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A New Scheme to Direct Torque Control of Matrix Converter-Fed Five-Phase Permanent Magnet Synchronous Motor

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Abstract

Multiphase machines have gained an increasing attention due to their more advantages in comparison with three-phase machines. In recent literatures, only voltage source inverters (VSIs) have been used to supply five-phase drives. Matrix converters (MCs) pose many advantages over conventional VSIs, such as lack of dc-bulk capacitors, high quality power output waveform and higher number of output voltages. Due to some special applications of multiphase machines such as ship propulsion and aerospace, the volume of these drives is an important challenging problem. As a consequence, using MCs can be a reasonable alternative. In this paper, a new direct torque control (DTC) algorithm using a three-to-five phase MC is proposed for five-phase permanent magnet synchronous motors (PMSMs). All of output voltage space vectors of three-to-five phase MC are extracted and a new switching table is proposed. Because of higher number of output voltages in MCs, there is a degree of freedom to control input power factor to keep close to unit moreover the torque and flux control. In other words, this proposed method use the advantages of both DTC method and MCs. Simulation results show the effectivenessof presented method in different operation modes.

Keywords: dtc, matrix converter, five-phase pmsm, power factor

1. INTRODUCTION

Multiphase machines have gained an increasing attention due to their several advantages over three-phase systems, such as reducing the amplitude of torque pulsations, lowering the dc link current harmonics, reducing the stator current per phase without increasing the voltage per phase and increasing the reliability [1,2,3,4,5].

Direct Torque Control (DTC) is one of the active researched control schemes which is based on the decoupled control of flux and toque. This method was first proposed for three-phase induction machines and then was implemented on three-phase permanent magnet synchronous motors (PMSMs) [6,7]. DTC provides a very quick and precise torque response and also has very simple instruction, i.e., no need of rotary coordinate transformation, inner current regulator, or pulse width modulation (PWM) block. The basic principle of DTC is to directly select stator voltage vectors according to the differences between the reference and actual torque and stator flux linkage. Also, this method was presented for the first time in five and six-phase induction motors in [8,9]. L. Parsa, et al. investigated the DTC algorithm for a five-phase PMSM in [10].

Matrix converter (MC) is an interesting power converter that was developed in the last two decades [11,12,13]. These kinds of converters have many advantages such as including an adjustable input power factor, bidirectional power flow, high-quality power output waveforms and the lack of bulky capacitors. Due to their higher number produced output voltage space vectors, one can do more precise control. DTC method using MCs was first proposed for induction motors in [14]. In that literature, in addition to torque and flux control, input power factor has been controlled to be close to unit. In the next years, DTC scheme using MC has been implemented on PMSMs [15]. Despite of more advantages of MCs in comparison with conventional voltage source inverters (VSIs), in the literatures related to the multiphase motor drives, only VSIs have been used to feed these motors.

Five-phase voltage source inverters produce 32 output voltage vectors. Noting that three-phase VSIs produce 8 voltage vectors, it seems that due to higher number of output voltage vectors in five-phase VSIs, more precise control in electromagnetic torque and stator flux can be achieved. But it has been shown in [10] that, because of large stator currents harmonic problems, it is better to use just 10 voltage vectors. This issue will be explained in detail in this paper.

In this paper, a new DTC of five-phase PMSM using three-to-five phase matrix converter is proposed. Input power factor is controlled to be kept close to unit. In the other word, the advantages of both DTC scheme and MC are used in this presented method. All of output voltage vectors of a three-to-five phase MC are obtained and the effects of these vectors on torque and flux variations are investigated and also a proper switching table is proposed. Simulation results show that using this presented switching pattern table, besides the control of input power factor, good and precise control in electromagnetic torque and flux is achieved.

2. MATHEMATICAL EQUATIONS OF FIVE-PHASE PMSM

The stator voltage equation of the motor is as follow

$$V_s = R_s T_s + \frac{dl}{d} \tag{1}$$

R_s , I_s and Λ_s are the stator resistance, currents and flux linkages matrices respectively.
The equation of air gap flux linkage can be presented as follow

$$\Lambda_s = \Lambda_{ss} + \Lambda_m = L_s I_s + \Lambda_m \tag{2}$$

L_{ss} is the stator inductance matrix and Λ_m is the flux linkage of the rotor permanent magnet.

One can write the stator voltage, flux and torque equations of a five-phase sinusoidally wounded motor in synchronous rotating reference frame $(d-q-z_1-z_2-z_3)$ using the following transformation matrix.

$$T(\theta) = \frac{2}{5}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) & \cos(\theta + \frac{4\pi}{5}) & \cos(\theta + \frac{2\pi}{5}) \\ \sin(\theta) & \cos(\theta - \frac{2\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) & \sin(\theta + \frac{4\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) \\ \cos(\theta) & \cos(\theta + \frac{4\pi}{5}) & \cos(\theta - \frac{2\pi}{5}) & \cos(\theta + \frac{2\pi}{5}) & \cos(\theta - \frac{4\pi}{5}) \\ \sin(\theta) & \sin(\theta + \frac{4\pi}{5}) & \sin(\theta - \frac{2\pi}{5}) & \sin(\theta + \frac{2\pi}{5}) & \sin(\theta - \frac{4\pi}{5}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

In above equation, θ is the rotor electrical angle.
The stator flux linkages are given by

$$\begin{aligned} \lambda_{ds} &= L_d i_{ds} + \lambda_m \\ \lambda_{qs} &= L_q i_{qs} \\ \lambda_{z1s} &= L_{ls} i_{Z1s} \\ \lambda_{Z2s} &= L_{ls} i_{Z2s} \\ \lambda Z3s &= L_{ls} i_{Z3s} \end{aligned} \tag{4}$$

Stator voltage equations in transformed reference frame are obtained as

$$
\begin{aligned}
V_{qs} &= r_s i_{qs} + \omega\lambda_{ds} + \frac{d\lambda_{qs}}{dt} \\
V_{ds} &= r_s i_{ds} + \omega\lambda_{qs} + \frac{d\lambda_{ds}}{dt} \\
V_{Z1s} &= r_s i_{Z1s} + \frac{d\lambda_{Z1s}}{dt} \\
V_{Z2s} &= r_s i_{Z2s} + \frac{d\lambda_{Z2s}}{dt} \\
V_{Z3s} &= r_s i_{Z3s} + \frac{d\lambda_{Z3s}}{dt}
\end{aligned}
\tag{5}
$$

Where, ω is the rotor electrical speed.

