

A Comparative Study on Predictive and ISVM Direct Torque Control Methods for a Doubly Fed Induction Machine Fed by an Indirect Matrix Converter

M. Aghasi*, D. A. Khaburi*, V. Faraji* and H. Behnia*

Abstract: This paper presents a comparative study on the Predictive Direct Torque Control method and the Indirect Space Vector Modulation Direct Torque Control method for a Doubly-Fed Induction Machine (DFIM) which its rotor is fed by an Indirect Matrix Converter (IMC). In Conventional DTC technique, good transient and steady-state performances are achieved but it presents a non constant switching frequency behavior and non desirable torque ripples. However, in this paper by using the proposed methods, a fixed switching frequency is obtained. In this model Doubly-Fed Induction Machine is connected to the grid by the stator and the rotor is fed by an Indirect Matrix Converter. Functionally this converter is very similar to the Direct Matrix Converter, but it has separate line and load bridges. In the inverter stage, the Predictive method and ISVM method are employed. In the rectifier stage, in order to reduce losses caused by snubber circuits, the rectifier four-step commutation method is employed. A comparative study between the Predictive DTC and ISVM-DTC is performed by simulating these control systems in MATLAB/SIMULINK software environments and the obtained results are presented and verified.

Keywords: Direct Torque Control; Indirect Matrix Converter; Indirect Space Vector Modulation; Predictive DTC.

1 Introduction

Doubly-Fed Induction Machines (DFIMs) have windings in both stator and rotor and both windings are participating to power transfer between shaft and system. DFIMs have clear superiority for the applications of large capacity and limited-range speed control case due to the partially rated inverter, lower cost and high reliability. These characteristics have enabled the doubly-fed wound rotor induction machine to have vast applications in wind-driven generation [1, 2].

The Direct Torque Control (DTC) method has been introduced in the 1980s by I. Takahashi and T. Noguchi as an alternative to Field Orientated Control (FOC), with the twofold objective of simplifying the control algorithms and achieving similar or even better performances [3].

The DTC is commonly used with a Voltage Source Inverter (VSI), where electrolytic capacitor is used on the dc link of the AC/DC/AC converter in order to smooth the dc voltage and store the energy recovered from the machine during regeneration braking. Large electrolytic capacitors in dc link considerably increase the size and weight of converter and also decrease the longevity of the system [4].

In recent years researches on direct frequency conversion using Matrix Converters (MC) have become popular. Matrix converters have many desirable feature compared to the conventional voltage or current source inverter such as: no need to large energy storage components, compact size, longer lifetime, regeneration capability and unitary power factor for any load [4, 5].

There are two typical current commutation methods which do not require snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components. The first method is named rectifier zero current commutation and the second method is named rectifier four-step commutation [6]. Because of using rectifier four-step commutation method in the rectifier stage, this commutation process is firstly described in detail.

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In this paper, also a novel predictive DTC strategy for Doubly-Fed Induction Machine (DFIM) based on Indirect Matrix Converter is proposed which is characterized by a simple structure, minimal torque ripple and constant switching frequency.

The paper is organized as follows: in section II, a review of Predictive DTC for doubly-fed induction machines is presented; then, in section III, the Indirect Matrix Converter is introduced. The current commutation method for rectifier stage (rectifier four-step commutation) is explained in section IV. In section V, the Predictive DTC and ISVM DTC methods, where an IMC is used to supplying the DFIM, is modeled and explained. Simulation results for comparison between two methods are available in section VI. Finally, the conclusions are exposed in section VII.

2 Predictive Direct Torque Control for a DFIM

The block diagram of the Predictive Direct Torque Control is depicted in Fig. 1. In this strategy the directly controlled variables are the electromagnetic torque and rotor flux amplitude which are the same variables in the conventional DTC method. As it can be seen from Fig. 1, firstly by using the DFIM equations, the estimated values of torque, rotor flux and sector number of the rotor flux are calculated. The estimated torque and rotor flux magnitude are then compared with their respective desired values and then, the resulting errors are fed into two two-level hysteresis comparators. The outputs of both flux and torque comparators together with the sector number of rotor flux, are used as inputs of the active vector selection block.

