A Comparative Study of Matrix Converter Based DTC with Complete Vectors Application and an Improved Predictive Torque Control Using Two-Level Inverter

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Abstract

In this paper two methods of torque control for induction motor have been investigated. First, DTC method is implemented by using complete Voltage Vectors of the Matrix Converter. Second, an improved predictive torque control is developed and performed with two-level inverter. In the proposed predictive control the next torque and flux are predicted by discrete model of motor and inverter. Afterward the feasible switching states are examined in a cost function. The switching state that minimizes the cost function has to be exerted during the portion of control interval in order to minimize the torque ripples. The method of active time calculation for reducing the torque ripples is presented. The torque response of the proposed predictive method is simulated and investigated in two different conditions. The results are compared with the torque response of the simulated MC-DTC (Matrix Converter based DTC).

1. Introduction

The Direct Torque Control (DTC) method for AC machines is prevalently utilized in many variable speed drives, especially in case the torque control is more desired than speed control. The DTC method has the dominant advantages such as fast transient toque response and low calculation burden [1]. However because of “Bang-Bang” control characteristic and not using modular regulators, conventional DTC has two drawbacks. First, the switching frequency is variable and dependent to the hysteresis bands and speed of the motor. Second, the torque ripples are considerable especially when it is comparing with the Field Oriented Control method. Reducing the torque ripple in conventional DTC has the cost of small sampling interval that may lead to high switching frequency [2]. In recent years, several investigations have been performed with the aim of improving steady state performance of the DTC method, e.g., Direct Self Control (DSC) [3], utilizing Space Vector Modulation (SVM) [4], utilizing multi level inverters [5], [6] or Matrix Converter [7] and Predictive Torque Control [8]-[20].

Recently, three phase matrix converters (MC) have emerged to become a good alternative to the well known voltage source inverter (VSI). The matrix converter is an advanced circuit topology capable of converting AC-AC, providing generation of load voltage with arbitrary amplitude and frequency, bidirectional power flow, sinusoidal input/output waveforms, and operation with unity input power factor. Furthermore, since no inductive or capacitive elements are required, matrix converter allows a very compact design [21]. By combining the advantages of matrix converters with the advantages of DTC schemes, it is possible to achieve fast torque and flux responses in a wide speed range. By suitably selecting the space vector, the current deviations and the torque ripple of the motor can be effectively reduced. Beside all these advantages, utilizing MC causes the cost of the drive system to be increased and complicates the switching algorithm. Furthermore, if MC-DTC is performed by hysteresis method the variable switching frequency will remain as a drawback of DTC branch methods.

On the other hand, the predictive method has a precise and fast torque response because of the characteristic of predictive control. Different kinds of Predictive Torque Control have been investigated to date.

Direct mean Torque Control (DMTQ) [8], was introduced to control the mean value of the torque at reference value. In this method, the torque slope is predicted by considering the voltage vectors attained from the switching table. Afterwards, the active time (the interval of exerting active voltage vector) and the zero time (the interval of exerting zero voltage vector) is calculated.

Many predictive DTC methods, that attained the main idea from DMTC, introduced during last decade. In these methods, the control interval is divided into active and zero intervals. These intervals are calculated with the aim of minimizing torque ripple [9]-[12].

Dead-beat control [13]-[15] is based on calculating the voltage vector that leads the next step torque to the reference value. This kind of control strategy needs a PWM method in order to build the calculated voltage vector.

Generalized predictive control is performed for controlling ac machines also [16], [17]. In this method, the derivative of the cost function is set to zero in order to find the voltage vector that minimizes it. The calculated voltage vector has to be exerted to motor by means of a PWM method.

Another approach to minimize the cost function is examination of the feasible voltage vectors (including zero voltage). The voltage vector that minimizes the cost function is the most appropriate one [18]-[20]. This method is less time consuming. However, because the selected voltage vector is exerted for the whole control interval, the torque ripples rises if the control interval is not very small. These methods perform excellently if the matrix converter or three-level inverter is contemplated.