All the 10n±1th (n=0,1,2…) winding space harmonics and voltage time harmonics with abcde phase sequence are related to $q-d$ subspace, while all the 10n±3th (n=0,1,2…) winding space harmonics and voltage time harmonics with acebd phase sequence are related to $Z_1 - Z_2$ subspace. For a sinusoidally wounded motor, magnitude of third space harmonic within stator winding function is very low, which leads to tiny magnetizing inductance in $Z_1 - Z_2$ model and the only impedance to $Z_1 - Z_2$ voltage is stator resistance plus stator leakage inductance as can be seen in (5). Thus, Even a low order voltage harmonic in $Z_1 - Z_2$ plane, cause to large distortion in stator current.

Electromagnetic torque equation in dq reference frame can be written as follow

$$T_e = \frac{p}{2}\frac{5}{2}\left[\lambda_m i_{qs} + (L_d - L_q) i_{ds} i_{qs}\right] \tag{6}$$

3. DIRECT TORQUE OF FIVE-PHASE PERMANENT MAGNET SYNCHRONOUS MOTOR

A five-phase VSI is illustrated in Figure 1. Five-phase VSI inherently produce 32 output voltage space vectors with two zero vectors andthirty active voltage vectors as it shown in Figure 2. In a five phase system there are two orthogonal subspaces namely $D-Q$ subspace and $Z_1 - Z_2$ subspaces which are shown in Figure 3. As can be seen in this figure, these 32 voltage vectors are composed of three sets of different amplitudes namely small, medium and large vectors, respectively. From the following equation, the output voltage vectors in $D-Q$ and $Z_1 - Z_2$ subspaces are obtained. If the upper switches of converter are closed, S is considered to be 1 and on contrary, if the lower switches are closed, S is 0.

$$\overline{V_0^{D-Q}} = \frac{2}{5}V_{dc}(S_A + S_B e^{j\frac{2\pi}{5}} + S_C e^{j\frac{4\pi}{5}} + S_D e^{-j\frac{4\pi}{5}} + S_E e^{-j\frac{2\pi}{5}})$$
$$\overline{V_0^{D-Q}} = \frac{2}{5}V_{dc}(S_A + S_B e^{j\frac{2\pi}{5}} + S_C e^{j\frac{4\pi}{5}} + S_D e^{-j\frac{4\pi}{5}} + S_E e^{-j\frac{2\pi}{5}}) \quad (7)$$

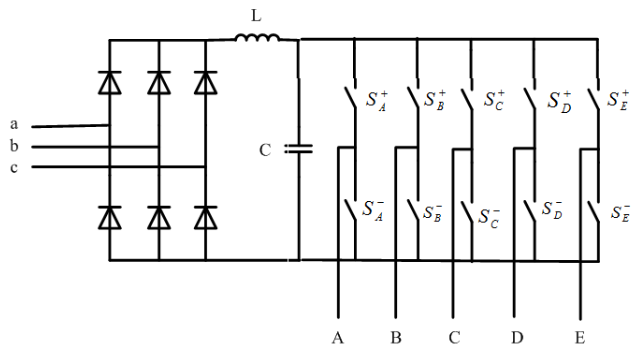


Figure 1: Five-phase voltage source inverter

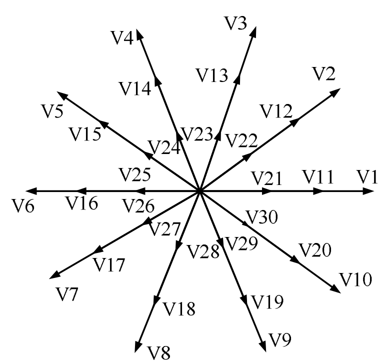
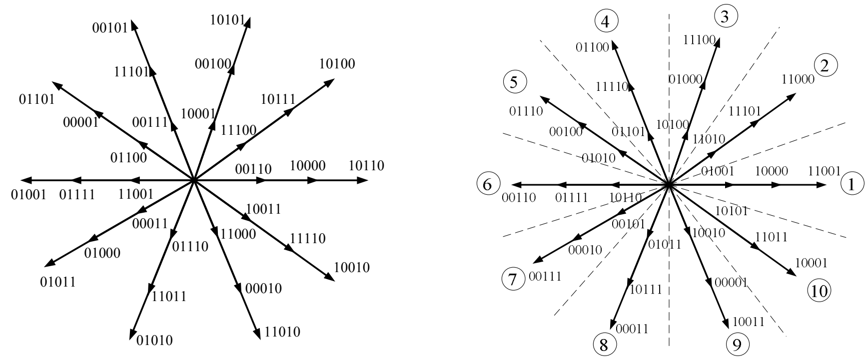


Figure 2: Thirty two voltage vectors of a five-phase VSI



D-Q plane Z1-Z2 plane

Figure 3: Thirty two voltage vectors of a five-phase VSI in D-Q and Z1-Z2 subspaces

The principle of selecting a voltage space vector in the conventional DTC of five-phase drive is similar as that in DTC of three-phase drives. It is shown in [7] that, for three-phase PMSM with uniform air gap, electromagnetic torque is

$$T_e = \left(\frac{3p}{2}\right)\left(\frac{1}{L}\right)\phi_{r\max}\left|\phi_s(t)\right|\sin\delta \tag{8}$$

Where, $|\varphi_s(t)|$ presents the amplitude of stator flux, $\varphi_{r\max}$ is explanatory of rotor flux permanent magnet, p is the number of poles and δ is angle between stator flux and rotor flux.