Two voltage vectors are outputs of vector selection block. The first is active vector and in general, the second permitted vector will be a zero vector. Furthermore, in order to have a constant switching frequency in this Predictive DTC control technique, the switching period h is fixed constant ($h=1/f$).

At the beginning of each switching period, the control strategy calculates the optimum active vector, which is required to maintain torque and flux near the reference value and it can reduce their ripples. These active vectors are obtained by using a look up table method. The look-up table is made up according to Table 1. When the output of the comparator is set to 1, i.e. positive error, it means a positive slope variation is required. On the contrary, when the output is set to -1, i.e. negative error, a negative slope variation is needed. The portion of active vector in the sample period, with h_c is shown. The typical torque and flux waveforms, for this control strategy are represented in Fig. 2.

Considering the applied vector and the initial conditions at the current switching period, the slopes of the torque and flux variations can be calculated by using derived equations of torque and flux [7, 8]. At each sample period, the slope of torque is called S_1 if the active vector is applied, and is called S_2 if the zero

vector is applied. Similarly, S_{11} and S_{22} are the slopes of the flux for the active and the zero vectors.

During one sample period, the square of the square torque ripple is calculated as follows [7, 8]:

$$T_{em-ripple}^2 = \frac{1}{h} \int_0^{h_c} (s_1 \cdot t + T_{em}(k) - T_{em_ref})^2 \cdot dt + \frac{1}{h} \int_{h_c}^h (s_2 \cdot t - s_2 \cdot h_c + s_1 \cdot h_c + T_{em}(k) - T_{em_ref})^2 \cdot dt \quad (1)$$

By deriving from last expression respect to the active vector interval, h_c , and equaling it to zero, the minimum ripple torque is obtained.

$$\frac{dT_{em-ripple}^2}{dh_c} = 0 \quad (2)$$

By solving this equation, the optimal switching interval, h_c is obtained as:

$$h_c = \frac{2 \cdot (T_{em_ref} - T_{em}(k)) - s_2 \cdot h_c}{2 \cdot s_1 - s_2} \quad (3)$$

3 Indirect Matrix Converter

Indirect Matrix Converter as shown in Fig. 3, is an AC/DC/AC converter, but bulky DC link capacitor is eliminated in it and a filter in entrance is used instead. Also, bi-directional switches in rectifier-bridge are used instead of traditional unidirectional switches.

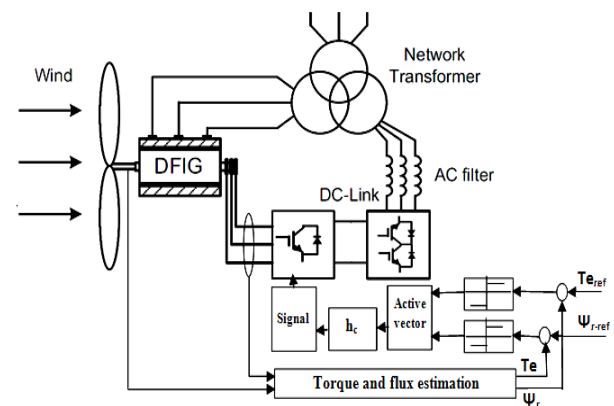


Fig. 1 Predictive DTC block diagram for DFIM.

