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Direct Torque Control for Matrix Converter-fed Three phase Induction Motor

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Abstract— **This paper develops a direct torque control method (DTC) using a matrix converter fed induction motor. The advantages of matrix converters are combined with the advantages of the DTC technique; under the constraint of the unity input power factor, the required voltage vectors are generated to implement the conventional DTC method of induction motor. The proposed DTC algorithm is applied to induction motors and the simulation results are given in steady-state and transient conditions, while the discussion about the trend of the DTC method using the MC is also carried out.**

Keywords- Matrix converte; induction motor; direct torque control method

I. INTRODUCTION

In the past two decades, due to the need to increase the quality and the efficiency of power supply and usage, the three phase matrix converter has become a major modern energy converter and has emerged from the previously conventional energy conversion modules as one of the best substitutions [1], [2].

Matrix converter fed motor drive is superior to pulse width modulation (PWM) inverter drives because it provides bidirectional power flow, sinusoidal input/output currents, and adjustable input power factor [3], [4]. Furthermore, matrix converter allows a compact design due to the lack of dc-link capacitors for energy storage. However, only a few of practical matrix converters have been applied to vector control system of induction motors (IM) for the reason: Modulation technique and commutation control are more complicated than conventional PWM inverter [4].

Since the Direct Torque Control (DTC) method has been proposed in the mid 1980's, 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 [6]. 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 [7]. 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) [8], utilizing Space Vector Modulation (SVM) [9], utilizing multi level inverters [10], [16] or Matrix Converter [17] and Predictive Torque Control [13]-[14].

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.

In this paper, a new DTC control for matrix converter is proposed which allows under the constraint of unity input power factor, the generation of the voltage vectors required to implement the DTC of three phase induction motor. Depending on the induction motor operating point such vectors might be applied and consequently the electromagnetic torque ripple is reduced. Simulation results demonstrate the effectiveness of the proposed control scheme was presented. Both, steady-state and transient behaviour have been investigated.

II. DTC AND DTC MATRIX CONVERTER (DTC-MC) STRUCTURES

II.1. DTC STRUCTURES

The basic model of DTC induction motor scheme is shown in Fig. 1. At each sample time, the two stator currents i_{sa} and i_{sb} and the DC bus voltage V_{dc} are sampled. Using the inverter voltage vector, the α,β components of the stator voltage space vector in the stationary reference frame are calculated as follows.

$$\begin{cases} V_{s\alpha ref} = \frac{2}{3} V_{dc}\left(s_a - \frac{s_b+s_c}{2}\right) \\ V_{s\beta ref} = \frac{1}{\sqrt{3}} V_{dc}(s_b - s_c) \end{cases} \tag{1}$$

The α,β components of the stator current space vector are calculated using

$$\begin{cases} I_{s\alpha} = i_{sa} \\ I_{s\beta} = \frac{i_{sa}+2i_{sb}}{\sqrt{3}} \end{cases} \quad (2)$$

The stator flux is a function of the rotor flux which is provides from the flux observer.

$$\begin{cases} \varphi_{s\alpha} = \sigma L_s I_{s\alpha} + \frac{M}{L_r}\varphi_{r\alpha} \\ \varphi_{s\beta} = \sigma L_s I_{s\beta} + \frac{M}{L_r}\varphi_{r\beta} \end{cases} \quad (3)$$

Then the magnitude of the stator flux is calculated by

$$|\varphi_s| = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \quad (4)$$

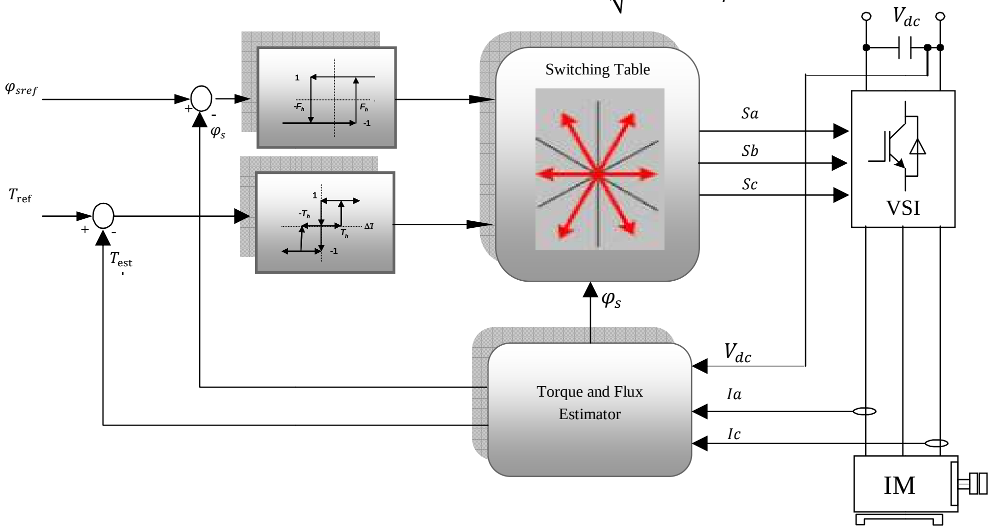


Figure. 1. Block diagram of classical DTC

The electromagnetic torque is calculated by

$$T_e = \frac{3}{2}p(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}) \quad (5)$$

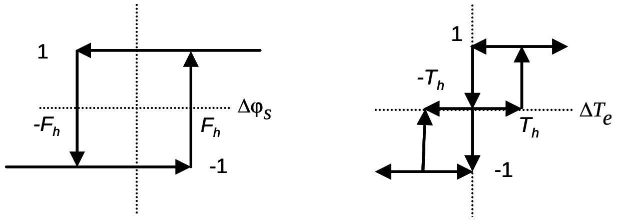
where *p* is the number of pole pairs.