For a five-phase motor equation (8) can be rewritten as

$$T_e = \left(\frac{5p}{2}\right)\left(\frac{1}{L}\right)\phi_{rD-Q}\left|\phi_{sD-Q}(t)\right|\sin\delta \tag{9}$$

As it is shown in Figure 3, the switching pattern plane is divided to ten sectors. Each voltage vector has a radial component and a tangential component. The variation of radial component is related to stator flux variation and the variation of tangential component is related to variation of electromagnetic torque. For example it is supposed that the position of flux is in sector 1 and both electromagnetic torque and stator flux need to be increased. As can be seen in Figure 4, the radial components of voltage vectors V_2 ,V_3 V_9 and V_{10} align with φ_{s1} , and therefore these voltage space vectors increase the stator flux magnitude. Among these 4 vectors, the tangential components of vectors V_2 and V_3 increase the angle δ and therefore electromagnetic torque and on the contrary, tangential components of voltage space vectors V_9 and V_{10} , decrease the angle δ and electromagnetic torque. Thus, if stator flux and electromagnetic torque are need to be increased, voltage vectors V_2 and V_3 should be chosen. As it is illustrated in Figure.4, the tangential component of voltage V_3 is bigger than tangential component of V_2. Therefore, voltage space vector V_3 is more effective on increasing electromagnetic torque. On the other hand, the radial component of voltage vector V_2 is bigger than voltage V_3. Thus, V_2 is more effective on increasing stator flux. Due to the control of electromagnetic torque is more demanding than stator flux, thus, voltage vector V_3 will be selected. As the same, if stator flux needs to be increased and electromagnetic torque needs to be decreased, voltage space vector V_9 should be chosen. On the other hand, to decrease stator flux magnitude and increase electromagnetic torque, voltage V_4 is chosen. Finally, voltage vector V_8 decreases both stator flux magnitude and electromagnetic torque.

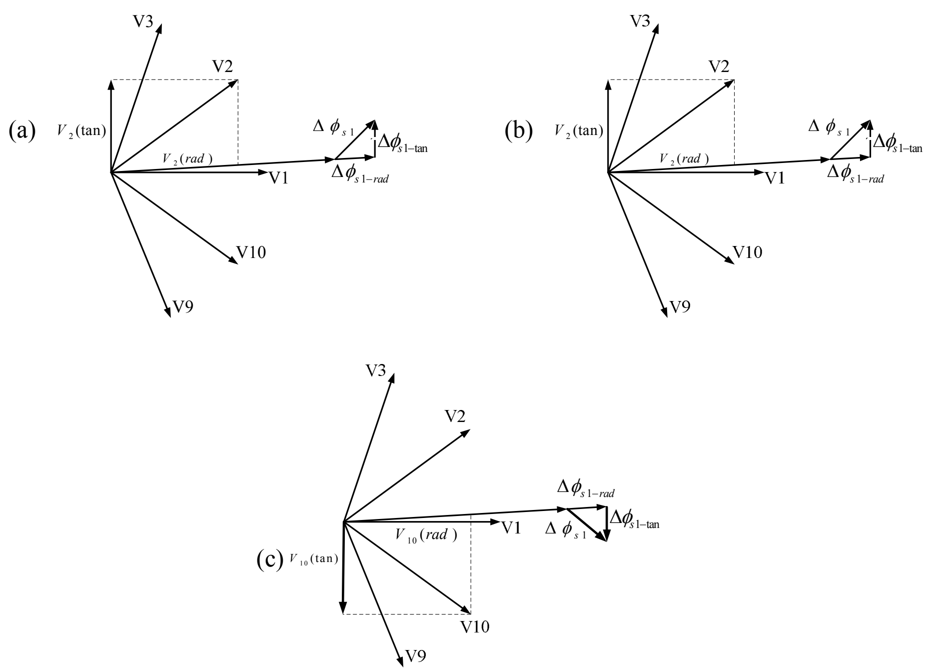


Figure 4: Effects of voltage vectors on electromagnetic torque and stator flux magnitude. (a) Effectsof voltage vector V2, (b) Effects of voltage vector V3, (c) Effects of voltage vector V10

As can be seen in Figure 3, voltage space vectors V_{12} and V_{22} have the same direction that of V_2. Having the same direction, these vectors have the same effects on changing electromagnetic torque and stator flux magnitude but Voltage V_2 has faster response due to its bigger magnitude than V_{12} and also V_{22}.

As aforementioned in previous section and can be seen from equation (9), only the components of $D-Q$ subspace, produce output torque and components of Z_1-Z_2 subspace produce harmonics in stator currents. It should be noted that, the outer decagon of the $D-Q$ subspace is mapped into the inner decagon of the Z_1-Z_2 subspace and vice-versa. The medium decagon of $D-Q$ is mapped into the medium decagon of Z_1-Z_2. If the large voltage space vectors of $D-Q$ subspace are energized, the small voltage vectors of Z_1-Z_2 subspace will be energized simultaneously. Therefore, less harmonic currents will be obtained. If the medium vectors of $D-Q$ subspace are selected to be applied to motor, then medium vectors of Z_1-Z_2 subspace will be selected at the same time. Thus, because of applying larger vectors of Z_1-Z_2 subspace in comparison with previous status, harmonic currents will be increased in this time. The same conception is true for selecting small vectors of $D-Q$ subspace and large vectors of Z_1-Z_2 subspace, i.e., in this condition, the higher harmonic currents will be achieved in comparison with the last two status of selecting switching voltage vector. Thus, according to this analysis, it is preferable to choose only large voltage space vectors of $D-Q$ subspace.

According to aforementioned analysis, a switching table has been proposed in [10] which is shown in table.1. It should be noted that, $d\varphi=-1$ ($d\varphi=1$), show that the stator flux linkage has to be decreased (increased). On the other hand, $dT_e=-1$ ($dT_e=1$) is the explanatory of this fact that the electromagnetic torque has to be decreased (increased).

