Predictive Direct Power Control Drive System of Doubly-Fed Induction Machine Fed by Indirect Matrix Converters

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Abstract—**This paper presents a novel predictive Direct Power Control (DPC) for Doubly-Fed Induction Machine (DFIM) based on Indirect Matrix Converter (IMC), which is characterized by a simple structure, minimal power ripple and constant switching frequency. Nowadays, the control strategies based on predictive methods have proved their efficiency to improve drive systems capabilities. So, in this paper, one of the best predictive methods that has recently been suggested for DFIM drive systems, is applied to Indirect Matrix Converter. The purpose of this combination is modifying the control parameters and size / volume reduction of drive system structure which it is difficult to achieve in conventional systems based on VSI converters. By suitably selecting switching pattern, the strategy is able to improve the steady state and transient response behaviors of the machine.The good tracking behavior with reduced power ripple for the both motoring and generating modes as well as removing bulky electrolytic capacitor from dc-link of converter are resulted by using two active vectors plus one zero vector per switching period and apply these vectors to inverter stage of IMC. This paper investigates the use of four-step commutation in rectifier stage of indirect matrix converters to reduce losses and input currents waveform distortion caused by circuit snubbr. Using this proposed strategy, the advantages of the DPC schemes and the benefits of the indirect matrix converters can be combined. In the inverter stage, the predictive DPC method is employed. The simulation results of proposed model confirm its effectiveness and accuracy.**

Keywords-Doubly-Fed Induction Machine, Indirect Matrix Converter (IMC), Indirect Space Vector Modulation (ISVM), Predictive Direct Power Control.

I. INTRODUCTION

The Doubly-Fed Induction Machines (DFIM) are motors or generators that have winding on both stator and rotor and both winding transfer power between shaft and system. DFIM 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 enable the doubly-fed wound rotor induction machine to have vast applications in wind-driven generation [1], [2].

Among all Doubly Fed Induction Machine (DFIM) control methods, direct control because of high dynamic performance is more known than others.These direct control techniques, are based on a direct control of the torque and flux magnitudes for the case of the Direct Torque Control (DTC), or on a direct control of the stator active and reactive power, for the case of the Direct PowerControl (DPC) [2].

Several researchers on their efforts have focused on the progress DPC techniques that operate at a variable switching frequency [3]. Expensive and complicated AC harmonic filters and power converters, is the consequence of using the variable frequency switching.Recently in [4,5]DPC at constant switching frequency have been developed for the DFIM. Constant converter switching frequency makes the design and implementation of the power converter and ac harmonic filter easier.

On the other hand, predictive control with a prediction horizon equal to one sample period is employed to achieve constant frequency [5]. In [4] and [5], the theoretical background developed by these authors was employed to design a new predictive DPC technique for the DFIM with constant switching frequency and reduced active and reactive ripples. Although, lots of papers published on solving predictive DTC and DPC drawbacks, but these methods commonly have been used with a voltage source inverter (VSI) or current source inverters (CSI) and to achieve a good performance, these methods needs high control sampling frequency that means need of high speed processors which are expensive. Therefore, in recent years, research on direct frequency conversion using Matrix Converters (MC) has become popular in order to find a possible solution.

In recent years research on direct frequency conversion using Indirect Matrix Converters (IMC) has become popular. IMC 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 switch in rectifier stage are used. IMC have many desirable feature compared to the conventional voltage or current source inverter such as: No large energy storage components are needed, also have compact size, longer lifetime, regeneration capability and unitary power factor for any load [6] , [7]. IMC has shown several advantages over the traditional Direct Matrix Converter (DMC). Because it has converter configuration with two separate stages (rectifier and inverter stages), it has been considered more flexible to modify its topology [8].

The paper is organized as follows: in section II, a review of Doubly-Fed Induction Machine model is presented; then, in section III, predictive DPC for DFIM is explained, Indirect Matrix Converter topology and it's Rectifier Four-Step Commutation are explained in section IV and V respectively. In section VI the predictive DPC system based on IMC for DFIM is modeled and explained. ISVM method andsimulation results of proposed model are available in section VII and VIII respectively. Finally, the conclusions are exposed in section IX.