Table 1 Predictive DTC Switching table

H_T		1		-1	
H_Φ		1	-1	1	-1
Rotor flux sector	1	6	5	2	3
	2	1	6	3	4
	3	2	1	4	5
	4	3	2	5	6
	5	4	3	6	1
	6	5	4	1	2

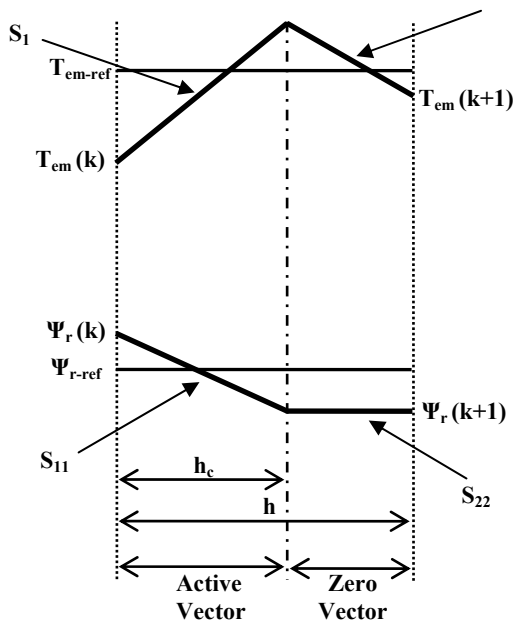


Fig. 2 Steady state Torque and Flux waveforms at motor and generator modes.

As it is clear from Fig. 3, the input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminals are connected to a three phase current-fed system, like an induction motor. Because it has converter configuration with two separated stages, therefore its topology is more flexible to modify. Also, Pulse width modulation algorithms of conventional inverters can be utilized in IMC with some modifications, which can greatly simplify its control circuit. Furthermore commutation problem of DMC are considerably reduced by using specific current commutation methods in IMC [4-6].

Regarding commutation strategies of IMC, two main rules should be taken into account:

- 1) In order to prevent short circuit in the converter input, the incoming and outgoing switches should not be switched on together at any point in time.
- 2) Also, in order to prevent the occurrence sudden overvoltages and switches damage, these switches should not be turned off simultaneously [6, 9].

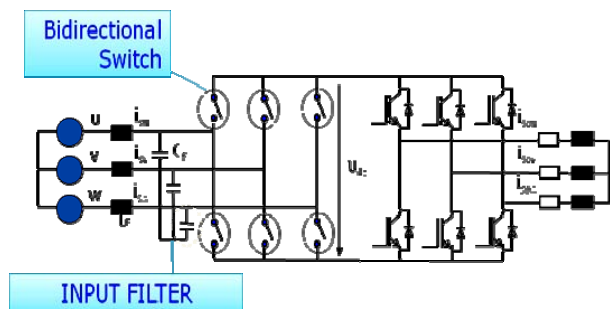


Fig 3 Indirect Matrix Converter.

To ensure the establishment of two condition at anytime, snubber circuits are used in rectifier bridge of IMC, but since the DC link part in IMC has no smoothing circuit such as electrolytic capacitors in conventional VSI, the load current must be diverted to the snubber circuits during the period switching dead-time in rectifier-bridge. On the other hand, the currents discharge of the snubber capacitor flows through the filter capacitors, therefore additional losses will be generated in converter. Furthermore these currents disturb to input current waveform [6].

Typically two types of commutations methods have been proposed which don't require snubber circuits for a PWM rectifier. The first method is named rectifier zero current commutation and the second method is named four-step commutation. Although the losses in snubber circuits can be reduced by these methods, but a complicated control circuit must be added to synchronize the switching of both the rectifier and the inverter [6].

4 Four-Step Commutation Strategy

As stated in the previous section, the commutation process of matrix converter is more complicated compared with traditional AC-DC-AC converter due to having no natural free-wheeling paths. This complex commutation is the main reason that matrix converter could not be widely entered in industrial application.

In the past decade, improved commutation methods were suggested by researchers, which made this topology becoming closer to the industrial application. One important method which firstly presented by Nandor Burani in 1989 is four-step commutation strategy. Since this time on wards new optimized methods based on this strategy were presented one after another that each had own unique set of its advantage and disadvantages. This commutation strategy to prevent short circuits and open circuits uses four steps. To execute this strategy exactly, it is necessary to obtain information about DC link current (i_{dc}) direction. In the other words, direction of output current and value of input voltage determine the switches sequence that use four-step commutation strategy and commutation reliability depending on accuracy in current output direction and two input-phase voltage differences [6].

