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Improved Torque Control Performance of Direct Torque Control for 5-Phase Induction Machine

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ABSTRACT

In this paper, the control of five-phase induction machine using Direct Torque Control (DTC) is presented. The general D-Q model of five-phase induction machine is discussed. The de-coupled control of stator flux and electromagnetic torque based on hysteresis controller similar to conventional DTC is applied to maintain the simplicity of the system. Three sets of look-up tables consist of voltage vectors with different amplitude that selects the most optimal voltage vectors according motor operation condition is proposed. This provides excellent torque dynamic control, reduces torque ripple, lower switching frequency (high efficiency) and extension of constant torque. Simulation results validate the improvement achieved.

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1. INTRODUCTION

The popularity of induction machine has been on the rise and became the major driving factors in the development of high performance control strategy. Although there are many proposed control strategies available, Field Oriented Control (FOC) and Direct Torque Control (DTC) are the most researched [1,2].The objective of both of the control strategies are similar although their operation principal are different. Their objectives are to precisely control the torque and flux of rotary machine regardless of load condition and other external disturbance. F. Blaschke proposed the Field Oriented Control (FOC) [3]. This control strategy imitates the control method of separately excited dc motor where the stator current is decomposed into flux and torque component through the means of coordinate transformation and rotor flux orientation [3, 4,5]. In DTC, the flux and torque of the rotating machine are controlled directly. This method functions based on space vector theory where by selecting the optimal space vector in each sampling period, the stator flux and torque are controlled effectively [6, 7, 8].

The multiphase was originated in the late 1960's. Multiphase drives are developed in order to overcome the problem in three phase six-step inverter fed machines which are low frequency torque ripple [9,10]. Multiphase induction drive possesses many advantages compared to the conventional three-phase drive. Those advantages are reduced amplitude and increased frequency of torque pulsation, reduced rotor harmonic current, reduced current per phase without increase in voltage per phase and lower dc link current harmonics with increased reliability [7,9,10]. Fig. 1 illustrates the 5-phase VSI connected to the star windings of 5-phase induction machine. In each inverter leg, the power switches are represented with the upper and lower switches which are complementary to each other. The switching state of an inverter leg indicates 1 when the upper switch of the inverter leg is ON and the lower switch is OFF, and vice-versa. The switching state is corresponds to [S_a S_b S_c S_d S_e]. The combination of switching states can produce 30 non-zero active voltage switching space vectors together with 2 zero space vectors which is illustrated in Fig. 2 together with the voltage modes. In general terms of switching states, the phase voltage space vectors of the 5-phase is given as follow:

$$\boldsymbol{v_k} = \frac{2}{5} V_{DC}(S_a + a\, S_b + a^2\, S_c + a^{-2}\, S_d + a^{-1}\, S_e) \tag{1}$$

where $a = e^{j2\pi/5}$ and k=0, 1, 2,…..,31.

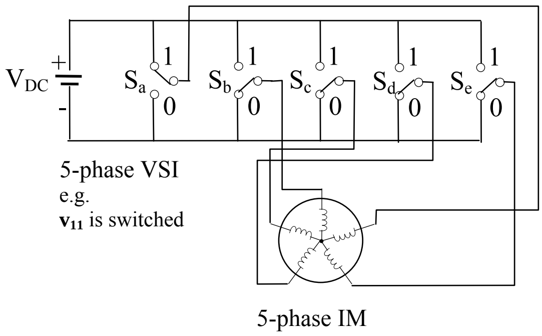

Figure 1. 5-phase VSI connected to 5-phase induction motor.