II. DOUBLY FED INDUCTION MACHINE MODEL

A. *Supplying topology of DFIM*

General DFIM supply system is shown in Fig. 1. As it is apparent, the stator side is directly connected to the grid and so, it supplied at constant frequency and constant three phase amplitude. By adjusting the amplitude, phase and frequency of the voltage introduced in the rotor side, it is possible to control the speed and the flow of active and reactive power through the rotor and the stator. Since, in this configuration, back to back converter dealing with about 30% of the generated power, so it's more attractive in comparison with full scale based topology because of modification cost and efficacy [4].

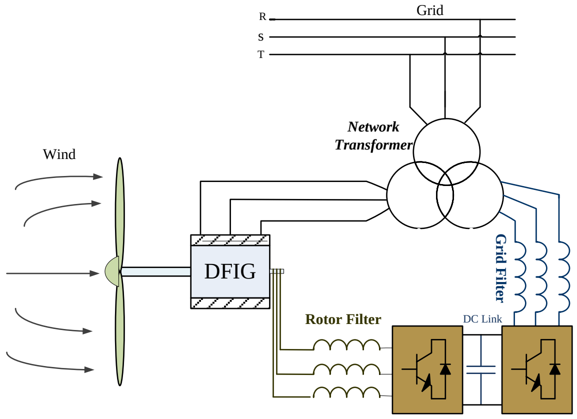


Fig. 1. General DFIM supply system

B. *Model Equations*

The doubly fed induction machine can be modeled with the following voltage and flux equations in the stator reference frame [9]-[10]:

$$V_s = R_s i_s + \frac{d\psi_s}{dt} \tag{1}$$

$$V_r = R_r i_r + \frac{d\psi_r}{dt} - j\,\omega_m p \psi_r \tag{2}$$

$$\psi_s = L_s i_s + L_m i_r \tag{3}$$

$$\psi_r = L_r i_r + L_m i_s \tag{4}$$

Also, the stator active and reactive power of doubly fed induction machine can be concluded as follows:

$$p_s = \frac{3}{2}\,\mathrm{Re}\left\{\vec{V}_s^{\,s} . \vec{\mathrm{L}}_s^{\,s}\right\} \tag{5}$$

$$Q_s = \frac{3}{2}\,\mathrm{Im}\left\{\vec{V}_s^{\,s} . \vec{\mathrm{L}}_s^{\,s}\right\} \tag{6}$$

In order to provide required information to analyze the DPC, finding the relation of the active and reactive power of the stator and rotor fluxes is necessary which can be calculated by substituting the equation (1-4) into (5) and (6):

$$Q = \frac{3}{2}\frac{\omega_s}{\sigma L_s}\left|\vec{\psi}_s\right|\left[\frac{L_h}{L_r}\left|\vec{\psi}_s\right| - \left|\vec{\psi}_r\right|\cos\delta\right] \tag{7}$$

$$P_s = \frac{3}{2}\frac{L_h}{\sigma L_s L_r}\,\omega_s \left|\vec{\psi}_s\right|\left|\vec{\psi}_r\right|\sin\delta \tag{8}$$

Where $\sigma = 1 - \frac{{L_m}^2}{L_s L_r}$ is leakage coefficient.

These equations show that stator active and reactive power can be controlled by modifying the relative angle between the rotor and stator flux space vectors (δ) and their amplitudes. By knowing the relative position of the stator and rotor fluxes and the rotor voltage vector, it is possible to predict the rotor flux space vector time evolution. In the [5], the quality of the voltage effect on the fluxes has been explained in detail. (9) and (10) show the variation of stator active and reactive power in the rotor reference frame [5]:

$$\begin{aligned}\frac{dP_s}{dt} &= -p_s\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) - \omega_r Q_s + \frac{3}{2}\omega_r \frac{\left|\vec{v}_v\right|^2}{\sigma L_s \omega_s} \\ &+ \frac{L_h}{\sigma L_s L_r}\upsilon_{bus}\left|\overrightarrow{\upsilon_s}\right|\sin\left(\omega_r t + \delta - \frac{\pi}{3}(n-1)\right)\end{aligned} \tag{9}$$

$$\begin{aligned}\frac{dQ_s}{dt} &= -Q_s\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) - \omega_r P_s + \frac{3}{2}\frac{R_r}{L_r}\frac{\left|\vec{v}_v\right|^2}{\sigma L_s w_s} \\ &+ \frac{L_h}{\sigma L_s L_r}\upsilon_{bus}\left|\overrightarrow{\upsilon_s}\right|\cos\left(\omega_r t + \delta - \frac{\pi}{3}(n-1)\right)\end{aligned} \tag{10}$$

