

Direct Torque Control of Asymmetrical Multiphase (6-Phase) Induction Motor Using Modified Space Vector Modulation



Vishal Rathore and K. B. Yadav

1 Introduction

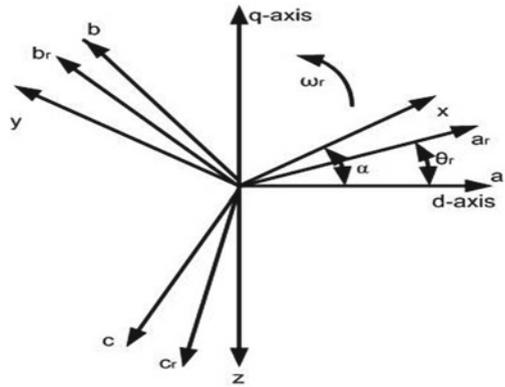
The machine with high phase order, greater than three, increases the rating and power handling capability of a drives system. The drives with more number of phases in the stator of the machine are called multiphase drives. These multiphase drives possess various potential benefits over its three-phase counterparts, such as increase in frequency of torque pulsation by reducing the amplitude of pulsating torque, lowering per phase current without increase in voltage per phase, reduces the rotor and D.C link current harmonics, posses high fault tolerant capability. As an effect of which if a fault occurs in one or more phases the machine will continue to run without any interruption [1]. The Six-Phase Induction Machine (SPIM) is more commonly used multiphase machine and is also known as the dual star induction machine. Such type of machine is used where high power is required, as in case of aircraft applications, electric/hybrid vehicles, naval system, mine hoist, cement mills, rolling mills [2].

In the mid of 1980 I. Takahashi first proposed the direct torque control (DTC) of induction machine [3], this control strategy is highly efficient and more commonly used for AC machine drives system to provide quick flux and torque control. The DTC control strategy proposed here is based on the principle of rectifying error between the estimated values and the required values of corresponding torque and flux, the different states of two-level VSI are directly controlled to reduce the errors of flux and torque in between the band limits [4, 5].

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Fig. 1 Generalized phasor representation of a multiphase machine



The work presented in this paper is discussed in five sections. The second section presents phase arrangement of A6PIM. Whereas the DTC based control strategy is implemented in section three. The results of simulation are discussed in section four. Finally, the summary of the work is made in conclusion.

2 A6PIM Phasor

The model implemented for the analysis, consists of two sets of six phases winding on the stator with a phase shift of 120° and displaced by an angle α . The rotor winding of 6-phase motor is same as that of its three-phase counterparts [6, 7]. The motor under consideration has no friction and windage losses and is also free from magnetic saturation of the core. The stator winding of a six-phase motor has two sets of winding, namely, 'abc and xyz', and their axes are phase displaced by $\alpha = 30^\circ$ [8, 9]. The rotor windings a_r, b_r, c_r as shown in Fig. 1 has sinusoidal distribution with the phase displacement of 120° .

3 Direct Torque Control

As the name indicate, DTC allows control of flux and electromagnetic torque directly and independently by selecting proper switching vector [10, 11]. Figure 2 represents the basic blocks of modified DTC method implemented to A6PIM. The reference values of torque (T_e^*) and flux (Φ_s^*) are analyzed with the obtained values and the resultant errors are fed into a PI controller which allows the control of the motor in both directions of rotation.

The idea of the DTC is to lower the value of errors in flux and torque between the specified hysteresis band of torque and flux by the proper selection of switching