In this paper MC-DTC is performed with improvement in look-up table for direct torque control by matrix converter in order to include the small, medium and large voltage vectors of MC. With the new look-up table and new hysteresis comparator with seven levels output the system will differentiate between small, medium and large torque errors and consequently reduce the torque ripple.

Also, this paper proposes a new predictive torque control by examination of feasible voltage vectors. However, the selected voltage vector is exerted during a portion of control interval. Therefore, the feasible voltage vectors include active voltage vectors only. The zero voltage will be exerted for the rest of the control interval. With this method, the torques ripples will reduce. Because the prediction is not performed about zero voltage, the calculation time reduces also.

In order to qualify the proposed methods, torque control of induction motor is simulated via two methods. First, MC-DTC with complete voltage vectors application is simulated as a method possesses excellent response. However, obviously the cost increases because of using Matrix converter. Second, the proposed predictive torque control with two-level inverter is simulated. The comparison between two methods is performed based on the attained results.

2. Matrix Converter Based DTC (MC-DTC) with Complete Application of Voltage Vectors

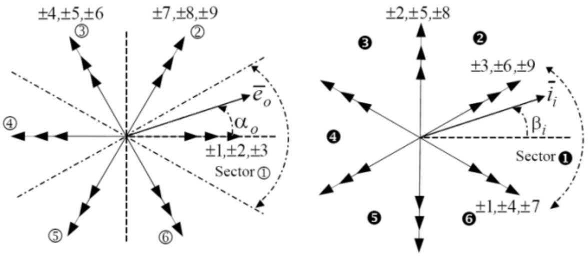
The three-phase to three-phase matrix converter consists of nine bidirectional switches that allow any output phase to be connected to any input phase.

Direct Matrix converter has six fixed positions of the output voltage space vector which are not dependent on the input voltage space vector phase angle and six prefixed positions of the input current space vector which are not dependent on the output current space vector phase angle. The magnitude of the output voltage space vector and input current space vector is variable and depends on the instantaneous values of the input line voltages and output line currents respectively.

The representation of the Direct Matrix converter output voltage space vectors and input current space vectors is shown in Fig. 1.

By dividing the input voltage vector path into twelve sectors, according to Fig. 2 and using new MC switching table for DTC presented in Table 1, DTC algorithm will be able to distinguish between small, medium and large vectors. In order to reduce the torque ripple, in addition to the large vectors of MC, the medium and small vectors can also be used. Thus the DTC scheme must be modified resulting in a new torque hysteresis comparator that will provide seven different levels instead of three levels to distinguish between small, medium and large positive and negative torque errors. The new seven-level hysteresis comparator is shown in Fig. 3.

If ideal value of H_ψ for power factor hysteresis comparator, in one input voltage sector can't be found, then the other vector in same sector from Table 1 can be select for control of unit input power factor.



(a) (b)

