Direct Torque Control of Symmetrical Six-Phase Induction Machine using Nine Switch Inverter

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***Abstract*— This paper presents the direct torque control (DTC) scheme for symmetrical six-phase induction machine by using Nine Switch Inverter (NSI). When this motor is controlled by conventional two level inverter, it provides 64 voltage vectors with switch count of 12. The proposed inverter is nine-switch two level having capability to produce 27 voltage vectors. The DTC control is implemented with these available voltage vectors by this inverter and flux of xy subspace is eliminated for the performance improvement. The torque ripple reduction is achieved by using five-level torque comparator. The performance is presented through simulation results and confirmed through hardware implementation.**

Keywords*— *direct torque control; symmetrical six-phase induction machine; nine switch inverter; xy flux elimination; three level torque comparator; five level torque comparator

I. Introduction

With increase in demand of Electric Vehicles (EVs) in the global market, also motivated the researchers so that EV fit in the requirements of the buyers. Therefore emphasis is given on the building of EV with the potential of higher efficiency, low torque pulsation, improved fault tolerance and less number of semiconductor switches. Performance of EV can be upgrade by the improvement in propulsion machines, inverter topologies and in control algorithms.

Multiphase machines provides the promising solutions for the torque pulsations and efficiency. In [1], it is shown that why multiphase machines have low torque pulsations and higher efficiency. Multiphase machines also have higher power density and fault tolerance property [2].These improvements are related to propulsion side, similarly inverter topologies [3] and control algorithms [4][5] also provides the better options. But the reduction in semiconductor switches are possible by only installing the reduced switch inverter in the EV. Minimum requirement for controlling of induction machines (IM) is the conventional two level inverter. As the number of phases increases in machines, number of switches also increases by the multiple of 2. Six-phase IM requires 12 switches in the inverter (2 switches for each phase). There are two types of six-phase induction machines and these are symmetrical and asymmetrical IM. In symmetrical IM two types are possible depending on the angle between two three phase windings of the stator (0 degree and 60 degree). In [6], it is presented that both machines have same performance. This paper provides a way to implement the DTC on the 0 degree symmetrical six-phase IM by using Nine Switch Inverter (NSI). Saving of three switches are possible therefore losses, size and weight of the inverter reduces. Thereby saving of space and cost is also possible in the EVs. Basic pulse width modulation technique for six-phase IM with NSI is presented in [7]. Field oriented control with NSI for six-phase IM under fault is explained in [8]. Space vector modulation technique for nine switch converter is described for controlling two independent loads in [9]. In this paper, DTC is implemented with NSI by using three level and five level torque comparator and it is described that with the available voltage vectors, elimination of xy subspace flux is possible.

This paper is organized as follows. Section II describes the machine model and formation of voltage vector for both conventional two level inverter and NSI. In section III, vector table for three and five-level torque comparator is developed. Simulation and hardware results are explained in section IV which validates the theoretical concepts and conclusion in section V.

II. Machine Model and Inverter Voltage Vectors

The modeling of 0 degree six-phase IM is developed in stator reference frame. The vector space decomposition theory is used to developed transformation matrix as shown in (1). Voltage equations for stator and rotor circuit are given in (2)-(13). Flux equations for motor modeling are given in (14)-(17). Electromagnetic torque developed by the motor is given in (18).

$$T = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1/2 & -1/2 & 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & -1/2 & -1/2 & -1 & 1/2 & 1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \quad (1)$$