The three constant terms in (9) and (10) are produced by zero vectors while the sine and the cosine terms are only valid for the active vectors. With a little calculation it is possible to show the angle δ as a function of the active and reactive power [5]:

$$\delta = arc\,\tan\left(\frac{L_r}{L_h}\frac{P_s}{\frac{3}{2}\frac{L_h}{\sigma L_r L_s}\frac{\left|\overrightarrow{\upsilon_s}\right|^2}{\omega_s} - Q_s}\right) \tag{11}$$

III. PREDICTIVE DPC FOR DFIM

First of all it is noteworthy that in order to implementation of predictive theory with various control strategies, the determination of active vectors portion and zero vectors portion plays the vital role. It's evident that if only one active vector always be used to minimize only active power ripple, the most natural result will be a poor reactive power quality. One of the proposed methods to improve active and reactive power control simultaneously has been presented in [4-5] and [9], where two active vectors with one zero vector per switching frequencies are used. In this present work, we tried to apply principle of this predictive DPC to indirect matrix converter in order to obtain all benefits of this modified method and indirect matrix converter topology simultaneously.

Active and reactive power errors and number of rotor flux sector are three terms which determine the priority of choosing one specific active voltage vector of the converter. The mentioned predictive DPC strategy uses a lookup table mapped by the output of two ON-OFF comparators without hysteresis bands for the first active voltage vector. After choosing first active voltage vector based on classical DPC look up table, predictive DPC control strategy employs a sequence of three different voltage vectors in a constant switching period h under steady state operation conditions [5]. The active and reactive power waveforms for this control strategy are represented in Fig. 2.

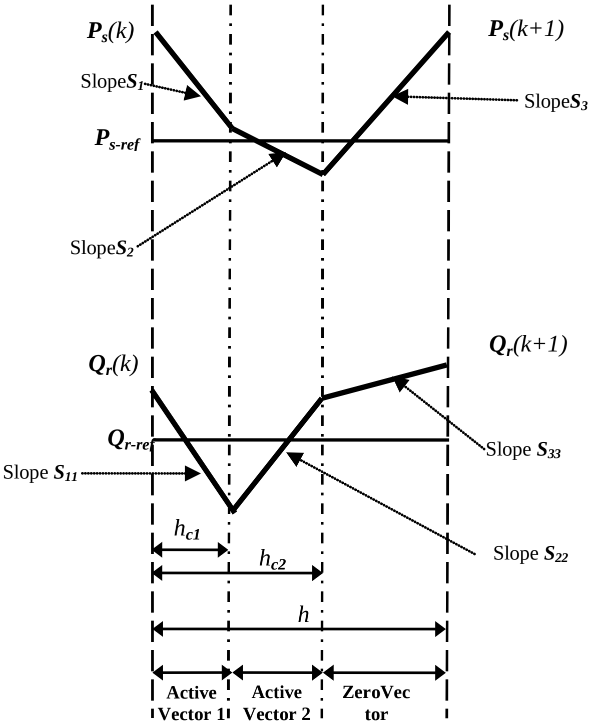


Fig. 2. Steady state Active and Reactive Waveforms at Motor and Generator Modes based on three vector based DPC strategy

S_1 and S_2 are the slopes of first and second active voltage vectors respectively while the slope of zero vector is shown by S_3. Similarly, S_{11}, S_{22} and S_{33} are the slopes of the reactive power when the first active vector, second active vector and zero vector has been applied, respectively. As can be seen from this figure, the second active vector produces the same sign variation with the first active vector in the active power, while it produces the opposite sign variation in the reactive power. Also, the reactive power is nearly maintained constant by applying zero vectors while the opposite sign active power variation is achieved [4,5]. This matter is the base of proposed predictive DPC to control active and reactive power ripple in the allowed bands. To reduce active and reactive power ripple at constant switching frequency solving some of equations is needed that explained in detail in [4,5] and as the final result the both switching instants are calculated by means of the (12) and (13). However it's quotable that to compute the portion of h_{c1} or h_{c2} by means of (12) and (13), it's possible to dealing with some particular situations. In general, one of these conditions may occurs, 1. The value of h_{c1} or h_{c2} obtained more than all switching period (h), 2. One of them achieved less than 0 and at last if the value of h_{c2} achieved less than the value of h_{c1}. All of these cases means that the machine active and reactive power aren't in their allowed band yet and it's necessary to apply the first active vector in all of switching period (h) in order to bring them to allowed band.