Fig. 1. (a) MC Output Voltage Space Vectors (b) MC Input Current Space Vectors

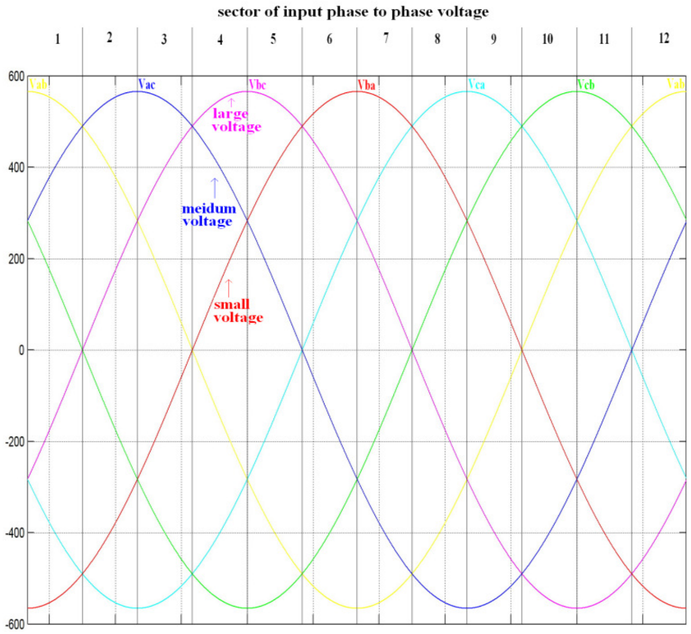


Fig. 2. Small, medium and large voltage vectors of matrix converter and 12 sector of input line voltage

Table 1. Look Up Table for the Use of All MC Voltage Vectors

SMALL VECTORS

Sector	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Hψ	-	+	-	+	-	+	-	+	-	+	-	+
V_{1-vsi}	-2	2	1	-1	-3	3	2	-2	-1	1	3	-3
V_{2-vsi}	8	-8	-7	7	9	-9	-8	8	7	-7	-9	9
V_{3-vsi}	-5	5	4	-4	-6	6	5	-5	-4	4	6	-6
V_{4-vsi}	2	-2	-1	1	3	-3	-2	2	1	-1	-3	3
V_{5-vsi}	-8	8	7	-7	-9	9	8	-8	-7	7	9	-9
V_{6-vsi}	5	-5	-4	4	6	-6	-5	5	4	-4	-6	6

MEDIUM VECTORS

Sector	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Hψ	+	-	+	-	+	-	+	-	+	-	+	-
V_{1-vsi}	-3	1	2	-3	-1	2	3	-1	-2	3	1	-2
V_{2-vsi}	9	-7	-8	9	7	-8	-9	7	8	-9	-7	8
V_{3-vsi}	-6	4	5	-6	-4	5	6	-4	-5	6	4	-5
V_{4-vsi}	3	-1	-2	3	1	-2	-3	1	2	-3	-1	2
V_{5-vsi}	-9	7	8	-9	-7	8	9	-7	-8	9	7	-8
V_{6-vsi}	6	-4	-5	6	4	-5	-6	4	5	-6	-4	5

LARGE VECTORS

Sector	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Hψ	-	+	-	+	-	+	-	+	-	+	-	+
V_{1-vsi}	1	-3	-3	2	2	-1	-1	3	3	-2	-2	1
V_{2-vsi}	-7	9	9	-8	-8	7	7	-9	-9	8	8	-7
V_{3-vsi}	4	-6	-6	5	5	-4	-4	6	6	-5	-5	4
V_{4-vsi}	-1	3	3	-2	-2	1	1	-3	-3	2	2	-1
V_{5-vsi}	7	-9	-9	8	8	-7	-7	9	9	-8	-8	7
V_{6-vsi}	-4	6	6	-5	-5	4	4	-6	-6	5	5	-4

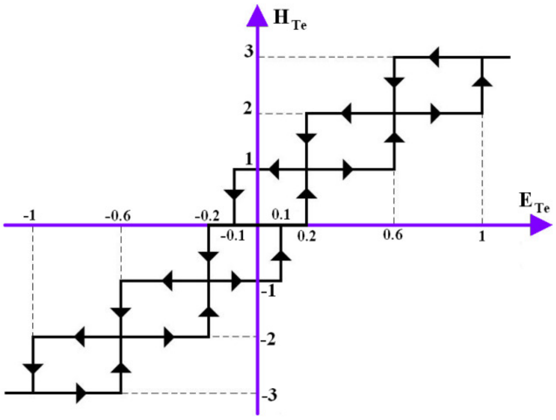


Fig. 3. New torque hysteresis comparator with seven output levels in order to distinguish between small, medium and large positive and negative torque errors

3. Improved Predictive Torque Control

In this paper the method of minimizing the cost function by means of examining feasible voltage vectors of two-level inverter is used. In order to improve the torque response, the selected voltage vector is not exerted for the whole control interval. Therefore, the control interval includes active time allocated for active voltage vector and zero time for zero voltage. The feasible voltage vector reduced to six active states in this procedure for two-level inverter.