The block diagram of DTC of five-phase PMSM is illustrated in Figure.5. As it can be seen, the measured stator voltages and currents are transformed to stationary reference frame. In the next step, torque and flux are estimated by measured voltages and currents and will be compared with their corresponding target values. Then, the errors between target and actual values will be sent to hysteresis comparators. By the outputs of hysteresis controllers and stator flux angle, a switching state will be selected from an offline switching table and command will be sent to the inverter.

Electromagnetic torque and stator flux are obtained using stator voltages and currents in stationary reference frame. Stator flux angle also can be achieved using equation (12).

$$T_e = \frac{5}{2}\frac{p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{10}$$

$$\begin{aligned} \lambda_a &= \int (V_\alpha - R_s I_\alpha) dt \\ \lambda_\beta &= \int (V_\beta - R_s I_{\alpha\beta}) dt \end{aligned} \tag{11}$$

$$\begin{aligned} \lambda_s &= \sqrt{(\lambda_\alpha^2 + \lambda_\beta^2} \\ < \lambda_s &= tg^{-1} \frac{\lambda_\beta}{\lambda_\alpha} \end{aligned} \tag{12}$$

Where, α is the direct axis and β is the perpendicular axis.

Table 1: Voltage vector switching table

$d\varphi$	dT_e	SECTOR 1	SECTOR 2	SECTOR 3	SECTOR 4	SECTOR 5	SECTOR 6	SECTOR 7	SECTOR 8	SECTOR 9	SECTOR 10
1	1	V3	V4	V5	V6	V7	V8	V9	V10	V1	V2
1	-1	V9	V10	V1	V2	V3	V4	V5	V6	V7	V8
-1	1	V4	V5	V6	V7	V8	V9	V10	V1	V2	V3
-1	-1	V8	V9	V10	V1	V2	V3	V4	V5	V6	V7

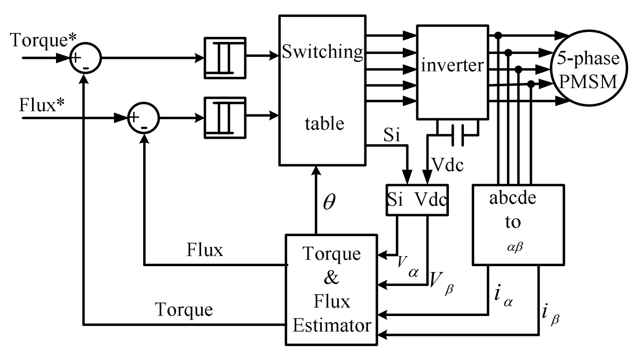


Figure 5: DTC of five-phase PMSM using standard VSI

4. DIRECT TORQUE CONTROL USING MATRIX CONVERTER

4.1 Three-phase to Five-phase Matrix Converter

The power circuit topology of a three-phase to five-phase matrix converter is illustrated in Figure.6. As can be seen, there are five legs which each leg have three bidirectional switches in series.

Switching constraint is $S_{ka} + S_{kb} + S_{kc} = 1$. Where, $k = \{A, B, C, D, E\}$ is the output phase of the converter and $j = \{a, b, c\}$ is the input phase of the converter. S , is the status of switches which 1 denotes that the switch is closed and 0 implies that the switch is open.

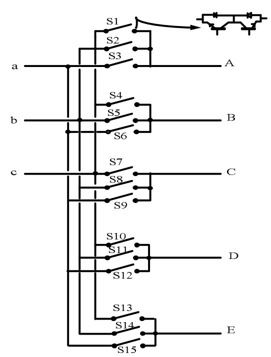


Figure 6: Schematic diagram of a three-phase to five-phase matrix converter

The state of converter can be represented using following transformation matrix.

$$T = \begin{bmatrix} S_{Aa}(t) & S_{Ab}(t) & S_{Ac}(t) \\ S_{Ba}(t) & S_{Bb}(t) & S_{Bc}(t) \\ S_{Ca}(t) & S_{Cb}(t) & S_{Cc}(t) \\ S_{Da}(t) & S_{Db}(t) & S_{Dc}(t) \\ S_{Ea}(t) & S_{Eb}(t) & S_{Ec}(t) \end{bmatrix} \tag{13}$$

Using transformation matrix, we will obtain

$$[V_o(t)] = [T][V_i(t)] \tag{14}$$

$$[T_i(t)] = [T^T][I_o(t)] \tag{15}$$

Where, V_o and I_o are output voltage and output current vectors, respectively. Also, V_i and I_i are input voltage and input current vectors.

A three-phase to five-phase MC produce $3^5 = 243$ output voltage space vectors. Among these vectors, 93 vectors have fixed direction and called stationary vectors group. As aforementioned for conventional five-phase VSIs, for a five-phase matrix converter, 30 output voltage space vectors are large vectors, 30 vectors are medium and the last 30 vectors are small vectors (Figure.7). It should be noted that three vectors are zero voltage space vectors. These 93 vectors consist of configuration which connects 4 of the output phases to one of the input phases and the fifth phase of output side is connected to another input phase (medium vectors). The other configuration of stationary vectors group connects 3 of the output phases to one of the input phases and the 2 other output phases to another input phase (Large and small vectors). If all of output phases are connected to a same input phase, zero voltage vectors will be produced. As it has been mentioned in previous sections, using medium and small vectors in $D-Q$ plane, leads to large harmonics in stator current. Thus, in this paper authors only will use large voltage vectors of $D-Q$ subspace.

The space vector of output voltages can be expressed as follow

$$\overline{V_0} = \frac{2}{5}(V_A + V_B e^{j\frac{2\pi}{5}} + V_C e^{j\frac{4\pi}{5}} + V_D e^{-j\frac{4\pi}{5}} + V_E e^{-j\frac{2\pi}{5}}) \tag{16}$$

Where, V_A, V_B, V_E, V_D and V_E are output line-to-neutral voltage vectors of five phase A, B, C, D and E, respectively.

