Comparative Study of Space Vector Controlled Three Phase-Six Phase Direct and Indirect Matrix Converter for Six Phase Induction Motor Drive

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Abstract

This literature gives a comparative study of multiphase (six phase) matrix converter (Direct and Indirect) feeding power to six-phase symmetrical induction motor. These converters are modulated by Space Vector Modulation technique with different modulation index 0.6 and 0.8 and behavior of six phase symmetrical induction motor is analyzed. Six-phase Induction Motor is modelled and both the converters are analyzed in MATLAB/Simulink environment. The separate simulation results of direct and indirect matrix converter fed induction motor is presented consists of output line voltage, phase voltage, speed, torque.

Keywords

Introduction

In the industrial applications, multiphase drives have been receiving increased attention due to their several advantages over the traditional three-phase induction machines such as reduced per phase currents, torque pulsation at a higher frequency, the possibility of controlling more than one motors when supplied by one multiple converter, higher reliability. Because of this features multiphase motor drives use for high power and medium voltage drive applications [1]. Six phase motor drives as the multiphase motor drive considered as a viable solution because they are the multiple of the existing three-phase numbers. Six-phase induction motor can be configured as symmetrical and asymmetrical motors. Symmetrical six-phase motor consists of six windings with 60^0 phase displacement. In asymmetrical type, two sets of balanced three-phase windings are displaced by 30^0 with isolated neutral point [2].

In earlier days, back-to-back converter that is three-phase rectifier and multiphase inverter was used to drive asynchronous machines with a bulky interlinked energy storage element in between. These is the main limitation of back-to-back converters because the weight of the energy storage element is almost 30% of the converter. Therefore, in recent days multiphase matrix converter are used which can convert the constant ac input voltage and constant input frequency into variable ac output voltage and variable frequency [3]. Matrix converter comes up with the drawback of back-to-back, features of matrix converters are i) Bidirectional power flow ii) capacitor free power exchange iii) sinusoidal source current iv) controllable input power factor [4]. Apart from advantages, Matrix converter has some limitations also, such as number of switches are more therefore multistep commutation is required also as there is no dc link capacitor there may be distortion at output voltage hence filter is required between input source and converter [5].

Mainly MC is categorized into two types i) direct matrix converter (DMC) and ii) indirect matrix converter (IMC). DMC works on the principle of single stage conversion while IMC works on the principle of dual-stage AC-AC conversion without associating interlinked storing element [6].

There are different control techniques to implement the matrix converter such as Pulse Width Modulation (PWM), Sinusoidal Pulse Width Modulation, Space Vector Pulse Width Modulation (SVPWM), Space Vector Modulation (SVM), Venturini method, Scalar method (Roy), Carrier-based PWM. A powerful and very elegant method nowadays using is SVM method [7]. SVM is of two types i) Direct SVM and ii) Indirect SVM, Direct SVM is difficult to implement and not flexible. On the other hand, advantage of indirect SVM is that input line current and output phase voltage of matrix converter can control independently [8] and gives maximum output voltage 0.776 without injecting third harmonic component, therefore in this paper indirect SVM (Space Vector Modulation), control technique is used to control the matrix converter [9]. Simulation is done using MATLAB/Simulink software package to compare the performance of three-six phase DMC and three-six phase IMC fed six-phase symmetrical motor, for this simulation, parameters has kept constant.

The paper structure is as follows: II presents the modelling of six-phase DMC, section III presents the modelling of six-phase IMC, SVM technique is presented in section IV, section V presents the mapping of pulses to get the

pulses for DMC and IMC. Finally, section VI gives the simulation results for both DMC, IMC fed IM, and section VII gives conclusion.

Materials & Methods
Direct Matrix Converter

For three-to-six phase DMC each input phase source is directly connected to the each output phase load terminals through the switch, hence it can be say that DMC works on the principal of direct ac-ac conversion. A three-six DMC fed six-phase induction motor is shown in Fig. 1. The output phase voltages are given as,

$$
\begin{bmatrix} Va \\ Vb \\ Vc \\ Vd \\ Ve \\ Vf \end{bmatrix} = \begin{bmatrix} SAa & SBa & SCa \\ SAb & SBb & SCb \\ SAc & SBc & SCc \\ SAd & SBd & SCd \\ SAe & SBe & SCe \\ SAf & SBf & SCf \end{bmatrix} \begin{bmatrix} VA \\ VB \\ VC \end{bmatrix}
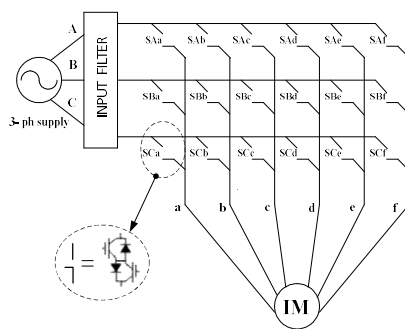$$