The cost function should correspond that how the torque and flux will track their references. Therefore, the following cost function will determine which state is the best apply.

$$J_j = \left|T_j(t_{n+1}) - T^*\right| + Q\left\|\overline{\psi}_{sj}(t_{n+1})\right| - \left|\overline{\psi}_s^*\right\| \qquad (1)$$

$$j = 1,2,....,6$$

where $T_j(t_{n+1})$ and $\left|\overline{\psi}_{sj}(t_{n+1})\right|$ are the predicted torque and flux by considering the application of each voltage vector. T^* and $\left|\overline{\psi}_s^*\right|$ are the torque and flux references. Q is a weighting factor that determines the importance of flux control in compare with torque control.

In order to predict the next step torque and flux, the discrete model of motor and inverter is used as below:

$$\overline{\psi}_{sj}(t_{n+1}) = \overline{\psi}_s(t_n) + t_s\, r_s \cdot \bar{i}_s + t_s\, \overline{V}_j \qquad (2)$$

$$T_j(t_{n+1}) = \frac{3}{2}\frac{p}{2}\left\{\overline{\psi}_{sj}(t_{n+1}) \times \bar{i}_{s\lambda}(t_n)\right\} \qquad (3)$$

where r_s and $\bar{i}_s$ is are the stator resistance and current respectively. $\overline{V}_j$ is the j^{th} active voltage vector. $\bar{i}_{s\lambda}(t_n)$ is calculated as below:

$$\begin{aligned}\bar{i}_{s\lambda}(t_n) &= \left(1 - \frac{t_s}{\sigma\tau_r}\right)\bar{i}_s(t_n) - \frac{\overline{\psi}_s(t_n)}{\sigma L_s} \\ &+ j\omega_r \cdot t_s\left(\bar{i}_s(t_n) - \frac{\overline{\psi}_s(t_n)}{\sigma L_s}\right)\end{aligned} \qquad (4)$$

where $\sigma = 1 - L_m^2 / L_s L_r$, τ_r is the rotor time constant, L_s, L_r and L_m are the stator, rotor and mutual inductances, respectively.

It is noticeable that the Voltage Model Observer [22] is used for present flux estimation.

For further limitation of the torque ripples, the voltage vector that minimizes (1) is not applied for the whole control interval (as all this kind of predictive torque control does). Instead, the torque derivative is predicted by considering the application of the selected voltage vector.

$$\dot{T} = \frac{T_{j-selected}(t_{n+1}) - T(t_n)}{t_s} \qquad (5)$$

$$1 \le j\text{-}selected \le 6$$

where *j-selected* is the number of selected voltage vector.

If the incline of the torque is assumed linear, the proper active interval to constrain the torque from violating an upper limit is calculated.

$$t_{vv} = \frac{1}{\dot{T}}\left[T^* + \Delta T - T(t_n)\right] \qquad (6)$$

Where t_{vv} is the active time and ΔT is the allowed upper band for torque rising.

The rest of the control interval is devoted to zero voltage.