V_1 [1 1 0 0 1]	V_2 [1 1 0 0 0]	V_3 [1 1 1 0 0]	V_4 [0 1 1 0 0]
V_5 [0 1 1 1 0]	V_7 [0 0 1 1 1]	V_8[0 0 0 1 1]	V_9 [1 0 0 1 1]
V_{10} [1 0 0 0 1]	V_{11} [1 0 0 0 0]	V_{12}[1 1 1 0 1]	V_{13}[0 1 0 0 0]
V_{14} [1 1 1 1 0]	V_{15} [0 0 1 0 0]	V_{16}[0 1 1 1 1]	V_{17} [0 0 0 1 0]
V_{18}[1 0 1 1 1]	V_{19}[0 0 0 0 1]	V_{20} [1 1 0 1 1]	V_{21} [0 1 0 0 1]
V_{22} [1 1 0 1 0]	V_{23} [1 0 1 0 0]	V_{24} [0 1 1 0 1]	V_{25}[0 1 0 1 0]
V_{26}[1 0 1 1 0]	V_{27} [0 0 1 0 1]	V_{28} [0 1 0 1 1]	V_{29} [1 0 0 1 0]
V_{30}[1 0 1 0 1]	V_0[1 1 1 1 1]	V_{31} [0 0 0 0 0]	

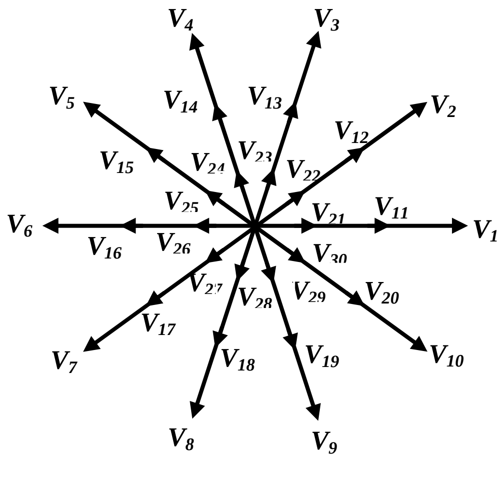

Figure 2. Space voltage vectors available in 5-phase VSI

In this paper, the DTC method is implemented for the five-phase induction machine. It can be shown that the greater number of switching states provided in five-phase DTC system can give more degrees of freedom to select the most optimal voltage vector to improve further DTC performances. The methametical model of five phase machine is given. Other than that, a detailed explanation regarding the impact of voltage vector selection in influencing the dynamic torque performance, extension of constant torque region, minimization in torque ripple and switching frequency are also given.

2. GENERALISED D-Q MODEL OF FIVE PHASE INDUCTION MACHINE

The D-Q Model of Five Phase Induction Machine is almost similar to the conventional three phase machine. The difference between them are there will be five new stator (current, voltage, and stator flux) with spatial displacement between any two consecutive stator phases equals $\alpha = 2\pi/5$ for the five phase machine.Assuming that the windings are connected in star with single neutral point , zero sequence component does not exist in five phase machine. The x-y component of the machine can also be neglected due to the sinusoidal distribution of the flux around the air gap. Assuming that the machine equation are transformed into an arbitrary frame of reference rotating at angular speed ωe, the model of n-phase (five) machine with sinusoidal winding distribution can be given as follow:

Stator circuit equations:

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \tag{2}$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} - \omega_e \varphi_{ds} \tag{3}$$

Rotor circuit equations:

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - (\omega_e - \omega_r)\varphi_{qr} \tag{4}$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} - (\omega_e - \omega_r)\varphi_{dr} \tag{5}$$

Flux linkage expression in terms of current:

$$\varphi_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \tag{6}$$

$$\varphi_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) \tag{7}$$

$$\varphi_{qs} = L_{ls} i_{ds} + L_m(i_{qs} + i_{qr}) \tag{8}$$

$$\varphi_{qr} = L_{lr} i_{dr} + L_m(i_{qs} + i_{qr}) \tag{9}$$

$$\varphi_{dm} = L_m(i_{ds} + i_{dr}) \tag{10}$$

$$\varphi_{dm} = L_m(i_{ds} + i_{dr}) \tag{11}$$

$$i_{ds} = \frac{\varphi_{ds}(L_{ir} + L_m) - L_m \varphi_{dr}}{(L_{is} + L_m)(L_{ir} + L_m) - L_{m^2}} \tag{12}$$