In the same way, the space vector of input currents can be expressed as follow

$$\overline{I_i} = \frac{2}{3}(i_a + i_b e^{j\frac{2\pi}{3}} + i_c e^{j-\frac{2\pi}{3}}) \tag{17}$$

Where, i_a, i_b and i_c are input line currents.

The switching states of a 3×5 MC are shown in table 2. It should be noted that, only the large vectors of MC are shown in this table. The medium and small voltage space vectors are shown in tables A and B,in appendix which are not used in this paper.

Output line-to-neutral voltage space vector configurations and also input line current vector configurations are illustrated in Figure7 and Figure 8, respectively.

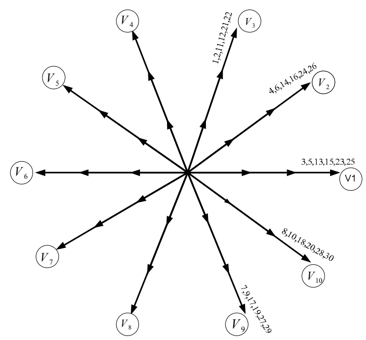


Figure 7: Output line-to-neutral voltage vector configurations (large vectors)

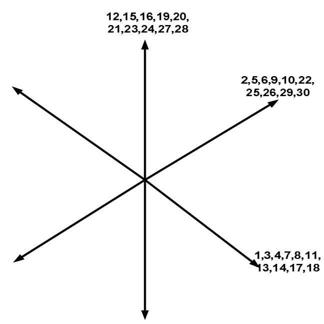


Figure 8: Input line current vector configurations (large vectors)

Table 2: Switching states for 3-phase to 5-phase matrix converter (large vectors)

State	A	B	C	D	E	|Vo|	α_o
1	a	a	a	b	b	0.647|Vab|	72°
2	a	a	a	c	c	0.647|Vac|	72°
3	a	a	b	b	a	0.647|Vab|	0°
4	a	a	b	b	b	0.647|Vab|	36°
5	a	a	c	c	a	0.647|Vac|	0°
6	a	a	c	c	c	0.647|Vac|	36°
7	a	b	b	a	a	0.647|Vab|	-72°
8	a	b	b	b	a	0.647|Vab|	-36°
9	a	c	c	a	a	0.647|Vac|	-72°
10	a	c	c	c	a	0.647|Vac|	-36°
11	b	b	b	a	a	0.647|Vba|	72°
12	b	b	b	c	c	0.647|Vbc|	72°
13	b	b	a	a	b	0.647|Vba|	0°
14	b	b	a	a	a	0.647|Vba|	36°
15	b	b	c	c	b	0.647|Vbc|	0°
16	b	b	c	c	c	0.647|Vbc|	36°
17	b	a	a	b	b	0.647|Vba|	-72°
18	b	a	a	a	b	0.647|Vba|	-36°
19	b	c	c	b	b	0.647|Vbc|	-72°
20	b	c	c	c	b	0.647|Vbc|	-36°
21	c	c	c	b	b	0.647|Vcb|	72°
22	c	c	c	a	a	0.647|Vca|	72°
23	c	c	b	b	c	0.647|Vcb|	0°
24	c	c	b	b	b	0.647|Vcb|	36°
25	c	c	a	a	c	0.647|Vca|	0°
26	c	c	a	a	a	0.647|Vca|	36°
27	c	b	b	c	c	0.647|Vcb|	-72°
28	c	b	b	b	c	0.647|Vcb|	-36°
29	c	a	a	c	c	0.647|Vca|	-72°
30	c	a	a	a	c	0.647|Vca|	-36°

4.2 Proposed DTC using Three-phase to Five-phase Matrix Converter

Matrix converter generates higher number of output voltage space vectors than conventional voltage source inverters. Thus, there are degrees of freedom, i.e., in a conventional DTC scheme, there is only one voltage vector to be chosen for a certain sector of stator flux and outputs of the two hysteresis torque and flux comparators, but in a DTC method using matrix converter, there are two voltage vectors to be chosen which it will beexplained. Thus, in addition to torque and flux control, a third variable can be controlled. Controlling the average value of the sine of the displacement angle (ψ) between input line-to-neutral voltage vector and corresponding input line current, is chosen as third variable. By controlling this variable, unity input power factor will be achieved.

The active output voltage vectors of a 3×5 matrix converter are shown in Figure.7 which $V_1 - V_{10}$ show the MC vectors as the same direction as those vectors delivered by VSI. The magnitude of output voltages is related to input line-to-line voltages. It can be seen in Figure.9 that the input voltage is divided to six sectors starting at $-\pi / 6rad$.

As an example, we can assume that V_1 is the VSI output voltage vector in a conventional DTC. From Figure 7 and table 2, it appears that voltage vectors (3, 5, 13, 15, 23 and 25) must be chosen. As it is illustrated in Figure.9, in each sector there are six voltage vectors. The two small vectors cannot be used for DTC method because of their change of sign in the middle of sector. If the input line-to-neutral lies in sector 1, the switching configurations which can be utilized are 3 and 5. The reason of not choosing the four other vector is that, vectors 15 and 23, are related to the small line to line voltage vectors in sector 1 (V_{bc} or V_{cb}) and cannot be used. Vectors 13 and 25 are in the opposite direction of V_1 and therefore cannot be used. Vector 3 and 5 impose two input current vectors with different directions, as shown in Figure 8. Thus, this degree of freedom can be used for controlling the input power factor. If the average value of $\sin(\psi)$ needs to be decreased, voltage vector 5 should be chosen. On the contrary, if the average value of $\sin(\psi)$ has to be increased, voltage vector 3 has to be applied.

Based on aforementioned principle, a switching table is proposed which is shown in table.3. The first column is related to the output voltage vectors selected by the conventional DTC. The other 6 columns contain the sectors which the input line-to-neutral voltage vectors lie in. If the average value of $\sin(\psi)$ needs to be increased the right sub-column is chosen. On the contrary, if the average value of $\sin(\psi)$ needs to be decreased the left sub-column is chosen.

