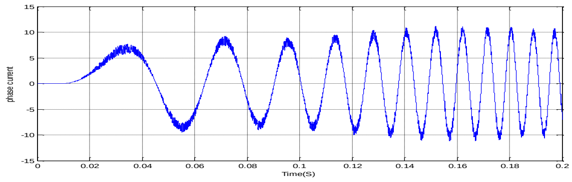
Fig.5 (a-d): Line voltage of 2, 3, 5 and 7-level inverter



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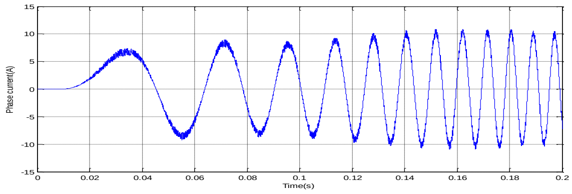

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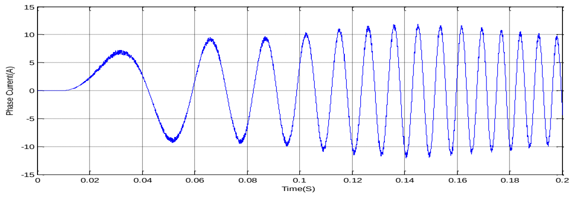

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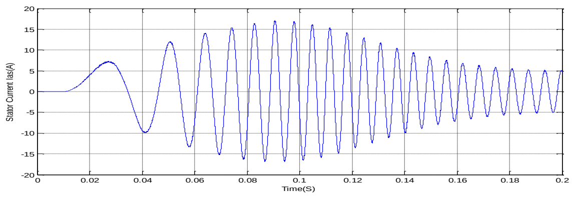

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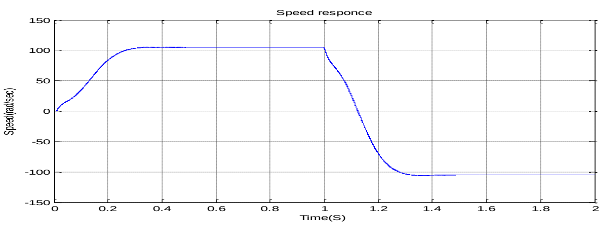
Fig.6 (a-d): Stator Phase Currents of Two-level, Three-level, Five-level and seven-level inverter fed DTC IM drive



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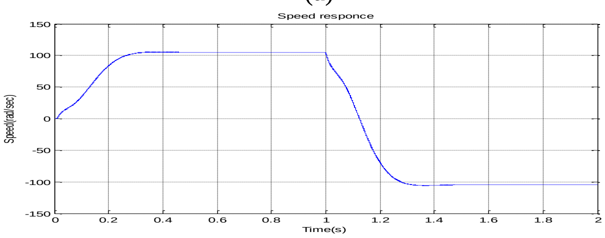

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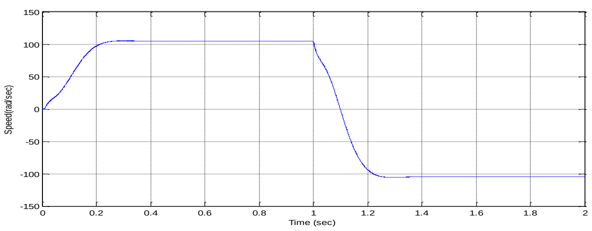

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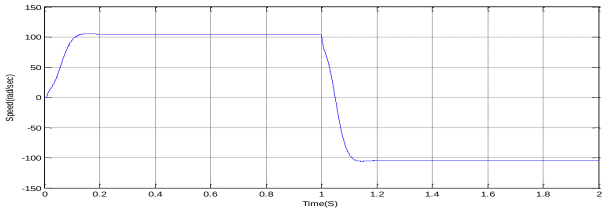

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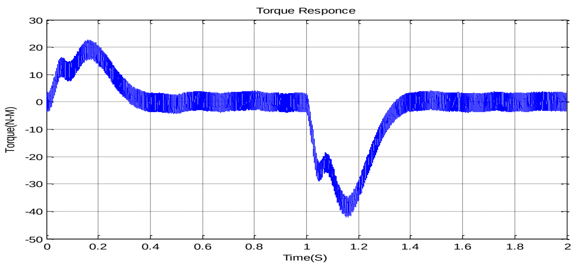
Fig.7 (a-d): Speed response of Two-level, Three-level, Five-level and Seven-level inverter fed DTC IM drive, current reversal at 1sec