IV. INDIRECT MATRIX CONVERTER THEORY

Indirect Matrix Converter (IMC) 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.

As it is clear from Fig. 5, 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 [11], [12].

$$h_{c1}=\frac{2s_{22}T_{em-ref}-2s_{22}T_{em}(k)-s_{22}s_3h+(2s_3-4s_2)\left|\Psi_r\right|_{ref}+(4s_2-2s_3)\left|\Psi_r\right|(k)}{2s_{22}s_1-4s_{11}s_2+2s_{11}s_3-s_{22}s_3} \tag{12}$$

$$h_{c2}=\frac{(2s_{22}-4s_{11})T_{em-ref}+(4s_{11}-2s_{22})T_{em}(k)+(2s_{11}-s_{22})s_3h+(4s_1-4s_2)\left|\Psi_r\right|_{ref}+4s_2-4s_1)\left|\Psi_r\right|(k)}{2s_{22}s_1-4s_{11}s_2+2s_{11}s_3-s_{22}s_3} \tag{13}$$

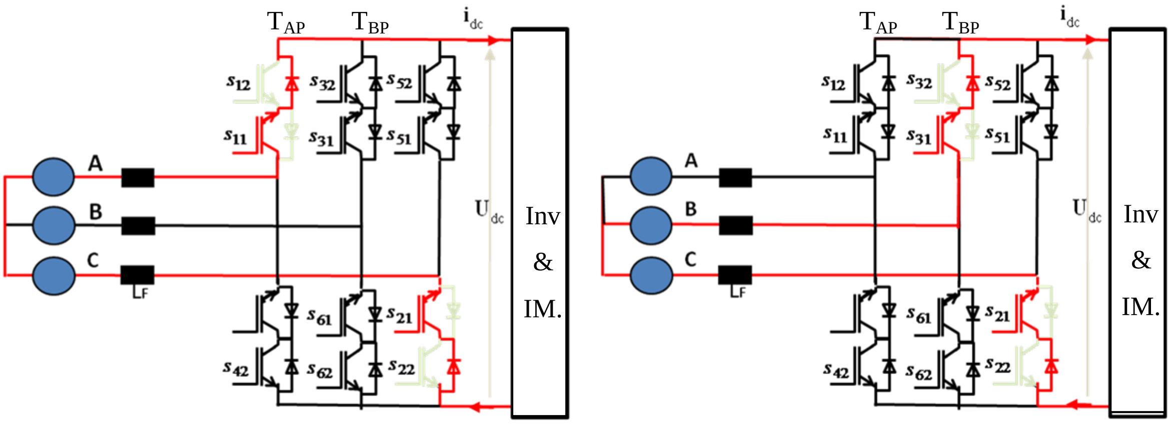


Fig.4. Commutation from TAP to TBP

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 sudden overvoltages occurrence and switches' damage, these switches should not be turned off simultaneously [11], [12]. To ensure the establishment of two conditions at any time, snubber circuits is 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 [12].

Typically two types of commutations methods have been proposed which don’t require snubber circuits for a PWM rectifier. The first method named rectifier zero current commutation and the second method 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 [12].

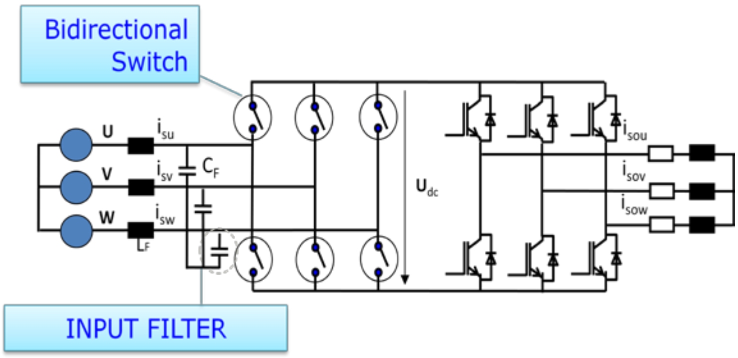


Fig. 3. Indirect Matrix Converter Topology

V. FOUR-STEP COMMUTATION STRATEGY PRINCIPLES

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 NandorBurani in 1989 [13], is four-step commutation strategy. Since this time onwards 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 [14]. The process of commutation is explained with Fig. 6. T_{AP} $\mathrm{T_{AP}}$ 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 connects 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 othertransistors 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} 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}

VI. MODELING AND INTERPRETATION OF THE PROPOSED METHOD

In this section, the proposed model of predictive DPC based on Indirect Matrix Converter (IMC) for DFIM will be explained in detail. The related block diagram of proposed method is shown in Fig. 5.