$$t_{zv} = t_s - t_{vv} \qquad (7)$$

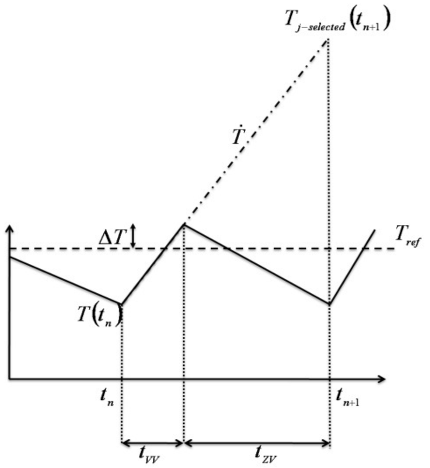


Fig. 4. Typical rise and fall of the torque

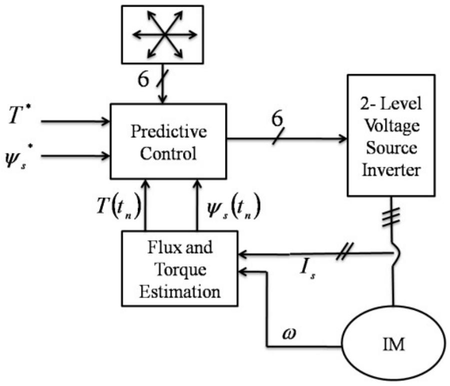


Fig. 5. Block diagram of the improved predictive torque control

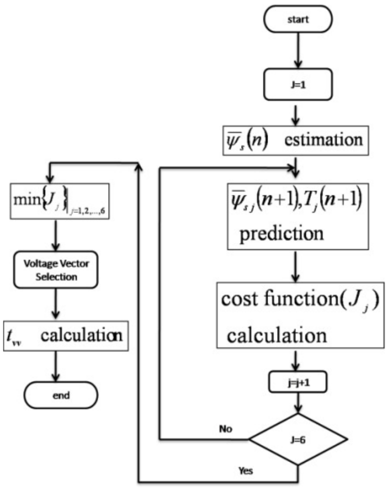


Fig. 6. Flowchart of the improved predictive torque control

Fig. 4 shows the torque rise and fall in a control interval. It is depicted that if the selected voltage vector remains for the whole interval, the torque will reach to $T(t_n)$, but because the active time is controlled the torque will reach to the desired ceiling and then started to descend by zero voltage insertion.

Noting that because the falling slope of torque, when the zero voltage is applied, is smaller than the rising slope, if the control interval is adjusted properly (less than 200μs), there is no need to constrain declining of the torque. This method provides the possibility of adjusting larger control interval in compare with the whole time inserting method.

Fig. 5 shows the block diagram of the proposed predictive torque control. Since the time calculation is not a time consuming calculation and two zero states are eliminated from the prediction and examination procedure, implementation of this method will be as fast as the method of whole interval inserting. Fig. 6 shows the flowchart of the improved predictive control.

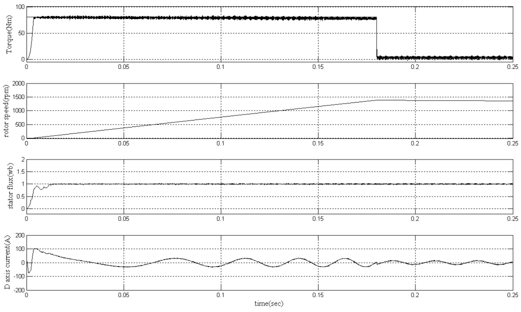


Fig. 7. Torque, Speed, flux and current response of MC-DTC scheme under nominal speed.

Table 2. system parameters

P_n=3hp	R_s=0.435 Ω
V_n=380 V	R_r=0.816 Ω
L_s=0.0856 H	J=0.08 kgm^2
L_r=0.0856 H	f=50 Hz
L_m=0.0832 H	p=2

4. Simulation Results

The proposed predictive torque control by using two-level inverter and MC-DTC are simulated and the comparison between the results is performed. The simulated induction motor parameters are shown in Table 2. Figs. 7 and 8 show the speed, torque and flux signals of the MC-DTC and proposed predictive method respectively under the load with the value of 5 N.m and nominal speed. The torque reference is set to 80 N.m for the acceleration mode. Then the reference is set to 5 N.m.