The block diagram of proposed DTC scheme is shown in Figure10. As it can be seen, the basis of this proposed DTC algorithm is as same as classical DTC. But, in each sampling period, in addition to measuring stator voltage and currents, voltage and currents of input side of MC should be measured to specify the sector that input line-to-neutral voltage vector lies in. Also, the current and voltage angle difference is measured and is sent to controller. Controller imposes this displacement angle to be close to zero. Thus, a close to unity input power factor will be obtained.

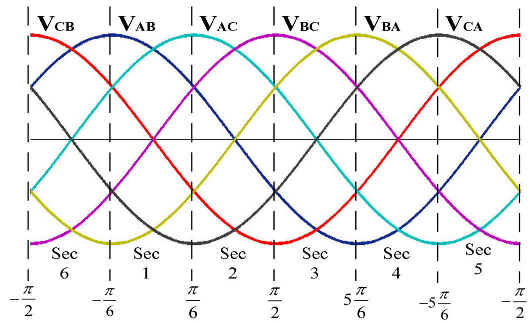


Figure 9: Six sectors of input voltage vectors

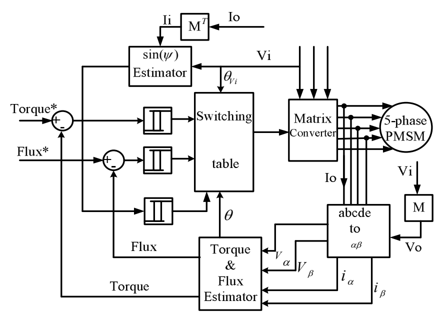


Figure 10: Schematic diagram of proposed DTC using matrix converter

Table 3: Switching Table

	Sec 1		Sec 2		Sec 3		Sec 4		Sec 5		Sec 6	
	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
V1	5	3	15	5	13	15	25	13	23	25	3	23
V2	6	4	16	6	14	16	26	14	24	26	4	24
V3	2	1	12	2	11	12	22	11	21	22	1	21
V4	29	17	27	29	7	27	9	7	19	9	17	19
V5	30	18	28	30	8	28	10	8	20	10	18	20
V6	25	13	23	25	3	23	5	3	15	5	13	15
V7	26	14	24	26	4	24	6	4	16	6	14	16
V8	22	11	21	22	1	21	2	1	12	2	11	12
V9	9	7	19	9	17	19	29	17	27	29	7	27
V10	10	8	20	10	18	20	30	18	28	30	8	28

5. SIMULATION RESULTS AND DISCUSSION

Simulation has been done using Matlab/Simulink to verify the effectiveness of proposed method. The parameters of motor are given in table.4. Simulation has been done in different situations without and with speed loops. Figure. 11 shows a case of open speed loop simulation that actual torque follows the command torque very well (Figure.11 (b)). Figure.11 (c) shows the electromagnetic torque waveform of classical DTC. As can be compared between figure 11(b) and 11(c), in the proposed DTC, electromagnetic torque follows its reference target as well as classical DTC. The average value of displacement angle of $\sin\varphi$ is shown in Figure.12. It can be observed that $\sin\varphi$ is controlled such a way that to be closed to zero. Therefore unity input power factor is achieved. Triangular speed command is implemented to proposed drive in no load situation which is illustrated in Figure.13. As can be seen in this figure, motor speed tracks its reference very well. Figure.14 and Figure.15 show the characteristics of electromagnetic torque, stator flux and stator current for classic DTC and proposed DTC respectively and both in rotor speed of 600 rpm. As it is shown in these figure, in proposed method electromagnetic torque and stator flux follow their references as well as that of classical method. Electromagnetic torque reference is produced using PI controller in speed loop and stator flux reference is set to be equal to rotor permanent magnet flux magnitude which is 0.5 Wb. As it was described in previous sections, stator current is distorted because of large magnitude of third harmonic currents. This distortion would be more if small and medium vectors of output voltage space vectors are implemented to motor. Filtered input line current and its corresponding line-to-neutral voltage are shown in Figure.16. As it can be shown, input voltage and input current are in phase as it is expected and therefore unity input power factor is achieved.

In the last part of simulation, step change load is applied to motor and effectiveness of proposed method to achieve close to unity power factor is investigated. As can be seen in Figure.17, load torque changes from 8 N.m to -8 N.m at Sec. 0.6 and from -8 N.m to 8 N.m at Sec. 0.9. Figure. 17(d) shows filtered input line current and the corresponding line-to-neutral voltage. In Figure.17 (e), the filtered input line current of phase-a, and its corresponding line-to-neutral voltage is shown from Sec. 0.4 to Sec. 0.55. As can be seen, current and its corresponding voltage are in phase. It can be seen in Figure 17 (f) that, input current is in phase with its voltage from Sec. 0.55to Sec. 0.6. From Sec. 0.6 to Sec. 0.85, input current is in opposite phase with its corresponding voltage, because of regenerative mode of motor in this period of time. Finally, in Figure 17 (g), it is shown that input current back to in phase mode with it voltage in Sec. 0.9.