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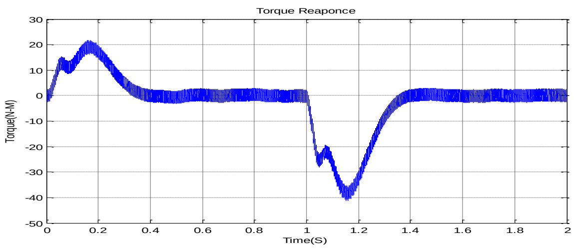

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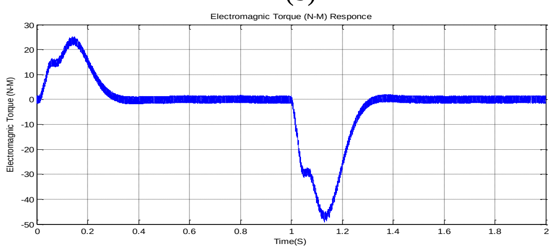

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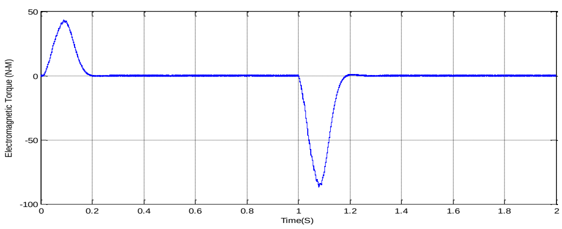

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Fig.8 (a-d): Torque response of Two-level, Three-level, Five-level and Seven-level inverter fed DTC IM drive, current reversal at 1sec

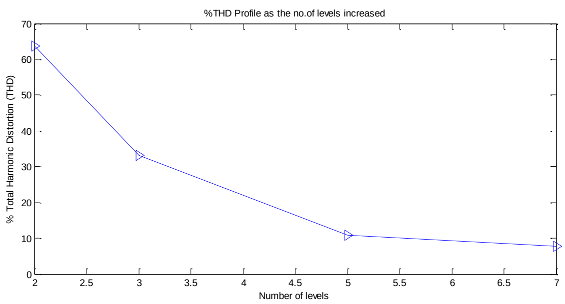

Fig.9: %THD profile as the number of levels increase

Table 1: Seven-level MPC leg relationships between configurations and output voltages

Switches state										Output Voltage (V_{AO})
S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_{a5}	S_{a6}	S_{a7}	S_{a8}	S_{a9}	S_{a10}	
ON	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	$-3U_0$
OFF	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	$-2U_0$
OFF	OFF	ON	ON	OFF	OFF	OFF	ON	OFF	OFF	$-U_0$
OFF	OFF	OFF	OFF	ON	ON	OFF	OFF	ON	ON	0
OFF	OFF	ON	OFF	OFF	OFF	OFF	ON	OFF	OFF	0
OFF	OFF	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	U_0
OFF	OFF	ON	ON	ON	ON	OFF	OFF	OFF	OFF	$2U_0$
OFF	OFF	OFF	OFF	ON	ON	ON	OFF	OFF	OFF	$3U_0$