$$V_{ds} = R_s i_{ds} + p\varphi_{ds} \quad (2)$$

$$V_{qs} = R_s i_{qs} + p\varphi_{qs} \quad (3)$$

$$V_{xs} = R_s i_{xs} + L_{ls} p i_{xs} \quad (4)$$

$$V_{ys} = R_s i_{ys} + L_{ls} p i_{ys} \quad (5)$$

$$V_{01s} = R_s i_{01s} + L_{ls} p i_{01s} \quad (6)$$

$$V_{02s} = R_s i_{02s} + L_{ls} p i_{02s} \quad (7)$$

$$V_{dr} = 0 = R_r i_{dr} + p\varphi_{dr} + \omega_r \varphi_{qr} \quad (8)$$

$$V_{qr} = 0 = R_s i_{qs} + p\varphi_{qs} - \omega_r \varphi_{dr} \quad (9)$$

$$V_{xr} = R_r i_{xr} + L_{lr} p i_{xr} \quad (10)$$

$$V_{yr} = R_r i_{yr} + L_{lr} p i_{yr} \quad (11)$$

$$V_{01r} = R_r i_{01r} + L_{lr} p i_{01r} \quad (12)$$

$$V_{02r} = R_r i_{02r} + L_{lr} p i_{02r} \quad (13)$$

$$\varphi_{ds} = (L_{ls} + 3L_{ms}) i_{ds} + 3L_{ms} i_{dr} \quad (14)$$

$$\varphi_{qs} = (L_{ls} + 3L_{ms}) i_{qs} + 3L_{ms} i_{qr} \quad (15)$$

$$\varphi_{dr} = (L_{lr} + 3L_{ms}) i_{dr} + 3L_{ms} i_{ds} \quad (16)$$

$$\varphi_{qr} = (L_{lr} + 3L_{ms}) i_{qr} + 3L_{ms} i_{qs} \quad (17)$$

$$T_e = 3P\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \quad (18)$$

This matrix is also used to map the voltage vectors of the symmetrical six-phase induction machine (displacement between two stator three phase winding is 0 degree) in dq and xy subspace. Voltage vectors (VVs) for conventional two level inverter are formed by the binary combination of the switches of each leg.

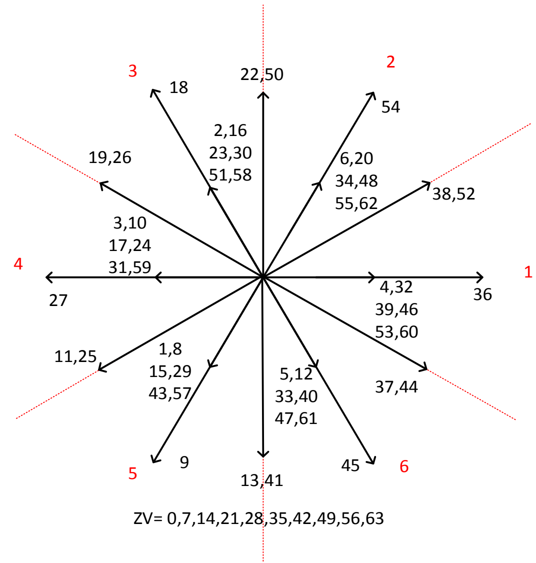
$$VV=[T][\, S_a \; S_b \; S_c \; S_{a'} \; S_{b'} \; S_{c'}] \quad (19)$$

S_x function can attain two values 1 or 0 for two level inverter in (19). When (1) is multiplied with (19), total 64 voltage vectors are developed and they are mapped in dq and xy subspace as shown in Fig.1. These vectors are classified in four groups namely large, medium, small and zero voltage vectors having 6, 12, 36 and 10 voltage vectors respectively. Now the same motor is fed from NSI as shown in Fig.2. In this reduced switch topology, all 64 voltage vectors are not available. Switch status for different switching state are shown in table I for the NSI. From the available vectors, only 27 voltage vectors are possible which satisfied the conditions of table I. These vectors are divided such that there are 6 large, 6 medium, 12 small and 3 zero voltage vectors and these are mapped in dq and xy subspace as shown in Fig. 3.

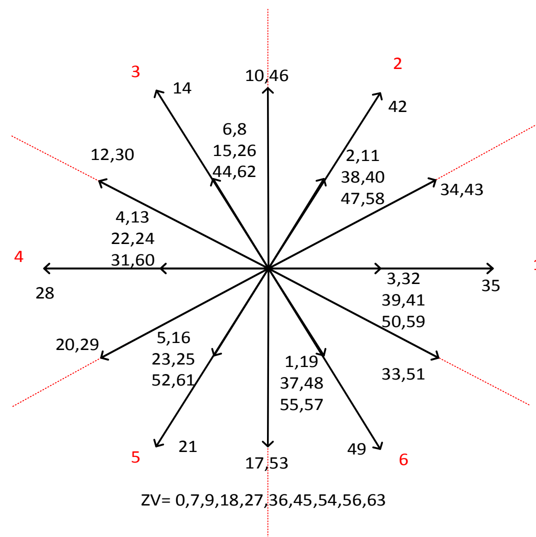
Table I: Switches ON-OFF position of legs