Table 4: Five-phase permanent magnet synchronous motor parameters

P	Ld	Lq	Rs	J	B	ψ_f
4	18mh	42mH	0.7 Ω	0.025	0.005	0.5 (Wb)

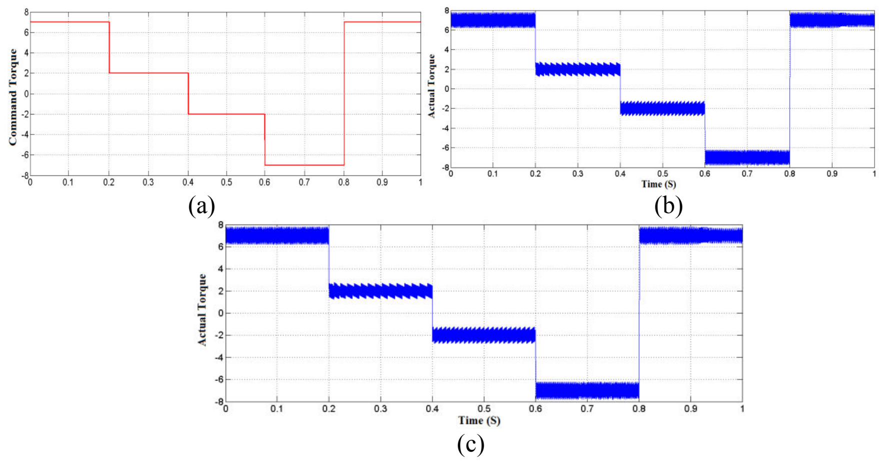


Figure 11: From top to bottom: (a) command torque, (b) actual torque for proposed DTC, (c) actual torque for classical DTC

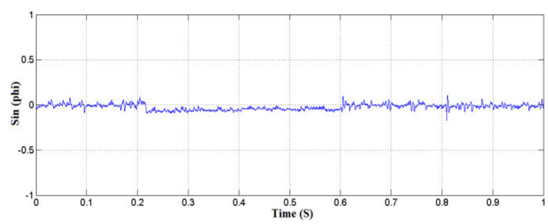


Figure 12: Power factor control capability, ($\sin\varphi = 0$)

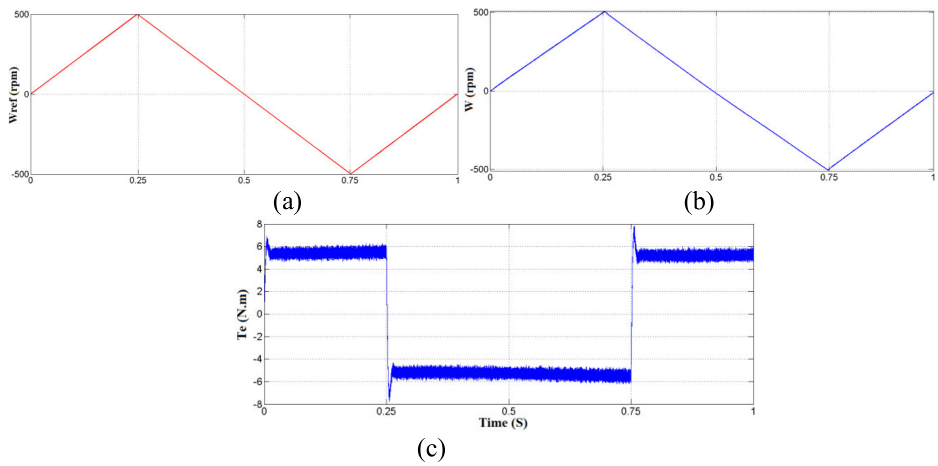


Figure 13: (a) command speed, (b) actual speed, (c) electromagnetic torque under no load condition

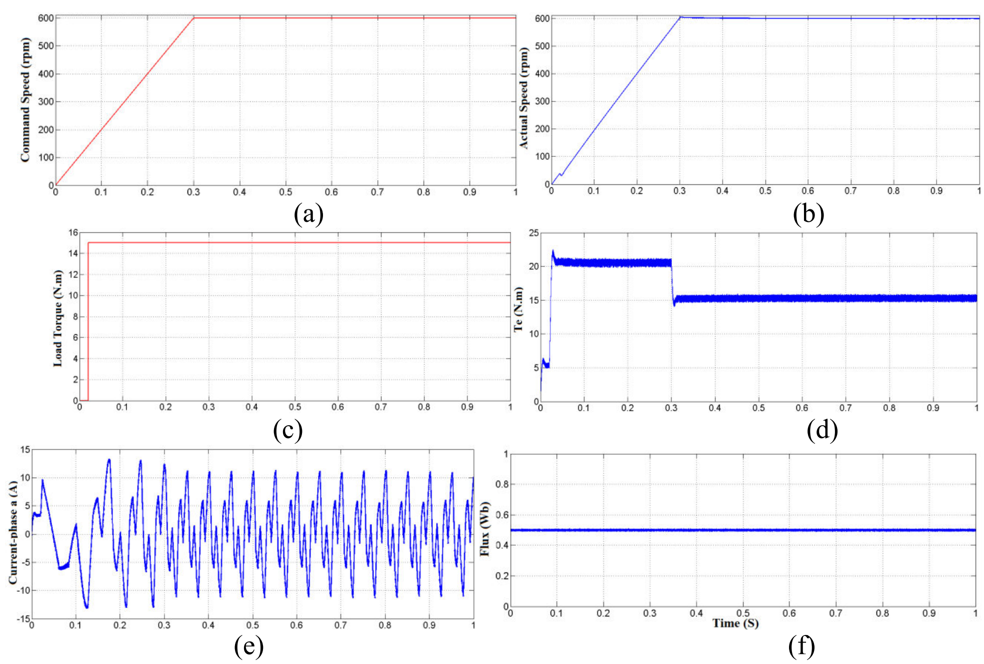


Figure14: Simulation of classical DTC, (a) command speed, (b) actual speed, (c) load torque, (d) electromagnetic torque, (e) stator current (phase-a), (f) stator flux