Fig 1: Diagram of Three-to-Six Phase Direct Matrix Converter

$V_o = T \times V_i$ (1)

Where V_o is the output phase voltage and V_i is the input phase voltage. T is the switching transfer function. The input current is given as,

$$
\begin{bmatrix} IA \\ IB \\ IC \end{bmatrix} = \begin{bmatrix} SAa & SBa & SCa \\ SAb & SBb & SCb \\ SAc & SBc & SCc \\ SAd & SBd & SCd \\ SAe & SBe & SCe \\ SAf & SBf & SCf \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \\ Id \\ Ie \\ If \end{bmatrix}
$$

Where I_i is the input phase current and I_o is the output phase current. The switching function can be derived as

$I_i = T \times I_o$ (2)

Sij = 1, Switch ON

= 0, Switch OFF (3)

Where i = (A, B, C) and j = (a, b, c)

Indirect Matrix Converter

The three-to-six phase indirect matrix converter is designed by cascading a 3-ph rectifier with a 6-ph inverter without associating dc link capacitor; hence, it can be say that IMC works on the principal of virtual ac-dc-ac conversion. Three-to-six IMC is shown in fig 2.
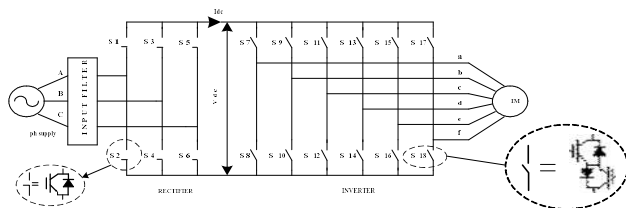
Fig 2: Diagram of Three-to-Six Phase Indirect Matrix Converter

Space Vector Modulation Technique

SVM divides the DMC indirectly into two stages, one is virtual rectifier and other is virtual inverter. SVM provides the independent control of output phase voltage and input line current therefore; switches of DMC can be control by applying the SVM on virtual rectifier and SVM on virtual inverter.

A. SVM on three-phase rectifier side

There are nine switching states of three phase rectifier out of which six are active input current vectors (I_1-I_6) and three are zero vectors (AA,BB,CC).Space vector diagram of rectifier is given in Fig 3. which is obtained by the equation (4).

$$I_i = \frac{2}{3}(I_A + kI_B + k^2 I_C) \tag{4}$$

Where, $k = e^{\frac{i2}{3}}$

For vectorI_1, switching state is AB it means that for a phase upper switch is ON and lower switch is OFF. For B phase upper switch is OFF and lower switch is ON. C phase it may both upper and lower be either ON or OFF. There are six sectors from 1-6, and each sector is spanned for 60^0. Sector 1 is lies between -30^0 to30^0. From I_1 to I_2 only one phase should change its direction similarly for other vectors also.

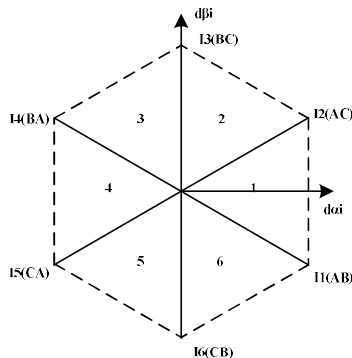Duty ratio of the current vectors are given in equations (5)-(7)

Fig 3: Current Space Vectors of Rectifier Side

$$d_{\alpha i} = m_i \cdot \sin(\pi/3 - \theta i) \tag{5}$$
$$d_{\beta i} = m_i \cdot \sin(\theta i) \tag{6}$$
$$d_{0i} = 1 - d_{\alpha i} - d_{\beta i} \tag{7}$$

Where m_i is the modulation index of rectifier stage, which is given by,

$$0 \le m_i = I_i/I_{dc} \le 1 \tag{8}$$

B. SVM on Six Phase Inverter Side

For six phase inverter there are $2^6 = 64$ output voltage vectors from which 54 are active vectors and 10 are zero vectors. These active vectors form 12 sectors with each spanning $30^0$and placed in x-y, d-q, 0^+- 0^-plane obtained by the equations (9)-(11) [10].