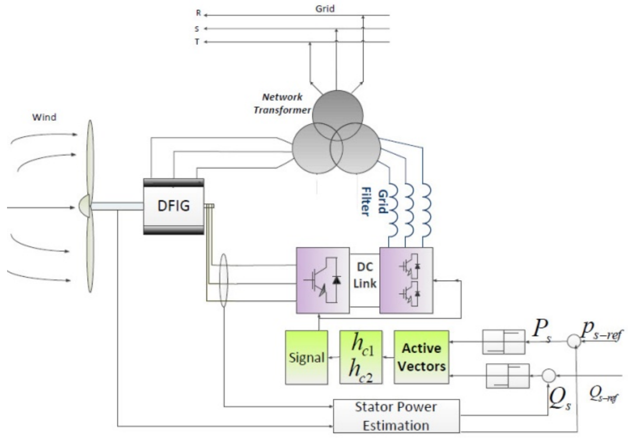


Fig. 5. DFIM Supplying System Using IMC

Applying this method to indirect matrix converter is implemented in this paper, which could improve the performance of drive system in comparison with classical DPC. The usage of this strategy is justifiable especially at high power demanding applications, when “low” switching frequency is needed. The most important matter to implement this method correctly is accurate portion determination of vectors in each cycle. In an intelligible manner, it’s explained in [5] that in each specific sector, there are always two vectors with uniform positive active power slope and there are two other vectors with uniform negative active power slope. So, depending on necessity to positive active power slope or negative active power slope, there are two specific choices in each sector. But the final selection will be done according to situation of the reactive power variation. It results from this point that the selected vectors to control torque variation can produce same sign slops or opposite sign slopes for the reactive power variation. Therefore the controller can take an optimum decision to minimize active and reactive power ripple at the same time.

In this paper, an indirect space vector modulation (ISVM) is used in the rectifier-bridge of indirect matrix converter in order to control input power factor, while at the same time predictive algorithm is employed in the inverter-bridge.

As mentioned, an indirect space vector modulation (ISVM) is often used for indirect matrix converters, providing full control of both the output voltage vector and the instantaneous input current displacement angle. Matching Predictive DPC strategy with ISVM method in order to apply to indirect matrix converter is the most important part of modeling. So, to indicate this modeling appropriately, first duty cycle of rectifier-bridge and inverter-bridge will be explained separately and then two-stage matrix converter will be discussed.

VII. INDIRECT SPACE VECTOR MODULATION

In the ISVM method, the objective of the modulation strategy is to synthesize the output voltages from the input voltages and the input currents from the output currents. The indirect space vector modulation (ISVM) was first proposed by Huber et al in 1989 [15], where direct matrix converter was described to an equivalent circuit combining current source rectifier and voltage source inverter connected through virtual dc link. The only difference in the proposed structure for direct matrix converter by Borojevic in 1989 and indirect matrix converter topology that was later proposed was in inverter stage. Since in the proposed structure by Borojevic, unlike the IMC structure which inverter stage contains unidirectional switches, all switches were bidirectional. The following sections describe two independent space vector modulations for rectifier stage and inverter stage then the two modulation results are combined to apply to all indirect matrix converter topology.

A. *Rectifier Stage*

The input currents can be represented as the virtual dc-link current I_{DC} multiplied by the switch state of the rectifier stage and the input current space vector I_{in} can be expressed as [16]:

$$I_{in} = \frac{2}{3}(I_a + I_b.e^{j\frac{2\pi}{3}} + I_c.e^{j\frac{4\pi}{3}}) \tag{14}$$

For example if input phase a and input phase b are connected to the positive rail of the virtual dc-link V_{DC+} and the negative rail V_{DC-}, respectively its vector magnitude will be calculated from:

$$\begin{aligned} I_{in} &= \frac{2}{3}(I_{DC} - I_{DC}.e^{j\frac{2\pi}{3}} + 0.e^{j\frac{4\pi}{3}}) \\ &= \frac{2}{\sqrt{3}} I_{DC}.e^{-j\frac{\pi}{6}} \end{aligned} \tag{15}$$

Similarly, using different modes of rectifier switches, there are six active current space vectors, each corresponding to a certain switching configuration, as shown in Fig. 6.