The process of commutation is explained with Fig. 4 T_{AP} and T_{BP} are shown in Fig. 4. For example in this case the purpose is showing the switching between phase A and B phase A is connected to rectifier output through IGBT of switch S_{11} and diode of switch S_{12} At this point, as it is shown current does not pass from the other transistors and diodes. It has been supposed that commutation begins from phase A to phase B.

When $i_{dc} > 0$ the following four-step switching sequence is:

- 1) turn off S_{12} ; 2) turn on S_{31} ; 3) turn off S_{11} ; 4) turn on S_{32} .

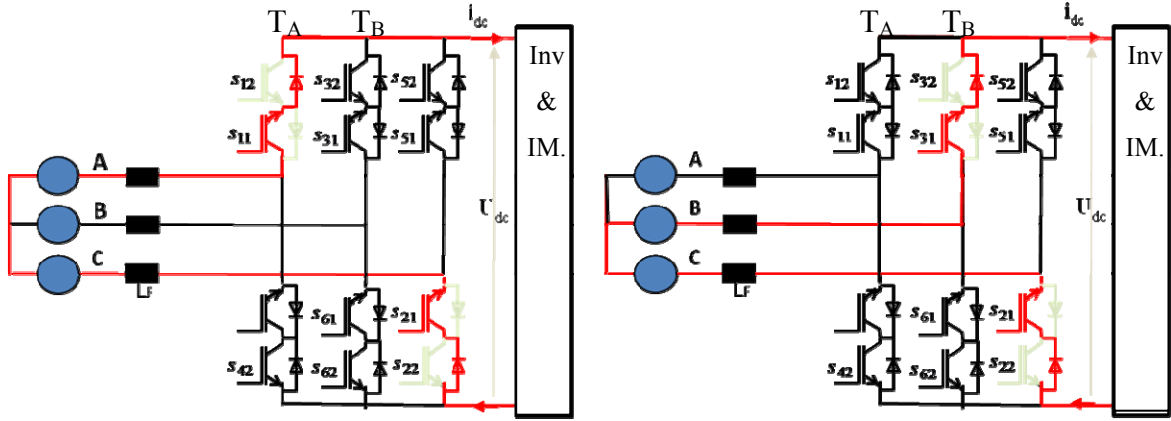


Fig. 4 Commutation from T_{AP} to T_{BP}

When $i_{dc} < 0$, the following four-step switching sequence is:

- 1) turn off S_{11} ; 2) turn on S_{32} ; 3) turn off S_{12} ; 4) turn on S_{31} .

5 Modeling ISVM DTC Based On IMC for DFIM

In this section the suggested model of Direct Torque Control based on Indirect Matrix Converter for doubly-fed induction machine is presented and analyzed. The Fig. 5 shows the related block diagram.

As it's shown, input voltages are sensed and along with torque and flux error and rotor flux sector are applied to control block. Input voltage and current direction in DC link are employed to determination mode of implementation of four-step commutation that explained in detail in last section. An indirect space vector modulation (ISVM) is often used for matrix converters, providing full control of both the output voltage vector and the instantaneous input current displacement angle. The proportion between the two adjacent vectors gives the direction and the zero-vector duty-cycle determines the magnitude of the reference vector.