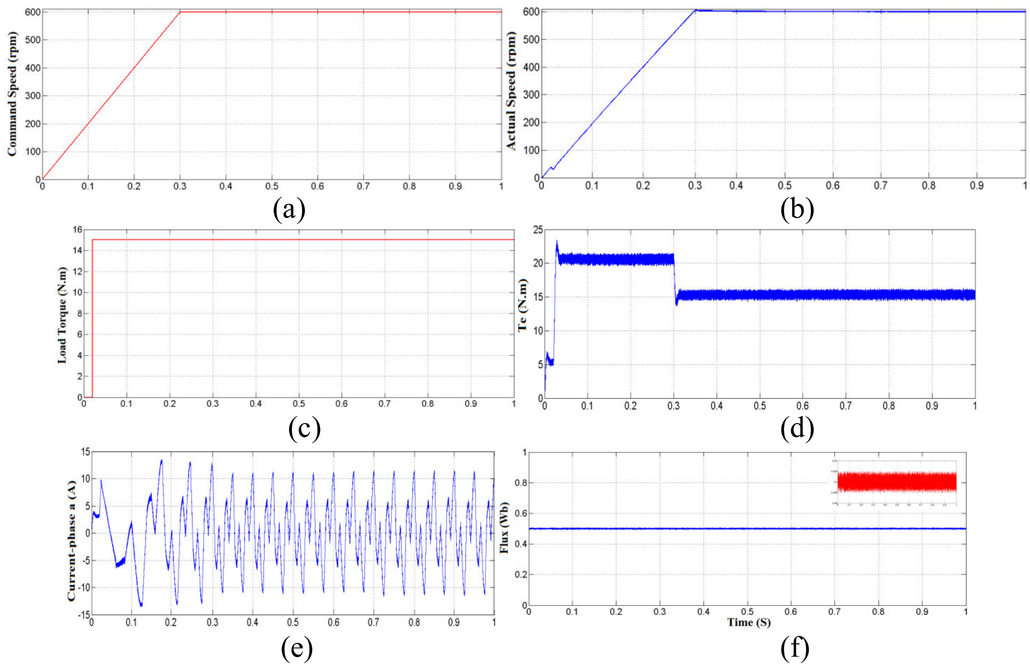


Figure 15: Simulation of proposed DTC, (a) command speed, (b) actual speed, (c) load torque, (d) electromagnetic torque, (e) stator current (phase-a), (f) stator flux

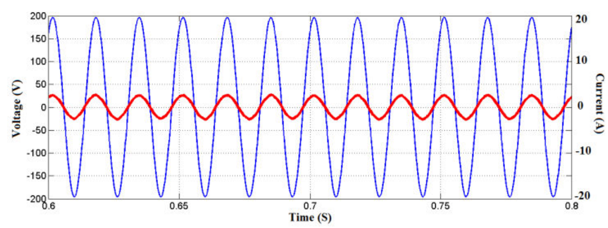


Figure 16: Filtered input line current and its corresponding voltage (phase-a)

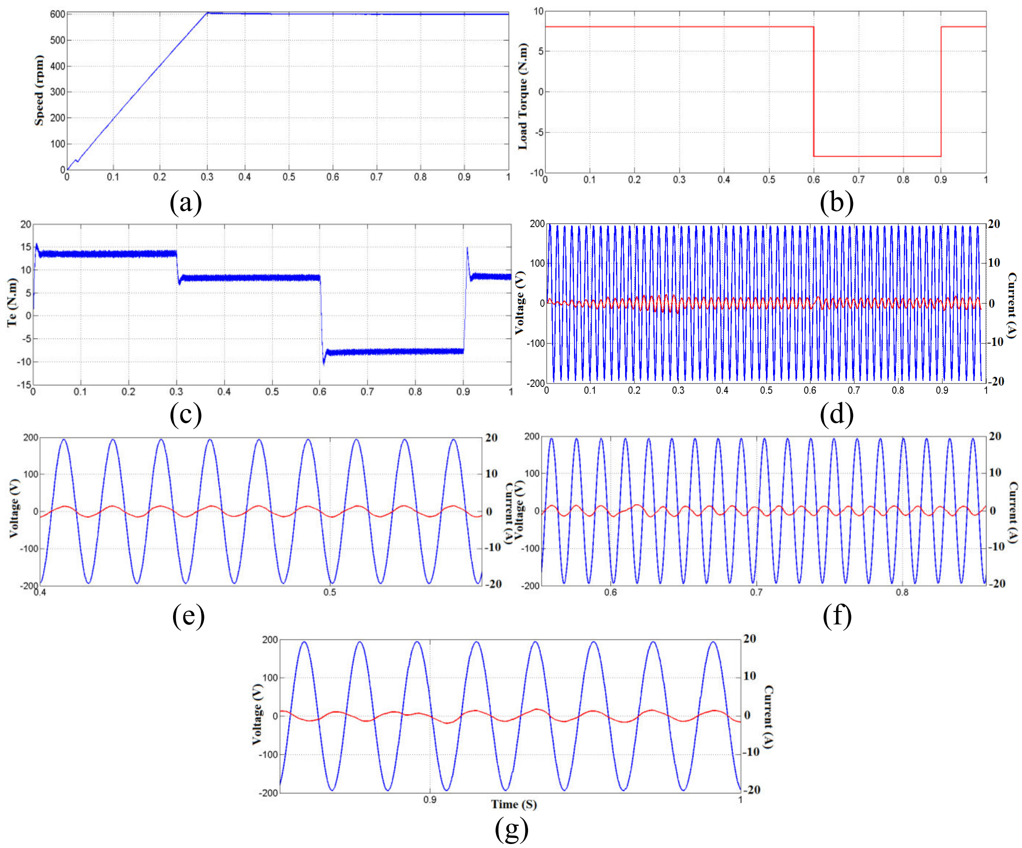


Figure 17: Simulation of proposed DTC, (a) actual speed, (b) load torque, (c) electromagnetic torque, (d) filtered input line current and its corresponding voltage (phase-a), (e) filtered input line current from Sec. 0.4 to 0.55, (f) filtered input line current from Sec. 0.55 to 0.85, (g) filtered input line current from Sec. 0.85 to 1

6. CONCLUSION

A new DTC algorithm has been proposed for matrix converter fed five-phase PMSMs. All of output voltage space vectors of a three-to-five phase MC have been extracted. It has been shown that, there are 93 output voltage vectors with fixes directions which can be use in DTC method. Moreover the torque and flux control, the input power factor has been controlled and kept close to unit. The presented method has been simulated in different operation mode, such as open speed loop, steady state situation, and dynamic performance. In all of situation, torque and flux followed their reference values as well as VSI-fed (classic) drives and beside of this, unity input power factor has been achieved.

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