	Switch Status		
Switching State →	1	0	-1
Upper switch (S1,S2,S3)	ON	OFF	ON
Middle switch (S4,S5,S6)	OFF	ON	ON
Lower switch (S7,S8,S9)	ON	ON	OFF

Large voltage vector is obtained when both three phase winding of six-phase machine having same voltage vectors. Small voltage vectors are developed by the combination of active voltage vectors and zero voltage vectors. There are two options for generating small voltage vectors. If first three phase winding is supplied with active voltage vector then other winding is having zero voltage vector and vice versa. Therefore each small voltage vector is obtained by two switching states. Medium voltage vector is the combination of two different



(a)



(b)

Fig.1. Voltage vectors for conventional two level inverter (a) dq subspace and (b) xy subspace

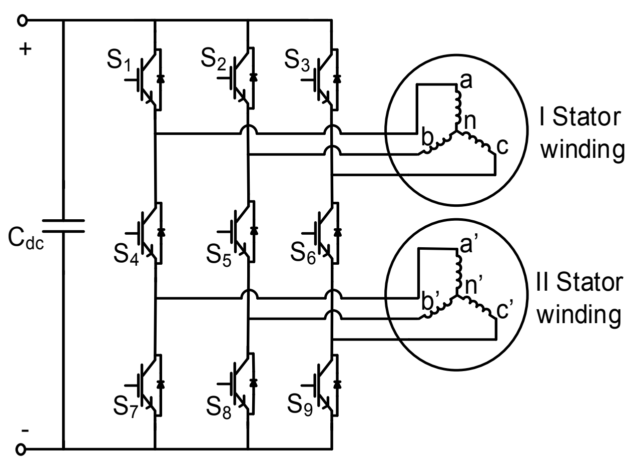


Fig.2. NSI for symmetrical six-phase IM

active voltage vectors. Analytically 6 active voltage vector are available for one three phase winding so that for two three phase winding displaced with zero degree having total 36 combinations but all of them are not valid for nine switch inverter. Therefore both active vectors are selected in such a way that operation of nine switch inverter is not interrupted. All possible voltage vector in NSI for 0 degree symmetrical six-phase IM are listed in table II.