5.1 Rectifier Stage

The input voltage can be calculated using the following definition:

$$V_i = \frac{2}{3}(v_a + av_b + a^2v_c) \quad (4)$$

Assuming that the displacement angle between the fundamental component of current and the input phase voltage is θ_i , therefore Phase current vector angle can be achieved by a fictitious vector I_x' as follows [9, 10]:

$$I_x' = i_x' + j i_y' \quad (5)$$

in which:

$$i_x' = v_x \cos \theta_i - v_y \sin \theta_i \quad (6)$$

$$i_y' = v_x \sin \theta_i + v_y \cos \theta_i$$

The direction of \bar{I}_i is given by:

$$\angle \bar{I}_i = \arctan \frac{i_y'}{i_x'} \quad (7)$$

Fig. 6 shows that there are six active current space vectors each of them is related to a certain switching configuration. As presented in Fig. 7 it is possible to obtain the input current vector by synthesize two adjacent fixed active vectors [10]:

$$I_i = d_\gamma i_\gamma + d_\delta i_\delta \quad (8)$$

where the relative duration of current vectors are:

$$d_\delta = \sin(60^\circ - \theta_i) \quad (9)$$

$$d_\gamma = \sin \theta_i$$

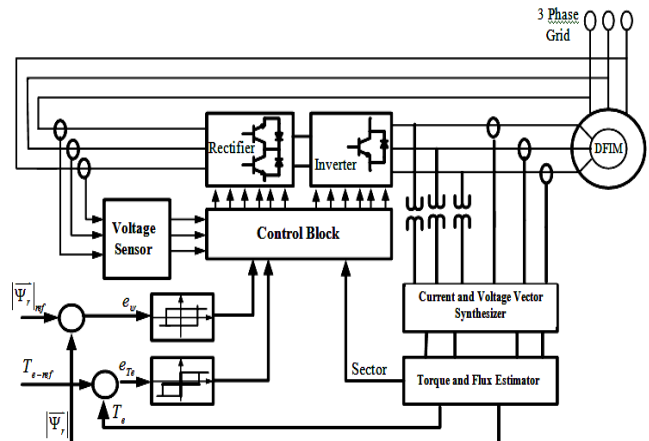


Fig. 5 Schematic diagram DTC based on IMC for DFIM

5.2 Inverter Stage

The space vector of IMC output line-to-line voltage V_{oL-L} may be defined [9]:

$$V_{oL-L} = \frac{2}{3}(v_{AB} + a v_{BC} + a^2 v_{CA}) \quad (10)$$

The output line-to-line voltage vector v_{oL-L} is synthesized by two adjacent fixed active vectors, as shown in Fig. 8.

$$V_{oL-L} = d_{\alpha} v_{\alpha} + d_{\beta} v_{\beta} \quad (11)$$

where the relative duration of voltage vectors are:

$$\begin{aligned} d_{\alpha} &= \sin(60^{\circ} - \theta_o) \\ d_{\beta} &= \sin \theta_o \\ d_0 &= 1 - d_{\alpha} - d_{\beta} \end{aligned} \quad (12)$$

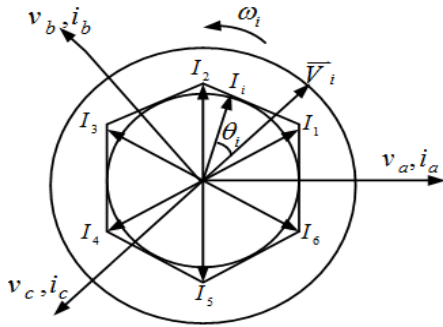


Fig. 6 Input voltage and current vectors

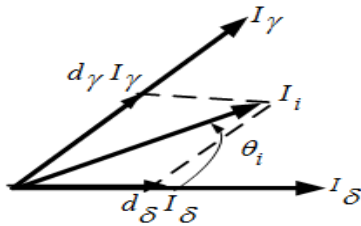


Fig. 7 Synthesis of input current vector

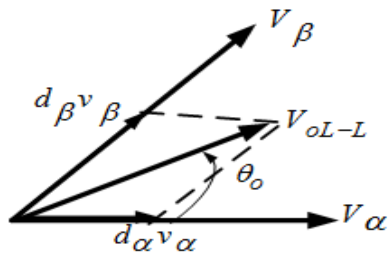


Fig. 8 Synthesis of output voltage vector

5.3 Two-Stage Matrix Converter

To balance the input currents and the output voltages properly in the same switching period, the modulation pattern should combine the rectification and inversion vectors uniformly, producing the following switching pattern: $\alpha \gamma - \alpha \delta - \beta \gamma - 0$. The combined duty-cycles of the rectification and inversion stages, using the previously presented switching pattern, are obtained as a cross product of their independent duty-cycles as shown in Eqs. (13) [9].