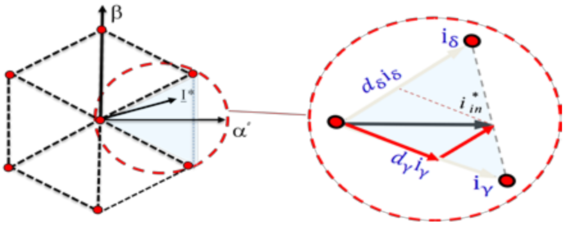


Fig. 6. Synthesis of Input Current Vector

In each current sector, I^*_{in} is synthesized by two adjacent switching vectors Iγ and Iδ with the duty cycles dγ and dδ, respectively [16].

$$I_i = d_\gamma i_\gamma + d_\delta i_\delta \tag{16}$$

The duty cycle of the active vectors are written as:

$$d_\delta = \frac{I_{in}^*}{I_{DC}} \sin(60^\circ - \theta_i)$$
$$d_\gamma = \frac{I_{in}^*}{I_{DC}} \sin\theta_i \qquad (۱۷)$$

Where, The current modulation index ($m_C = \frac{I_{in}^*}{I_{DC}}$) is often fixed to unity.

B. *Inverter Stage*

In the inverter stage, duty cycles of active vectors and zero vectors are calculated by applying predictive DPC. As explained III, predictive DPC strategy must generate two active vectors and one zero vector for each Tδ and Tγ generated by rectifier-bridge.

C. *Two-Stage Matrix Converter*

To balance the input currents and the output voltages properly in the same switching period, two independent space vector modulations should be merged into one. The virtual dc-link voltage is established by the two input line voltages determined by input current vectors Iγ and Iδ during dγ and dδ, respectively. Then, two output voltage vectors V_{act} and V_0 are applied to synthesize the desired output voltage from the two virtual dc-link amplitudes inside each switching period T_S. 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 (18), (19), (20), (21), (22) and (23).

$$T_{a1-\gamma} = h_{c1}\, T_\gamma = h_{c1} T_s \sin(\theta_i) \qquad (18)$$

$$T_{a2-\gamma} = (h_{c2} - h_{c1})\, T_\gamma = (h_{c2} - h_{c1}) T_s \sin(\theta_i) \qquad (19)$$

$$T_{0-\gamma} = (1 - h_{c2}) T_\gamma = (1 - h_{c2})\, T_s \sin(\theta_i) \qquad (20)$$

$$T_{a1-\delta} = h_{c1}\, T_\delta = h_{c1} T_s \sin(60 - \theta_i) \qquad (21)$$

$$T_{a2-\delta} = (h_{c2} - h_{c1})\, T_\delta = (h_{c2} - h_{c1}) T_s \sin(60 - \theta_i) \qquad (22)$$

$$T_{0-\delta} = (1 - h_{c2}) T_\delta = (1 - h_{c2})\, T_s \sin(60 - \theta_i) \qquad (23)$$

The switching pattern for an IMC is presented in Fig. 7. The ISVM strategy as well as predictive DPC method uses all different switches modes of indirect matrix converter to maintain active and reactive power near their relative reference in order to attain the higher control performance in the constant frequency.

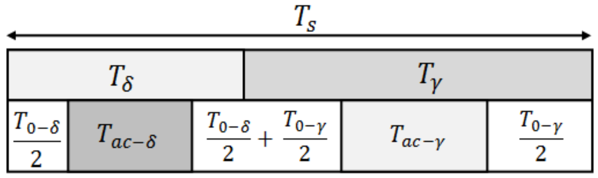


Fig. 7. Switching Pattern for Predictive DPC-ISVM

VIII. SIMULATION RESULTS

In order to validate the justness of the proposed predictive DPC applied to the Indirect Matrix Converter, some of the simulations results have been carried out. The machine test is a standard 15 kW, four-pole, 220V, 50Hz doubly fed induction machine and has the following parameters:

Rs=0.168 ΩRr=0.199 ΩLm=0.045 H Lls=0.050 H Llr=0.050 H

Also, the parameters of the Ac filter in entrance of converter for the MATLAB simulation are:

Filter inductor: 10 mH Filter capacitor: 100 µF

The simulation model of this novel Predictive DPC-ISVM indirect matrix converter is set up with Matlab/Simulink power system toolbox. In the simulation of space vector modulation method, it is possible to make the sampling time of the reference vector arbitrary small to have a high resolution vector, but due to practical limitations in switching frequency of power electronic switches, it is virtually impossible.