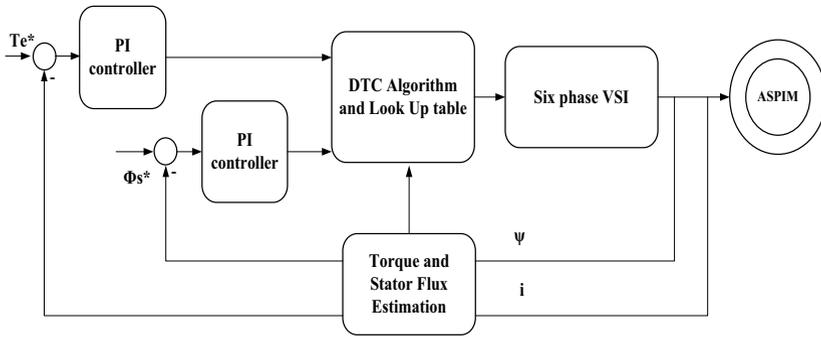


Fig. 2 Conventional DTC of SPIM

state of two levels inverter as shown in Table 1. In six-phase VSI, there are 64 states for switching that each state generates a voltage vector. In other words, there are 64 voltage vectors for the inverter. These voltage vectors can be shown in (x, y) and $(d-q)$ planes. Projecting the 64 voltage vectors in (x, y) plane, vectors with different lengths are appeared in this plane. In fact, the length of the switching vectors in (x, y) plane can be classified into four different sizes [12]. To obtain larger voltage amplitude, only switching vectors with largest size are selected in (x, y) plane [13, 14]. Figure 3 shows the projection of these 12 vectors in (d, q) and (x, y) planes.

Table 1 Switching states for DTC

Sector		Dm		
		$1 \uparrow$	0	$-1 \downarrow$
$d\psi$	$1 \uparrow$	V_{60}	V_0	V_{35}
	$0 \downarrow$	V_{28}	V_0	V_3

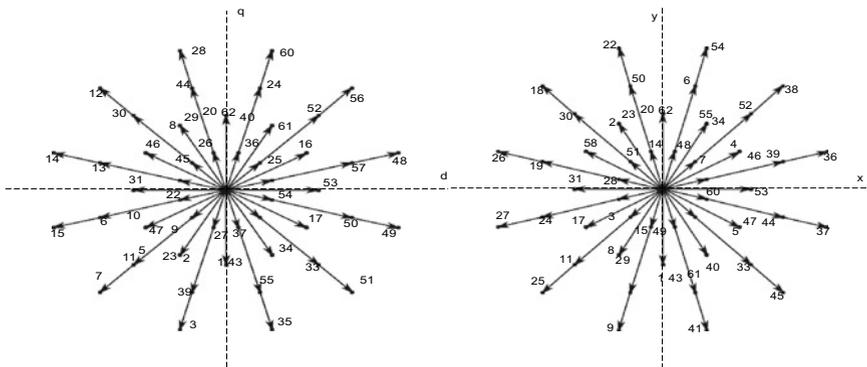


Fig. 3 a $d-q$ axis and b $x-y$ axis of voltage vectors [13]

The numbers written near the vectors represent the state of the six-phase VSI, when these numbers are converted to binary, six bits are obtained. Each zero/one in these binary numbers is corresponded to a switch in the related inverter leg.

The number zero means the lower switch is on and the number one means the upper switch is on. These vectors have the smallest lengths among vectors in (x, y) plane which decreases (d, q) voltage components; however, it is not enough a small amount of (x, y) voltage components results in large current of their axis. The DTC strategy should enforce (x, y) voltage components to become almost zero. If the flux and torque errors are increased, then the switching vector of the voltage is selected in such a way so that there is increase in stator magnitude and flux angle. Representation of space vectors of the voltage in $d-q$ and $x-y$ axis are illustrated in Fig. 3. All the space vectors of voltage that are active are categorized on the basis of their magnitude into four different groups (D_1, D_2, D_3 , and D_4), where D_1 is classified as the group of largest magnitude vectors and D_4 is classified as the group of smallest magnitude vectors. Vectors of the same group in $d-q$ subspace fall in the same group of $x-y$ sub-space, for example, D_1 of $d-q$ falls in $D1$ of $x-y$ and vice versa. Similarly D_2 and D_3 in $d-q$ subspace fall in D_2 and D_3 of $x-y$ subspace, respectively.

4 Result of Simulation

The result of the proposed direct torque control is presented in this section where A6PIM operates at a speed of 1p.u and a load torque of 1.5 p.u under steady-state condition is illustrated in respective Fig. 4 and Fig. 5. Waveform of phase current (I_a) with THD of 35.46% with respect to reference voltage (V_r) is shown in Fig. 6. By observing the current waveform it has been found that the current harmonics of the order 5th and 7th are present in proposed method. Figure 7 shows the ripple contain in power of the A6PIM under steady-state condition.