$$d_{\alpha\gamma} = d_{\alpha} d_{\gamma} = \sin(60^{\circ} - \theta_o) \sin(\theta_i) \quad (13a)$$

$$d_{\beta\gamma} = d_{\beta} d_{\gamma} = \sin(\theta_o) \sin(\theta_i) \quad (13b)$$

$$d_{\alpha\delta} = d_{\alpha} d_{\delta} = \sin(60^{\circ} - \theta_o) \sin(60^{\circ} - \theta_i) \quad (13c)$$

$$d_{\beta\delta} = d_{\beta} d_{\delta} = \sin(\theta_o) \sin(60^{\circ} - \theta_i) \quad (13d)$$

The zero-vector duty-cycle is determined as the complement of all active states combined. During the rest of the period all output phases are shorted and load voltage is zero, i.e. zero vector is taken:

$$d_0 = 1 - d_{\alpha\gamma} - d_{\alpha\delta} - d_{\beta\gamma} - d_{\beta\delta} \quad (14)$$

The switching pattern for an IMC is presented in Fig. 9. $d_{\beta(\delta+\gamma)}$ and $d_{0\gamma}$ that shown in Fig. 9 is given by [9]:

$$d_{\beta(\delta+\gamma)} = (d_{\delta} + d_{\gamma}) \cdot d_{\beta} \quad (15)$$

$$d_{0\gamma} = d_0 d_{\gamma} = d_{\gamma} \cdot (1 - (d_{\alpha} + d_{\beta})) \cdot (d_{\alpha} + d_{\beta}) \quad (16)$$

Rectifier stage commutation for predictive DTC and ISVM-DTC method is similar. Commutation differences occur in the inverter stage. In inverter stage, predictive DTC expressed method in section II is used. So, commutation pattern for predictive DTC is as follow [11].

6 Simulation Result

In order to validate the justness of the proposed control strategy, the developed control system, shown in Fig. 5, is implemented in MATLAB/SIMULINK. The machine parameters are provided by Matlab 7.8 as follows:

250 V stator line-line voltage, $P_N=15kW$, $f=50Hz$ the results of torque control for both predictive DTC and the ISVM method are presented in Fig.11. As it can be seen, the predictive method leads to less deviation from the set value of torque rather than the ISVM DTC.

Fig. 12 shows the flux response for these two methods. Fig. 13 shows the flux circular trajectory for both predictive DTC and the ISVM method. It is obvious that predictive method can improve steady and dynamic performance of the system and decrease unreasonable flux ripple. Fig. 14 shows rotor current