$$i_{qs} = \frac{\varphi_{qs}(L_{ir} + L_m) - L_m \varphi_{qr}}{(L_{is} + L_m)(L_{ir} + L_m) - L_{m^2}} \tag{13}$$

$$i_{dr} = \frac{\varphi_{dr}(L_{ir} + L_m) - L_m \varphi_{ds}}{(L_{is} + L_m)(L_{ir} + L_m) - L_{m^2}} \tag{14}$$

$$i_{qr} = \frac{\varphi_{qr}(L_{ir} + L_m) - L_m \varphi_{qs}}{(L_{is} + L_m)(L_{ir} + L_m) - L_{m^2}} \tag{15}$$

Torque equation:

$$T_e = PL_m(i_{qs} i_{qr} - i_{ds} i_{qr}) \tag{16}$$

Speed equation:

$$\omega_r = \int \frac{P}{2J}(T_e - T_L)dt \tag{17}$$

where Lis, Lir and Lm are the is the total leakage factor, J is inertia, P is the number of pole pairs and ω_r is the rotor electric angular speed in rad/s.

3. OPTIMAL DTC SWITCHING STRATEGY

This section discusses the optimal selection of voltage vectors to achieve high-performance DTC for 5-phase induction machine. Since the 5-phase VSI provides more number of switching vectors, it is therefore give more options to select the most optimal voltage vector for every operating condition.

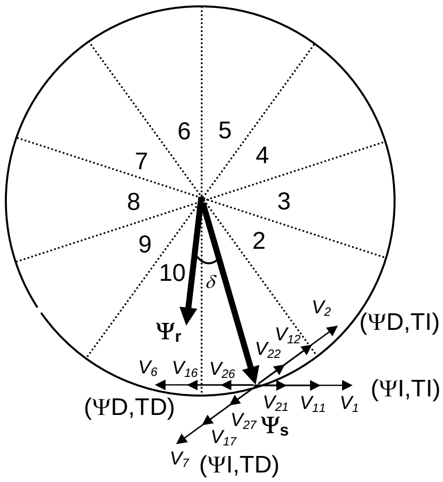

Figure 3. Selection of voltage vectors for controlling stator flux in Sector 1.

By applying 5-phase VSI, the trajectory of flux vector in stator flux plane can be mapped into 10 sectors which are equally divided by 36^0, as illustrated in Fig. 3. Figure 3 also shows possible voltage vectors to be selected whenever the flux lies within a Sector 1, in controlling both flux and torque. It should be noted that; the control of flux vector is directly affected by the applied voltage vector (both with same direction), while the control of torque is mainly determined by the load angle (δ). Assuming the trajectory of flux vector forming a circular locus in counter-clockwise direction. To increase both flux and torque (ΨI,TI), voltage vectors v_{21}, v_{11} and v_1 are chosen. If the torque is maintained to increase , on the other hand the flux needs to be decreased (ΨD,TI), voltage vectors v_{22}, v_{12} and v_2 are chosen. The voltage vector v_1 has the longest amplitude which gives the most significant impact on flux and torque increase followed by v_{11} (medium amplitude) and v_{21} (shortest amplitude). In another case, the voltage vector v_2 has the longest amplitude which gives the most significant impact on flux decrease and torque increase, followed by V_{12} (medium amplitude) and V_{22} (shortest amplitude). Among of three possible voltage vectors stated in both cases, there is only one voltage vector that could be the most optimal vector to be chosen to improve DTC performances.
In order to identify the most optimal vector, it is desirable to study the effects of torque slope due to the application voltage vectors for different operating conditions. The rate of change of torque can be controlled by applying the most optimal vector (either the one that has the longest amplitude, or medium amplitude, or shortest amplitude) according to the operating conditions, so that it can improve the switching frequency, torque ripple, torque regulation and torque dynamic control. Taking into account that the torque variation (or slope) is affected by the applied voltage vector as well as operating conditions which was reported in [11]. The torque slope equation can be used to analyze the effects of voltage vector application and operating conditions as given in (18).