Table 3: Proposed switching table for 7-Level MPC Inverter fed DTC IM drive

		Sectors											
C_ϕ	C_Γ	1	2	3	4	5	6	7	8	9	10	11	12
-1	-6	304	314	305	316	300	306	301	308	302	310	303	312
	-5	224	234	225	236	220	226	221	228	222	230	223	232
	-4	104	114	105	116	100	106	101	108	102	110	103	112
	-3	67	83	68	85	63	75	64	77	65	79	66	81
	-2	117	209	118	210	113	205	114	206	125	207	116	208
	-1	5	48	6	49	1	44	2	45	3	46	4	47
	0	Zero Vector											
	+1	3	46	4	47	5	48	6	49	1	44	2	45
	+2	115	207	116	208	117	209	118	210	113	205	114	206
	+3	65	79	66	81	67	83	68	85	63	75	64	77
	+4	102	110	103	112	104	114	105	116	100	106	101	108
	+5	220	228	221	230	222	232	223	234	218	224	219	226
	+6	298	306	299	308	300	310	301	312	296	302	297	304
+1	-6	300	306	301	308	302	310	303	312	304	314	305	316
	-5	226	221	228	222	230	223	232	224	234	225	236	220
	-4	101	108	102	110	103	112	104	114	105	116	100	106
	-3	77	65	79	66	81	67	83	68	85	63	75	64
	-2	207	116	208	117	209	118	210	113	205	114	206	115
	-1	48	6	49	1	44	2	45	3	46	4	47	5
	0	Zero Vector											
	+1	45	3	46	4	47	5	48	6	49	1	44	2
	+2	208	117	209	118	210	113	205	114	206	115	207	116
	+3	67	84	68	86	63	76	64	78	65	80	66	82
	+4	115	105	117	100	107	101	109	102	111	103	113	104
	+5	223	235	218	225	219	227	220	229	221	231	222	233
	+6	313	296	303	297	305	298	307	299	309	300	311	301
0	-6	305	316	300	306	301	308	302	310	303	312	304	314
	-5	225	236	220	226	221	228	222	230	223	232	224	234
	-4	105	116	100	106	101	108	102	110	103	112	104	114
	-3	68	85	63	75	64	77	65	79	66	81	67	83
	-2	210	113	205	114	206	115	207	116	208	117	209	118
	-1	49	1	44	2	45	3	46	4	47	5	48	6
	0	Zero Vector											
	+1	44	2	45	3	46	4	47	5	48	6	49	1
	+2	205	114	206	115	207	116	208	117	209	118	210	113
	+3	76	64	78	65	80	66	82	67	84	68	86	63
	+4	107	101	109	102	111	103	113	104	115	105	117	100
	+5	225	219	227	220	229	221	231	222	233	223	235	218
	+6	303	297	305	298	307	299	309	300	311	301	313	296

The stator line voltages of 2, 3, 5 and 7-level inverter system are illustrated in fig.5.In fig.6 stator current response of the 2, 3, 5 and 7-level inverters are compared. It is seen that the performance of the 7-level inverter fed DTC IM drive has lower ripple, so the proposed system is superior to control the flux with reduced ripple content. Fig.7 illustrate the speed response of 2,35 and 7-level inverter fed DTC IM drive, from simulation results proposed system has fast dynamic speed response.Fig.8 torque response of two-level, three-level, five-level and seven-level inverter fed DTC IM drive, current reversal at 1sec; demonstrates the developed DTC's achieved high dynamic performance in response to the changes in demand torque.Fig.9 shows the decrease of percentage of total harmonic distortion (%THD) in the motor line voltage as the number of levels increased (Table 4). This result in the smooth running of motor and thus the performance of the motor can be improved.

From the above discussion, the proposed DTC IM drive system behavior is optimum, even in extreme conditions like the reverse speed reference with nominal load torque applied. Reduction in ripple is observed in both electromagnetic torque and flux due to the use of hysteresis controllers.

Table 4: %THD profile as the number of level increased

Inverter	%THD
2-Level	63.78
3-Level	33.21
5-Level	10.86
7-Level	7.77

V. Conclusions

A multilevel inverter based DTC fed induction motor drive using space vector modulation is presented. The proposed DTC IM drive scheme is capable for enough degrees of freedom to control both electromagnetic torque and stator flux with very low ripple. Even with at the output voltages with extremely low distortion and lower *dv/dt*. They can operate with a lower switching frequency. As the number of levels increased the %THD in the motor line voltage decreased. As the number of levels increased the torque ripple is reduced to minimum and the stator flux ripple is also minimized. From this analysis high dynamic performance, good stability and precision are achieved.

A Seven-level inverter scheme for DTC induction motor drive is presented. The salient features of this scheme are, Results presented for a 2-level, 3-level and 5-level and 7-level inverter shows that an increase in the number of levels improves the torque quality reducing ripple amplitude. This enhancement results in a narrow torque spectrum even for high frequency harmonics. The proposed DTC IM drive system behavior is optimum, even in extreme conditions like the reverse speed reference with nominal load torque applied. From the simulation results, it can be concluded that the seven-level inverter fed DTC drive gives reduced steady state ripples and a harmonic distortion as the number of levels increased.

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