$$V_{dq} = \frac{2}{6}(V_a + aV_b + a^2 V_c + a^3 V_d + a^4 V_e + a^5 V_f) \tag{9}$$

$$V_{xy} = \frac{2}{6}(V_a + a^2 V_b + a^4 V_c + V_d + a^2 V_e + a^4 V_f) \tag{10}$$

$$V_{0^+ - 0^-} = \frac{2}{3}(V_a \pm V_b \pm V_c \pm V_d \pm V_e \pm V_f) \tag{11}$$

Where, $a = e^{-j\frac{\pi}{3}}$

To reduce the THD at the output voltage x-y components should be eliminated by selecting the proper vectors and dwell time hence considering only d-q components. Further 64-output voltage vectors are classified into large, medium and short vectors dependent on the length of the vectors which are given by the equations (12)-(15)

$$V_1\text{-}V_6 = \sqrt{\frac{2}{6}}\,V_{dc}\,2\exp\left(j\,(k\text{-}1)\frac{\pi}{3}\right) \quad k=1,\,2\ldots 6 \tag{12}$$

$$V_8,\,V_{15}\text{-}V_{22},\,V_{41}\text{-}V_{43},\,V_{56}\text{-}V_{58}=0 \tag{13}$$

$$V_9\text{-}V_{14},\,V_{16}\text{-}V_{21},\,V_{23}\text{-}V_{40},\,V_{50}\text{-}V_{55},\,V_{15}\text{-}V_{22},\,V_{15}\text{-}V_{22}=\sqrt{\frac{2}{6}}\,V_{dc}\exp\left(j\,(k\text{-}1)\frac{\pi}{3}\right) \quad k=1,\,2\ldots 6 \tag{14}$$

$$V_{44}\text{-}V_{49}\ \&\ V_{59}\text{-}V_{64}=\sqrt{\frac{2}{6}}\,V_{dc}\sqrt{3}\exp\left(j\,(2k\text{-}1)\frac{\pi}{6}\right) \quad k=1,\,2\ldots 6 \tag{15}$$

Where, equation (12) are large vectors, equation (13) are zero vectors, equation (14) are short vectors and equation (15) are medium vectors. That is 6 long vectors, 36 short vectors, 12 medium vectors and 10 zero vectors. The magnitude ratio of long, short and medium vectors are $2:1:\sqrt{3}$. Using above equations V_{xy}, V_{dq} and V_{0+-0-} drawn shown in Fig. 4 and Fig. 5.
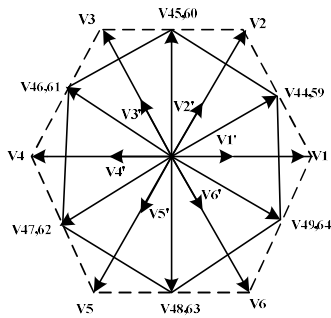
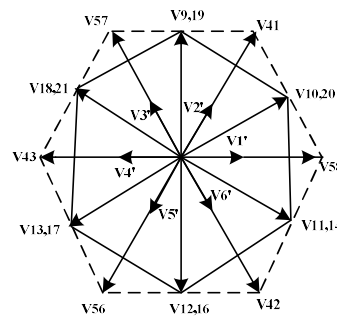

Fig 4: Voltage Space Vector for Inverter in d-q Frame

Fig 5: Voltage Space Vector for Inverter in x-y Frame

i) d-q
V1'=vectors - 9, 16, 23, 29, 35, 50   V2'= vectors-10, 17, 24, 30, 36, 51   V3'= vectors-11, 18, 25, 31, 37, 52
V4'=vectors -12, 19, 26, 32, 38, 53   V5'= vectors-13, 20, 27, 33, 39, 54   V6'= vectors-14, 21, 28, 34, 40, 55
ii) x-y
V1'= vectors-29, 32, 35, 38, 45, 48   V2'= vectors-25, 28, 52, 55, 59, 62   V3'= vectors-30, 33, 36, 39, 46, 49
V4'= vectors-23, 26, 50, 53, 60, 63   V5'= vectors-31, 34, 37, 40, 44, 47   V6'= vectors-24, 27, 51, 54, 61, 64
Vectors-1, 2, 3, 4, 5, 6, 7, 8, 15, 22 are zero vectors for x-y component
Dwell time for large, medium and short vectors are given in equations (16)-(19)

$$t_l=\alpha\frac{V_{m\beta}V_\alpha-V_{m\alpha}V_\beta}{V_{l\alpha}V_{m\beta}-V_{l\beta}V_{m\alpha}}\,t_s \tag{16}$$

$$t_{sh}=2(1\text{-}\alpha)\frac{V_{m\beta}V_\alpha-V_{m\alpha}V_\beta}{V_{l\alpha}V_{m\beta}-V_{l\beta}V_{m\alpha}}\,t_s \tag{17}$$