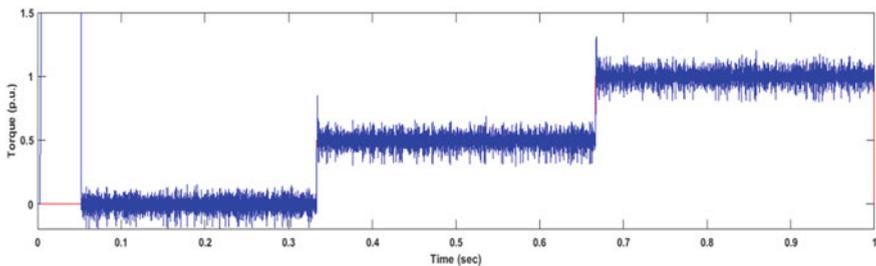


Fig. 4 Steady-state torque

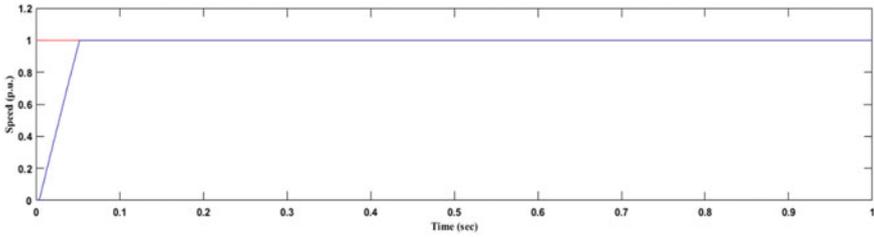


Fig. 5 Speed under steady state

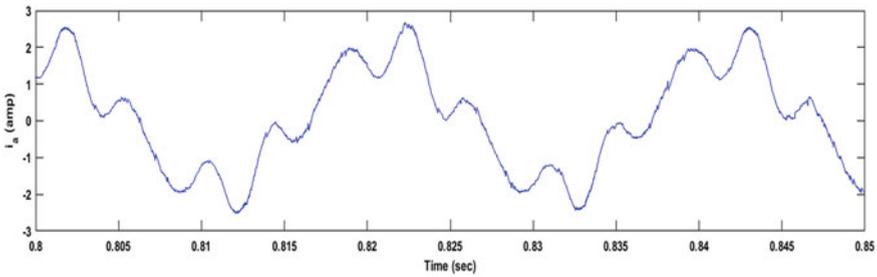


Fig. 6 Current waveforms of phases 'a'

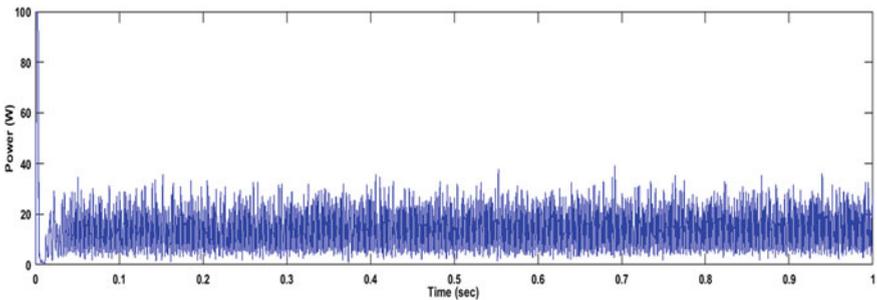


Fig. 7 Ripple contain in power

5 Conclusion

DTC of an asymmetrical multiphase 6-phase induction machine is proposed in this work. The proposed technique uses modified SVM to reduce the Total Harmonic Distortion around the acceptable limits, as obtained from commonly used conventional technique. The value of currents in x - y subspace is plotted. Vectors of groups D_1 and D_2 are formed by assigning proper times. The proposed method is free from switching sequence and no designed is required and dynamic behavior of the machine remains unchanged.

Appendix

Parameters and ratings of symmetrical six-phase induction motor under test

Poles (P)	2	Moment of inertia (J)	0.0030 Kg m ²
Stator and rotor resistance (r_s and r_r)	11.5 & 10.4 Ω	Power	1 HP
Frequency (f)	50 Hz	Mutual inductance (L_m)	550.7 mH
Speed (ω_{ref})	1450 rpm	Stator and rotor inductance (L_s, L_r)	579.17 mH

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