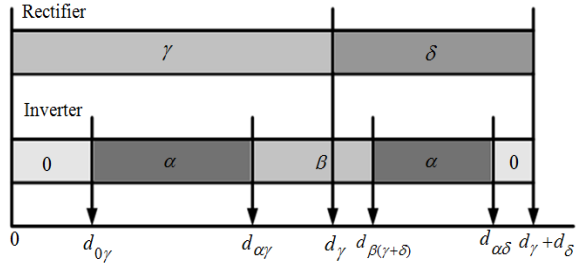


Fig. 9 Switching pattern for ISVM DTC

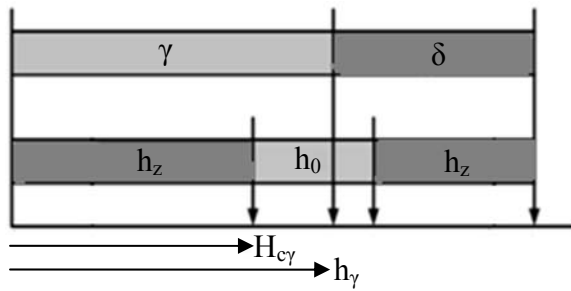


Fig. 10 Switching pattern for predictive DTC

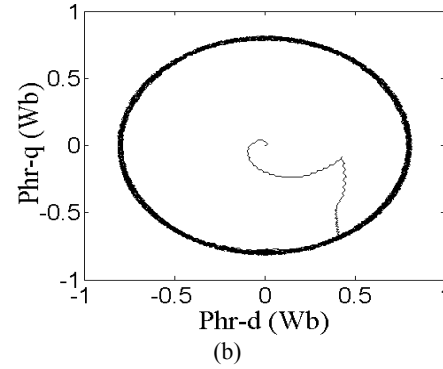
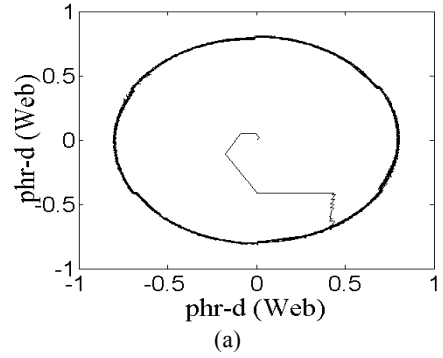


Fig. 13 Flux circular trajectory (a) predictive DTC (b) ISVM DTC

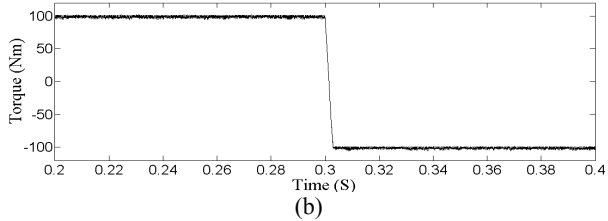
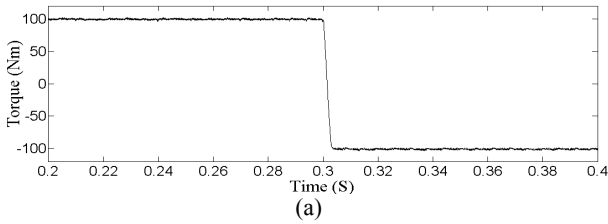


Fig. 11 Torque response: (a) predictive DTC (b) ISVM-DTC

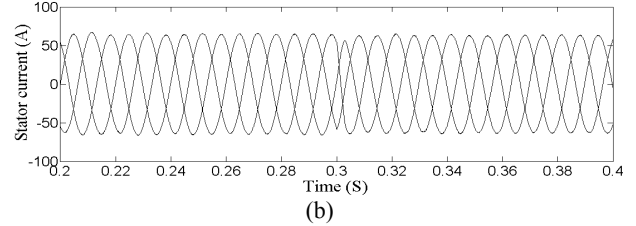
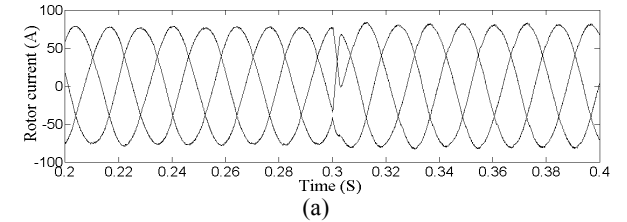


Fig. 14 Current waveform for predictive method (a) Rotor (b) Stator.