$$\frac{T_{e,n+1} - T_{e,n}}{\Delta t} = -T_{e,n}\left(\frac{1}{\sigma\tau_s} + \frac{1}{\sigma\tau_r}\right) + \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}[(v_{s,n} - j\omega_r \boldsymbol{\Psi}_{s,n}) \cdot j\boldsymbol{\Psi}_{r,n}] \tag{18}$$

where P is the number of pole pairs, ωr is the rotor electric angular speed in rad./s, L_s, L_r and L_m are the σ is the total leakage factor, τ_s and τ_r are the time constant, and τr is the rotor flux.

Equation (18) indicates that the torque slope depends on the rotor speed and applied voltage vector, whereby the rest of parameters can be assumed to have constant values. According to (18), the torque increases rapidly at low speed operations, thus an active voltage vector that has the smallest amplitude needs to be chosen in order to slower down the rate of increase. Hence, it can minimize the switching frequency as well as switching losses. Furthermore, it can prevent reversed voltage vectors to be selected whenever the output torque exceeds beyond the hysteresis band, especially in digital implementation, which causes extreme torque slope and consequently produces a larger torque ripple [12]. In the case of high speed operations, voltage vectors that have the longest amplitude should be chosen. This selection naturally enhances the output voltage to meet higher demand in controlling torque at high speed operations [13,14]. By applying the longest amplitude of voltage vector, it also can improve dynamic control performance for entire speed range of operations.

In this paper, three different look-up tables were introduced where each of the look up table represents a group of selection of voltage vectors, as tabulated in Table 1. The first look-up table represents the longest amplitude (Table 1(a)), second look-up table represents medium amplitude (Table 1(b)) and the third look-up table represents the shortest amplitude (Table 1(c)). Each set of voltage vector posseses a certain criteria according to the desired improvements and speed operating conditions, as discussed above.

Table 1. Selection of Voltage Vector for (a) Longest- (b) Medium- and (c) Smallest Amplitude

	Flux error status S_Ψ	Torque error status S_T	Sector 1	2	3	4	5	6	7	8	9	10
(a)	1	1	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
		0	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
		-1	V7	V8	V9	V0	V1	V2	V3	V4	V5	V6
	0	1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V1
		0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
		-1	V6	V7	V8	V9	V10	V1	V2	V3	V4	V5

	Flux error status S_Ψ	Torque error status S_T	Sector 1	2	3	4	5	6	7	8	9	10
(b)	1	1	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20
		0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
		-1	V17	V18	V19	V20	V11	V12	V13	V14	V15	V16
	0	1	V12	V13	V14	V15	V16	V17	V18	V19	V20	V11
		0	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
		-1	V16	V17	V18	V19	V20	V11	V12	V13	V14	V15

	Flux error status S_Ψ	Torque error status S_T	Sector 1	2	3	4	5	6	7	8	9	10
(c)	1	1	V21	V22	V23	V24	V25	V26	V27	V28	V29	V30
		0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
		-1	V27	V28	V29	V30	V21	V22	V23	V24	V25	V26
	0	1	V22	V23	V24	V25	V26	V27	V28	V29	V30	V21
		0	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
		-1	V26	V27	V28	V29	V30	V21	V22	V23	V24	V25

Figure 4 depicts the structure of DTC of 5-phase induction machine. Most components employed in conventional DTC are maintained in order to retain simple structure of DTC. Minor modifications on the original DTC structure were done, particularly in introducing three sets of look-up table (as given in Table I) and calculating the d-axis and q-axis components of currents and voltages based on 5-phase system. Note that, the rotor speed information (obtained from speed sensor) is required to determine the optimal vector to achieve desired improvements.