Fig. 8 and 9 shows the active and reactive power process where good tracking behavior of powers response is clear. It indicates that the predictive direct power control of DFIG based on IMC offers satisfying power control performance.

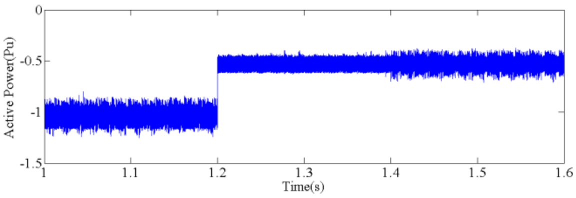


Fig.8. Active Power Response

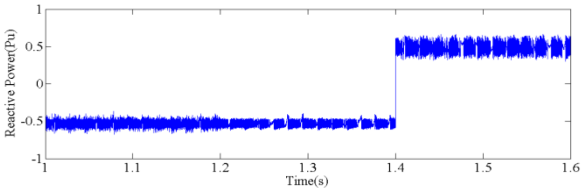
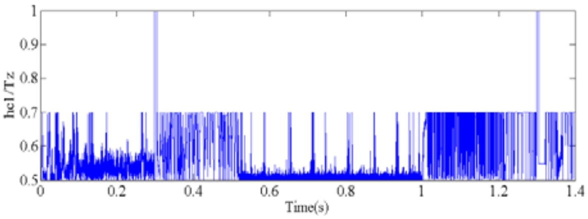
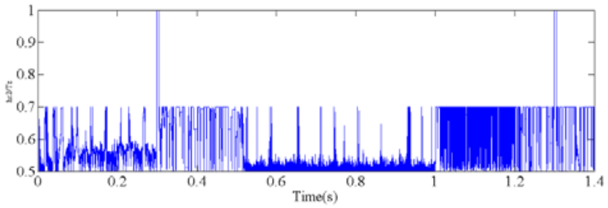


Fig. 9. Reactive Power Response

In order to examine the predictive method effectiveness, Fig.10 (a) and (b) shows the portion of active vectors h_{C1} and h_{C2} for T_Z during simulation which obtain by Equations (12) and (13).



(a)



(b)

Fig. 10. The Portion of Active Vectors:
(a) h_{C1}/T_Z (b) h_{C2}/T_Z

Fig.11 and 12 shows rotor current and stator current respectively. The effect of sudden changes in active and reactive reference values at t=1.2 and t=1.4 can be seen in these figures.

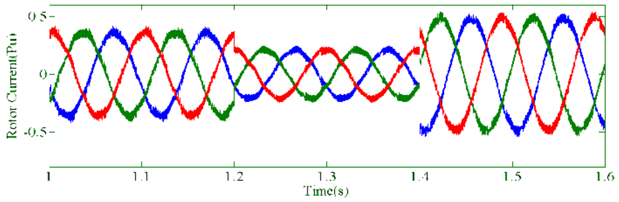


Fig. 11. Rotor Current

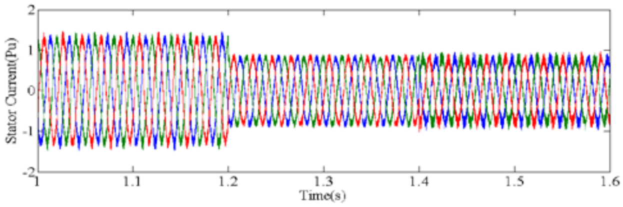


Fig. 12. Stator Current

IX. CONCLUSION

In this paper to solve some inherent problems of DPC such as large ripple in torque and variable switching frequency, a predictive direct power control scheme is employed which uses active vectors and zero vectors for each cycle to produce optimal vectors for indirect matrix converter drives. The predictive control as well as indirect space vector modulation (ISVM) strategy provides full control of both the output voltage vector and the instantaneous input current displacement angle. Also, to reduce problems with snubber circuits (such as: increasing losses and input current waveform distortion) rectifier four step commutation strategy is implemented. Simulation results show the capacity of this new predictive DPC technique based on indirect matrix converter to control the active and reactive of the DFIM at low constant switching frequency. As the matter of fact, because of using doubly-fed induction generator extensively in the wind power plant to generate energy, the proposed model can improve current injection into the network.

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