Figs. 9 and 10 show the low speed performance of the proposed methods. Since internal EMF of the motor is small in low speeds, the torque rising slope is high. Therefore, the hysteresis base method has large torque ripples despite utilizing MC. However, the improved predictive control has small ripples because the ceiling of the torque is limited.

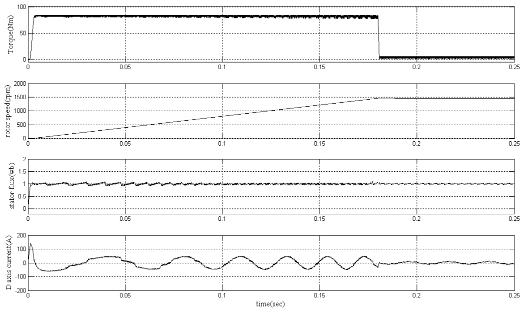


Fig. 8. Torque, Speed, flux and current response of the improved predictive scheme under nominal speed.

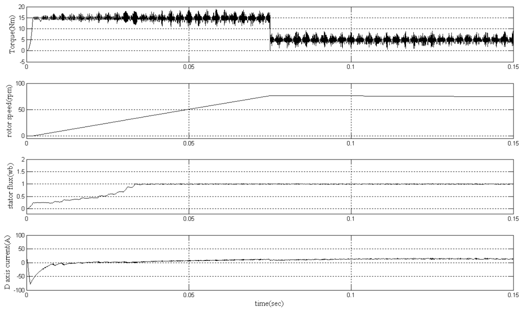


Fig. 9. Torque, Speed, flux and current response of MC-DTC scheme under low speed condition.

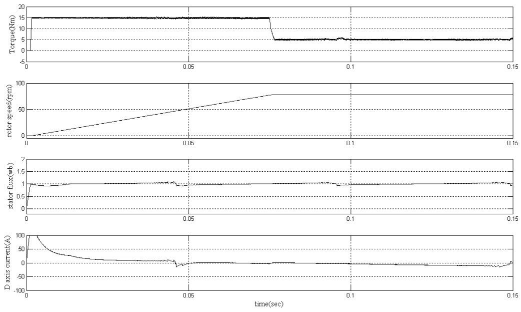
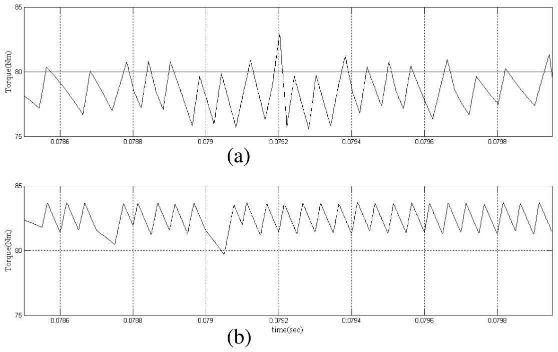


Fig. 10. Torque, Speed, flux and current response of the improved predictive scheme under low speed condition.



(a)

(b)

Fig. 11. Detailed torque signal of (a) MC-DTC (b) improved predictive torque control

Fig. 11 shows the detailed torque response of the MC-DCT and two-level predictive methods responses respectively. The results prove that the torque ripples of the proposed predictive method with two-level VSI are as low as that of in MC-DTC. In both methods, the torque ripple is about 4 N.m p-p.

5. Conclusion

An improved predictive torque control with two-level inverter and also MC-DTC with complete vector application methods are proposed and compared. Due to the scheme of examination of the cost function by applying feasible voltage vectors and dividing the control interval into active and zero time in predictive control, the torque ripples of proposed method with two-level inverter are as small as that of in MC-DTC.

The MC-DTC is reinforced by modifying the torque error hysteresis comparator in order to distinguish between small, medium and large positive and negative torque errors.

The simulation results prove the excellent transient torque response for both proposed methods. The predictive method has a better performance in low speeds. Since the torque control and torque ripples reduction was the main goal, the flux response of predictive method possesses more ripples in compare with MC-DTC.

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