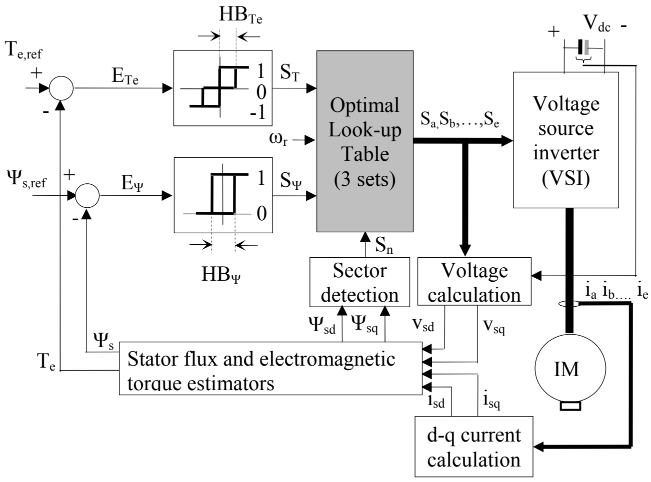

Figure 4. Structure of DTC of five-phase induction machine

4. SIMULATION RESULTS

Simulations were conducted using Matlab/Simulink to compare DTC performances for different applications of voltage vectors (i.e. shortest amplitude, medium amplitude and longest amplitude). For simplification in comparing the performances, a step change of reference torque from 0.5 p.u to 1.0 p.u is applied for every application of amplitude vector, as shown in Fig. 5. The zoomed images of the results shown in Fig. 5, are also given in Fig. 6 to present clearly the effects of torque regulation/slope.

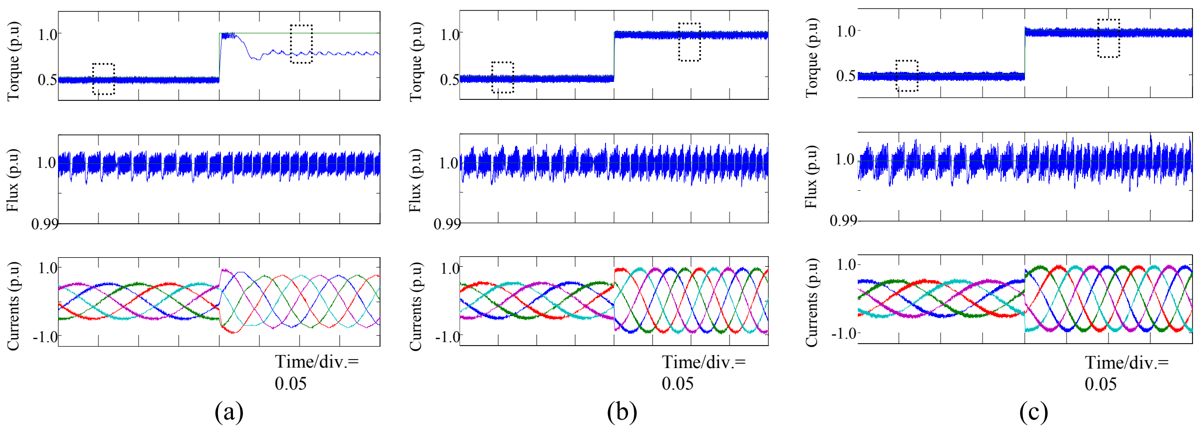

Figure 5. Simulation results of output torque, stator flux and stator currents with a step change of reference torque for different amplitude of voltage vector (a) smallest amplitude, (b) medium amplitude and (c) longest amplitude.