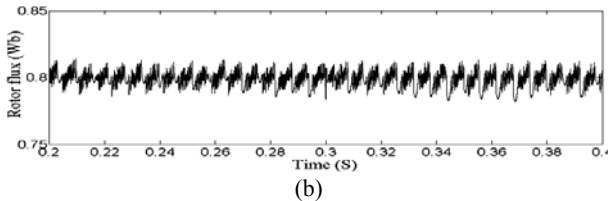
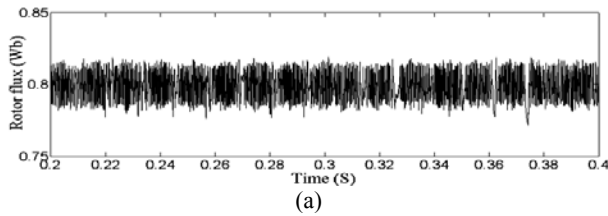


Fig. 12 Rotor flux response (a) predictive DTC (b) ISVM-DTC.

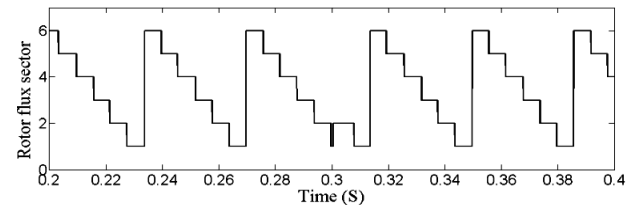


Fig. 15 Rotor flux sector.

and stator current respectively. Also, Fig. 15 and Fig. 16 shows rotor flux sector and DC link voltage of IMC respectively.

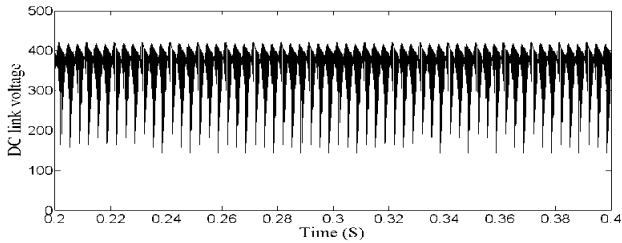


Fig. 16 DC link voltage of IMC.

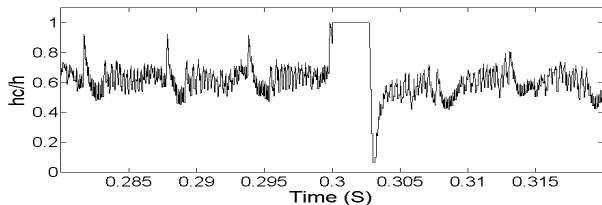


Fig. 17 Ratio of active vector to zero vector (h_c/h)

Table 2. comparison between predictive and ISVM

Method	ISVM	Predictive
Torque ripple	3.528	3.329
Flux ripple	0.0129	0.0099
Rotor current THD	3.56	3.16
Stator current THD	1.52	1.42

In Fig. 17 ratio of active vector to zero vector (h_c/h) is shown with obtain by Eqs. (7) and (8). The advantage of predictive method compared with ISVM clearly shows in Table 2. As can be seen, predictive method can improve machine behavior significantly.

7 Conclusion

Simulation results show the capacity of this new predictive DTC technique with indirect matrix converter, to control the torque and the flux of the DFIM at constant switching frequency. Compared with ISVM-DTC, ripple reduction of torque and flux in predictive DTC method is more. Both methods also presents good tracking behavior, capable of working at variable speed operation conditions for both motoring and generating modes. However, simulation results show that predictive method is more suitable for use in applications such as wind power generation. Beside the improvements of the proposed method, using indirect matrix converter as static converter in this project, the advantages of this converter (such as small size, near sinusoidal input current and long life-time) is also increased performance of model. Doubly-fed induction generator is used extensively in wind power plant to generate energy. To reduce problems of converter, snubber circuits were excluded from the converter and Four-step commutation strategy was used instead. In order to verify the predictive method, a Simulation task is prepared in SIMULINK/MATLAB software environment the obtained results confirm the superiority of the predictive method.

Acknowledgment

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