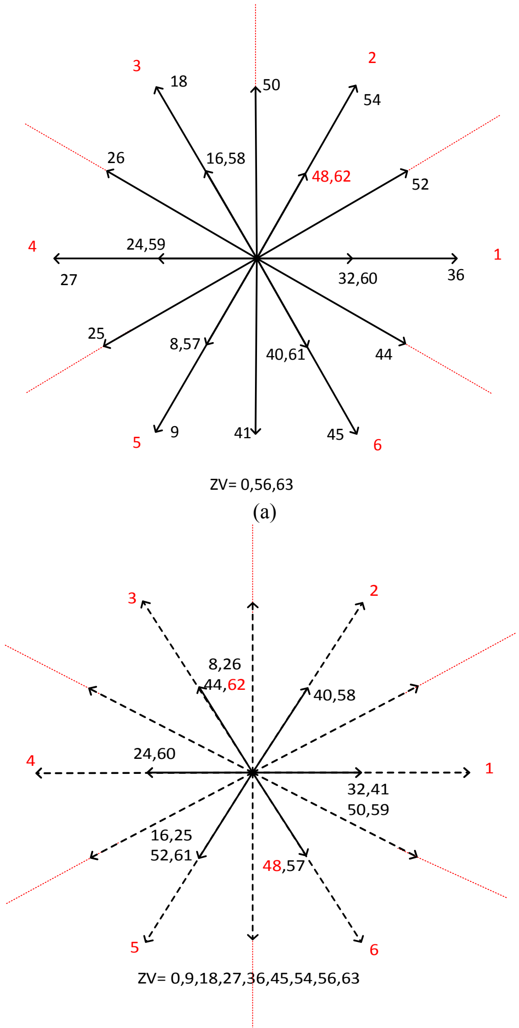


Fig.3. Voltage vectors for NSI (a) dq subspace and (b) xy subspace

Table II: Voltage vectors in NSI

Vector number	Switching State Leg A	Switching State Leg B	Switching State Leg C	Equivalent conventional vector for winding: First	Equivalent conventional vector for winding: Second	Vector Category
36	-1	0	0	V1	V1	LV
54	-1	-1	0	V2	V2	
18	0	-1	0	V3	V3	
27	0	-1	-1	V4	V4	
9	0	0	-1	V5	V5	
45	-1	0	-1	V6	V6	
52	-1	1	0	V2	V1	MV
50	1	-1	0	V2	V3	
26	0	-1	1	V4	V3	
25	0	1	-1	V4	V5	
41	1	0	-1	V6	V5	
44	-1	0	1	V6	V1	
32	1	0	0	V1	V0	SV
60	-1	1	1	V7	V1	
48	1	1	0	V2	V0	
62	-1	-1	1	V7	V2	
16	0	1	0	V3	V0	
58	1	-1	1	V7	V3	
24	0	1	1	V4	V0	
59	1	-1	-1	V7	V4	
8	0	0	1	V5	V0	
57	1	1	-1	V7	V5	
40	1	0	1	V6	V0	
61	-1	1	-1	V7	V6	
0	0	0	0	V0	V0	ZV
63	-1	-1	-1	V7	V7	
56	1	1	1	V7	V0	

LV-Large Vector, MV-Medium Vector, SV-Small Vector, ZV-Zero Vector

III. DTC OF SIX-PHASE IM USING NSI

Fig. 4 shows the basic block diagram of the DTC algorithm. In the three level torque comparator, depending on the output of sector identification (S), flux comparator (F) and torque comparator (T) blocks suitable voltage vector is selected from the table III where '+1' signifies an increase in flux and torque, '-1' signifies an decrease in flux and torque. When the output of the torque comparator T is 0 then zero voltage vector is selected which means no change is required. Sector identification gives the position

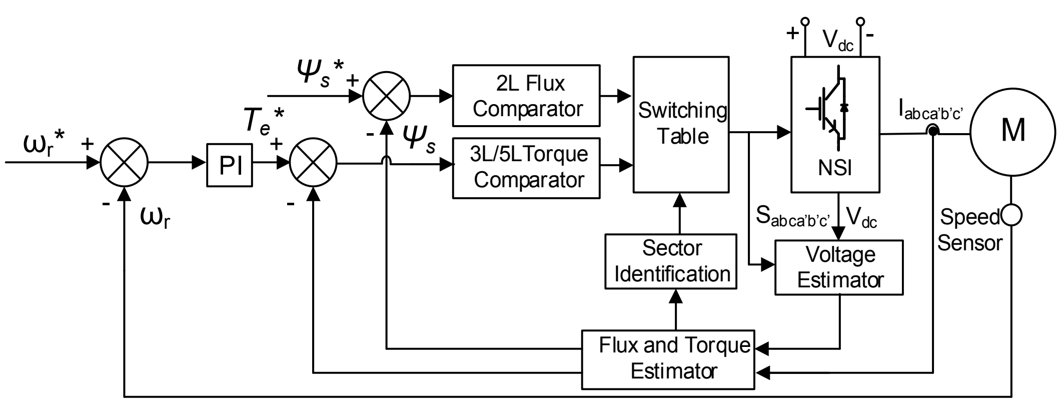


Fig. 4. DTC block diagram (L-Level)

of stator flux in dq subspace in form of sector. The dq and xy subspace is divided in six sectors. It is observed form the Fig. 3 that all large vectors of dq plane are projected as zero vector in xy plane. Therefore, when vectors of three-level torque comparator are applied, flux in xy subspace is not excited. So that elimination of xy flux is not required for the implementation of three-level torque comparator in NSI for 0 degree six-phase IM.