$$t_m=\alpha\frac{V_{l\alpha}V_\beta-V_{l\beta}V_\alpha}{V_{l\alpha}V_{m\beta}-V_{l\beta}V_{m\alpha}}\,t_s \tag{18}$$

$$t_0=t_s-t_l-t_m-t_{sh} \tag{19}$$

Where, $\alpha=\dfrac{t_l}{t_l+t_{sh}/2}$ generally taken as $\alpha=\dfrac{2}{3}$

$$V_l=V_{l\alpha}+jV_{l\beta} \tag{20}$$
$$V_m=V_{m\alpha}+jV_{m\beta} \tag{21}$$
$$V_{sh}=\frac{V_l}{2} \tag{22}$$
$$V_{ref}t_s=V_lt_l+V_mt_m+V_{sh}t_{sh}+V_0t_0 \tag{23}$$

Where, t_l is the dwell time for large vector , t_m is dwell time for medium vector, t_{sh} is dwell time for short vector, t_s switching period for one cycle, t_0 is dwell time for zero vector.
Now for all the sectors switching sequence selected as

$$V_0\text{-}V_{sh}\text{-}V_m\text{-}V_l\text{-}V_m\text{-}V_{sh}\text{-}V_0\text{-}V_{sh}\text{-}V_m\text{-}V_l\text{-}V_m\text{-}V_{sh}\text{-}V_0$$

For sector one switching sequence will be given as considering one large vector, two medium vectors and two short vectors

7, 29, 64, 1, 49, 23, 8, 23, 49, 1, 64, 29, 7

Mapping
In DMC pulses can be obtained by mapping pulses of rectifier and inverter by following matrix and by AND-OR logic

$$
\begin{bmatrix}
SAa & SBa & SCa \\
SAb & SBb & SCb \\
SAc & SBc & SCc \\
SAd & SBd & SCd \\
SAe & SBe & SCe \\
SAf & SBf & SCf
\end{bmatrix}
=
\begin{bmatrix}
S7 & S8 \\
S9 & S10 \\
S11 & S12 \\
S13 & S14 \\
S15 & S16 \\
S17 & S18
\end{bmatrix}
\begin{bmatrix}
S1 & S3 & S5 \\
S2 & S4 & S6
\end{bmatrix}
$$

Result & Discussion
Parameters used for simulation purpose is listed in TABLE 1. In Fig 7. and Fig 8. (a) shows phase voltage (b) line voltage (c) speed and (d) torque with respect to time for modulation index 0.6 and 0.8 for direct matrix converter. Similarly Fig 9. and Fig. 10 shows same sequence of results for indirect matrix converter.

Input supply	Vrms=220V, 50 Hz
Input filter	L=125mH C=75uF
Load parameters	220 V, 3 HP, 50Hz
Switching frequency	5 kHz

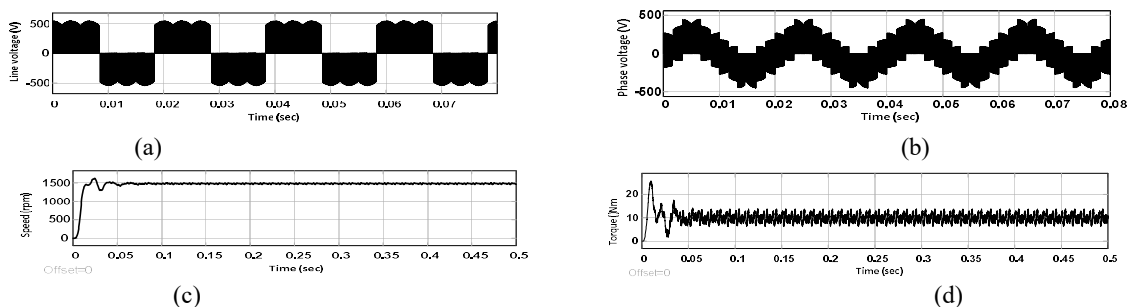**Table 1: Parameters for Simulation**

A. Simulation Results for DMC

(a)

(b)

(c)

(d)

Fig 7: Output of three-to=six phase DMC at MI=0.6 (a) Line Voltage (b) Phase Voltage (c) Speed (d) Torque

(a)

(b)

(c)

(d)