From the results obtained, the torque and flux ripples were reduced with the application of the smallest voltage vector. Moreover, this selection of vector results in lower switching frequency which may improve the efficiency of DTC drive system. However, the DTC performance in controlling the torque at rated condition deteriorates if the smallest amplitude of vector applied, particularly at high speed operations. In such condition, it is clearly seen that the torque regulation is excellent with the application of the longest amplitude of vector. Thus, the capability of torque regulated at its rated during motor acceleration can be further extended by applying the longest amplitude of voltage vector.

Figure 7 compares the torque dynamic performance of the three applications under the same test (as performed in Figures. 5 and 6). It can be clearly noticed from the figure that the fastest torque dynamic performance can be achieved with application of the longest amplitude of vector. As discussed in previous section, the longest amplitude of vector results in the highest torque slope or rate of torque increases. Based on the results obtained, it can also suggest that the selection of medium amplitude of vector is preferable to obtain better torque regulation, particularly at middle speed operations.

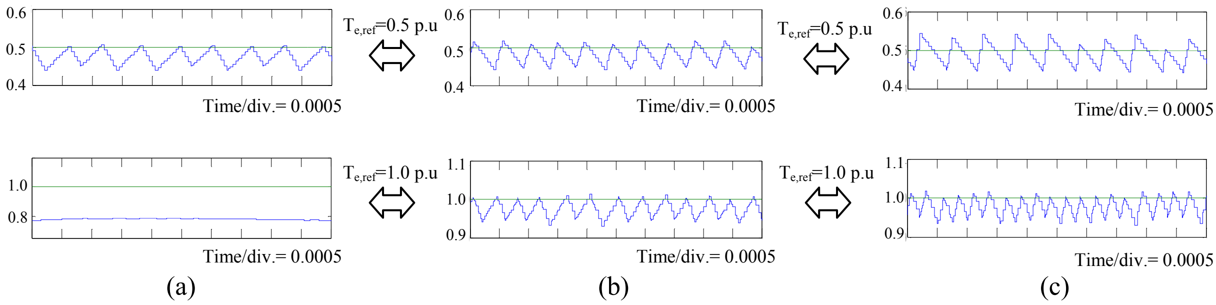

Figure 6. Magnified output torque waveforms for (a) $T_{e,ref}$ = 0.5 p.u and (b) $T_{e,ref}$=1.0 p.u., corresponding to the results obtained in Figs. 5(a),(b) and (c), respectively (i,e. area marked by dotted line).

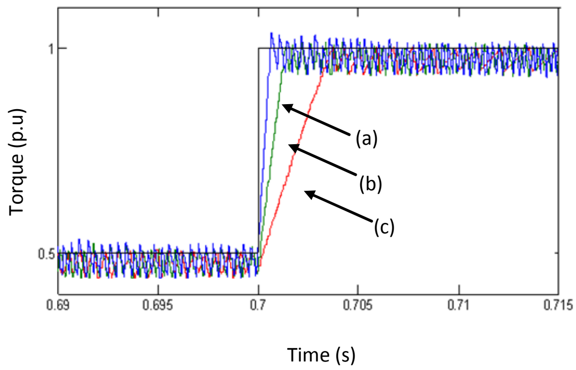

Figure 7. Comparison of torque dynamic performance for different application of voltage vectors (a) longest amplitude, (b) medium amplitude (c) shortest amplitude.

5. CONCLUSION

This paper has presented an optimal DTC switching strategy for five-phase induction machine. Three look-up tables consisting of voltage vectors with different amplitude were used to obtain the optimal switching strategy. It has shown that the DTC performances can be improved by selecting the most optimal vector which is different for every range of speed operation. Motor modeling of five phase induction machine is also discussed.The significance of the research is to highlight the potential of using five-phase DTC system that offers more options (i.e. number of switching vectors) in selecting the most optimal vector to achieve superior performance.

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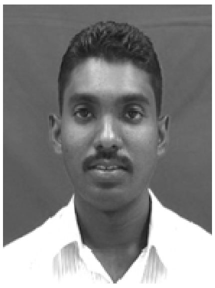

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