Table III: Three-level torque comparator

S		1	2	3	4	5	6
F	T						
+1	+1	54	18	27	9	45	36
	0	63	0	63	0	63	0
	-1	45	36	54	18	27	9
-1	+1	18	27	9	45	36	54
	0	0	63	0	63	0	63
	-1	9	45	36	54	18	27

S-Sector, F-Flux, T-Torque

Table IV: Five-level torque comparator

S		1	2	3	4	5	6
F	T						
+1	+2	54	18	27	9	45	36
	+1	48,62	16,58	24,59	8,57	40,61	32,60
	0	0	63	0	63	0	63
	-1	40,61	32,60	48,62	16,58	24,59	8,57
	-2	45	36	54	18	27	9
-1	+2	18	27	9	45	36	54
	+1	16,58	24,59	8,57	40,61	32,60	48,62
	0	63	0	63	0	63	0
	-1	8,57	40,61	32,60	48,62	16,58	24,59
	-2	9	45	36	54	18	27

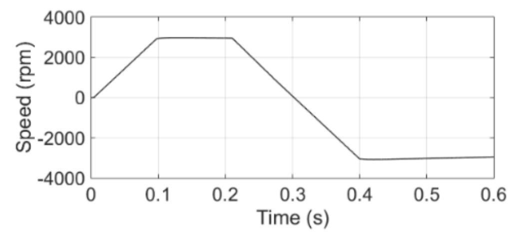
S-Sector, F-Flux, T-Torque

More number of voltage vectors are available for the five-level torque comparator. Large and small voltage vectors are selected from the dq plane for implementing five level comparator. Large and small voltage vectors of dq plane are plotted as zero and small voltage vector respectively in xy plane as shown in Fig.3. Flux in xy plane is induced when the small voltage vector is selected from the switching table IV. Therefore selection of the voltage vector is in such way so that the performance of motor is not affected and xy flux is also eliminated. This selection is explained with the help of an example. Let us assume that output of torque comparator, flux comparator and sector identification block is given by T=+1, F=+1 and S=1 respectively. Then from the table IV, two small voltage vectors (48 and 62) are selected. In dq plane both vectors are of same magnitude and angle therefore they have same effect on the flux and torque. But the firing of these small vectors are based on the position of stator flux in xy plane also. Therefore monitoring of stator flux in xy plane is also required. If the position of stator flux in xy plane is in between sector 2 and 4 then 48^th^ voltage vector is selected. For the sectors from 5 to 1, 62^th^ voltage vector is selected. 48^th^ and 62^th^ voltage vectors are opposite to each other in xy plane. Therefore the combination of these vectors will eliminates the xy flux and performance of machine is maintained [10].

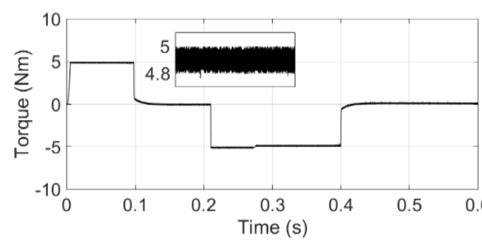
IV. RESULTS AND DISCUSSIONS

A. Three-level torque comparator

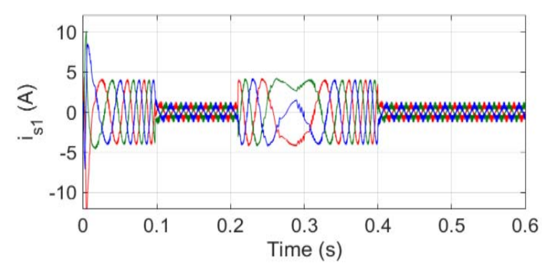
Operation of six-phase IM is evaluated by doing the speed reversal in no load condition by MATLAB platform. Fig. 5 shows the results where speed reference is changed from 3000 rpm to -3000 rpm at no load. During this operation torque ripples are 0.2Nm as shown in Fig. 5(b). Stator current for first and second three phase windings are shown in Fig. 5(c) and 5(d), both winding having an angle of zero degree therefore i_{s1} and i_{s2} are in phase. Stator flux is plotted in Fig. 5(e). Projection of large and zero voltage vectors of dq subspace in xy subspace is zero therefore flux in xy plane is not observed.