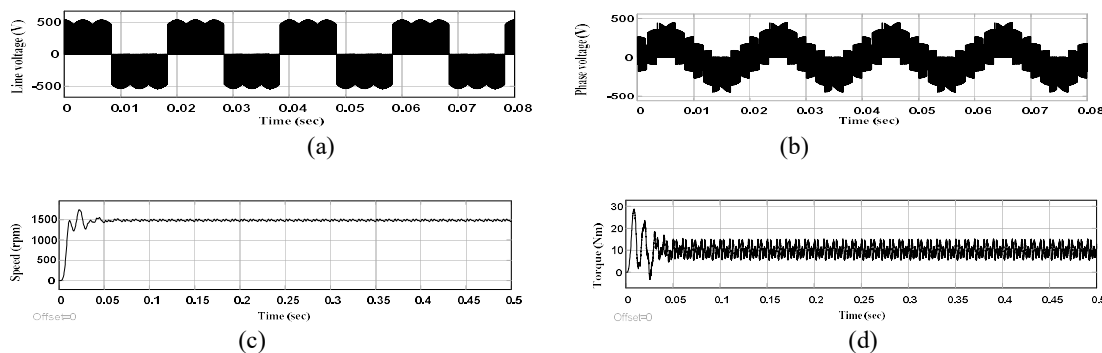**Fig 8: Output of three-to=six phase DMC at MI=0.8 (a) Line voltage (b) phase voltage (c) Speed (d) Torque**
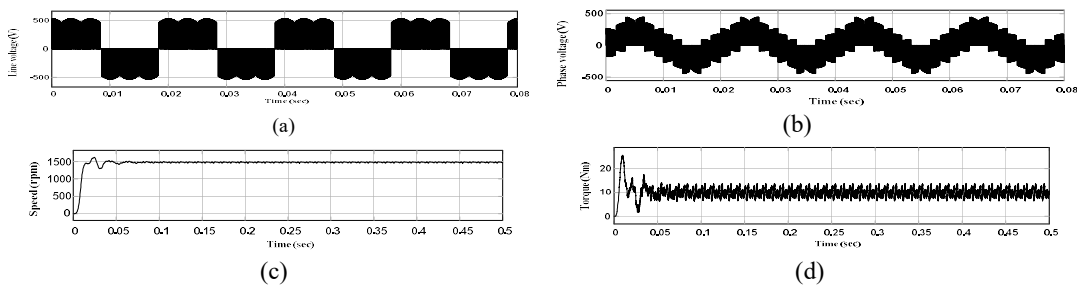
B. Simulation Results for IMC

(a)

(b)

(c)

(d)

Fig 9: Output of three-to=six phase IMC at MI=0.6 (a) Line Voltage (b) Phase Voltage (c) Speed (d) Torque
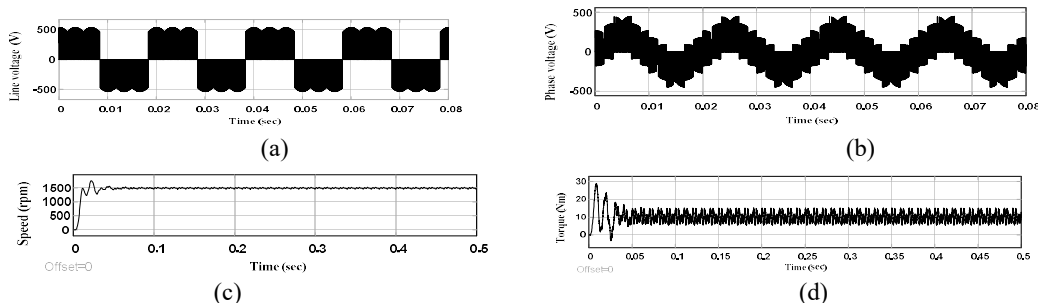

(a)

(b)

(c)

(d)

Fig 10: Output of three-to=six phase IMC at MI=0.8 (a) Line Voltage (b) Phase Voltage (c) Speed (d) Torque

Parameters	Three-to-six phase DMC		Three-to-six phase IMC	
Modulation Index	0.6	0.8	0.6	0.8
Phase voltage (rms)	114.3V,THD=121.9%	136.1V,THD=104.75%	114.3V,THD=122.05%	136.2V,THD=104.79%
Line voltage (rms)	198.2V,THD=115.42%	236.6V,THD=96%	198V, THD=113.81%	236.7V, THD=96.04%
Speed (rpm)	1500	1500	1500	1500
Torque (Nm)	10	10	10	10

Table 2: Simulation Results

Conclusion

Simulation analysis of both, three-to-six phase direct matrix converter and three-to-six phase indirect matrix converter fed to six-phase symmetrical induction motor are shown in above figures. Results are presented for modulation index 0.6 and 0.8. From the results, it is clear that quality of output phase voltages and line voltages are same for both the converters for respective modulation indexes therefore both the converters can used to feed induction motor. In addition, speed vs time and torque vs time characteristics are studied.

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