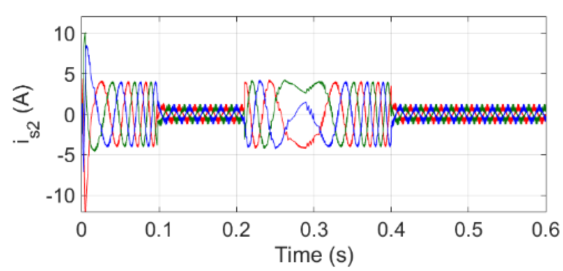
(a)



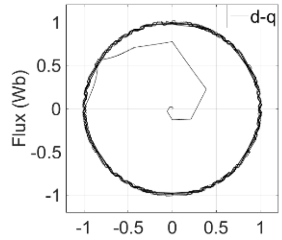
(b)



(c)



(d)

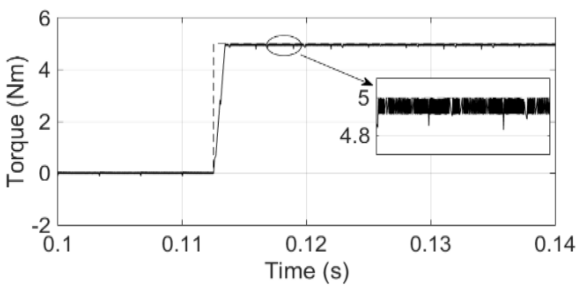


(e)

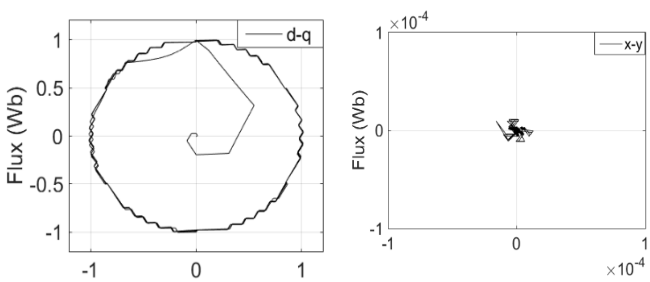
Fig. 5. For three-level torque comparator (a) speed of motor, (b) torque dynamics, (c) first stator winding current, (d) second stator winding current and (e) flux of dq plane.

B. Five-level torque comparator

Vector table of five-level torque comparator is tested with machine when load of 5Nm is applied. With the applied load torque ripples are observed as shown in Fig. 6(a). Because of the use of five-level torque comparator, torque ripples are reduced to 0.09Nm from 0.2Nm (in three-level torque comparator). Flux of dq plane is shown in Fig. 6(b) and xy flux is almost eliminated with the help of combination of two small voltage vectors as shown in Fig. 6(c).



(a)

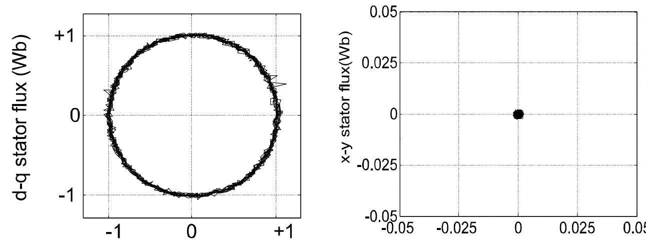


(b) (c)

Fig. 6. For five-level torque comparator (a) torque dynamics, (b) flux of dq plane and (c) flux of xy plane.

In order to verify the simulation results, five-level torque comparator is implemented on hardware and stator flux in both subspaces are observed. It is found that with the proper selection of the voltage vectors, xy flux is eliminated as shown in Fig. 7.

Simulation results are obtained with the following parameters: V_{dc}=450V, R_s=3.6Ω, R_r=6.37Ω, L_{ls}=12.5mH, L_{lr}=14mH, L_m=190mH, P=2, Nominal flux=0.996Wb, Nominal torque=5Nm.



(a) Stator flux in dq subspace (b) Stator flux in xy subspace

Fig. 7. Experimental result for five level torque comparator

V. Conclusion

Multiphase machines have air gap flux with reduced space harmonics so that efficiency will increase. These machines are less influenced by time harmonics therefore torque pulsations are reduced. In this paper, symmetrical six-phase IM drive with NSI using DTC is presented. It is found that the available 27 voltage vectors of NSI are sufficient to operate and eliminate the xy flux of motor with three-level and five-level torque comparator. When multiphase machines are operated with DTC algorithm of five-level torque comparator, torque ripples are further reduced. NSI has less number of switches therefore losses of the inverter is reduced which means that drive will become more efficient. And on the other side space, cost and weight of the EV is also reduces. Therefore it can be concluded that NSI provide the suitable alternative over the conventional two level inverter for the symmetrical six-phase IM drive using DTC algorithm. Extensive simulation and experimental results are provided for the viability of the proposed work.

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