The torque and flux errors are defined as

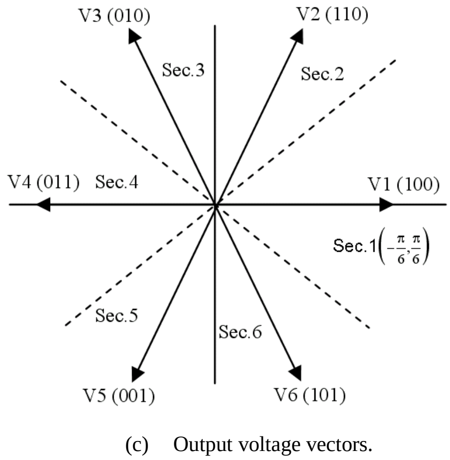
$$\begin{cases} \Delta\varphi_s = |\varphi_{sref}| - |\varphi_s| \\ \Delta T_e = T_{ref} - T_e \end{cases} \quad (6)$$

The inverter switching states are determined by the torque and flux errors according to the sector determined.

In order to maintain the estimated stator flux and torque within their boundaries which are determined by the two hysteresis bandwidths as shown in figure 2a & 2b, at each sampling period, the torque and the stator flux are estimated and compared with the corresponding reference values before passing the hysteresis comparator. The position of the stator flux is detected, and the most suitable space vector among 8 space vectors generated by a VSI is selected from the switching table given in Table 1 to compensate the load torque and the stator flux.



(a) Flux comparator. (b) Three-level torque comparator.



(c) Output voltage vectors.

Figure.2. DTC definition of the voltage vectors and comparators.

Table 1. Classical DTC Switching table.

		Sector 6 $(-\frac{\pi}{2},-\frac{\pi}{6})$	Sector 5 $(-\frac{\pi}{6},,\frac{\pi}{6})$	Sector 4 $(\frac{\pi}{6},\frac{\pi}{2})$	Sector 3 $(\frac{\pi}{2},\frac{5\pi}{6})$	Sector 2 $(\frac{5\pi}{6},\frac{7\pi}{6})$	Sector 1 $(\frac{7\pi}{6},\frac{9\pi}{6})$
Decrease Flux	Increase Torque	100	110	010	011	001	101
	Decrease Torque	011	001	101	100	110	010
Increase Flux	Increase Torque	110	010	011	001	101	100
	Decrease Torque	001	101	100	110	010	011

II.2. DTC MATRIX CONVERTER (DTC-MC) STRUCTURES

Figure 3 shows a schematic block diagram of the matrix converter has a simple topology and a compact design due to the lack of DC-link capacitor for energy storage.

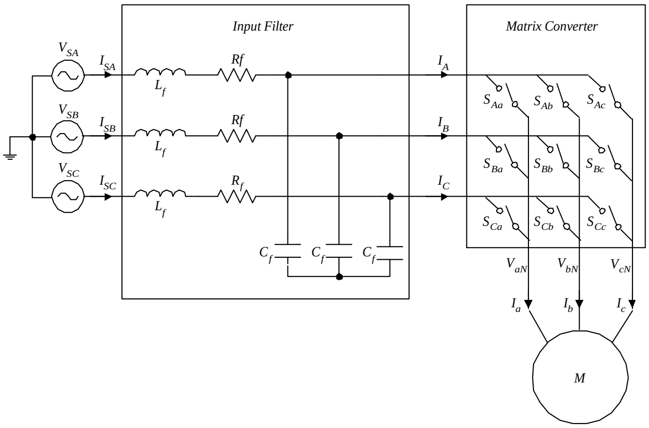
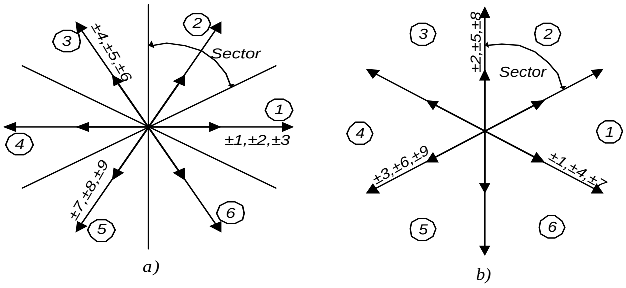


Figure3. Matrix converter schematic block diagram

Matrix Converter Theory

The three-phase matrix converter module includes nine bi-directional switches as shown in Figure 1. There are 27 switching configuration states, which mean 27 possible space vectors can be used to control IM and can be split respectively into 3 groups as shown in Table 1; in Group I, two output lines are connected to one of the other input lines; in Group II, all output lines are connected to a common input line; while in Group III, each output line is connected to a different input line. The corresponding output line-to-neutral voltage vector and input line current vector have fixed directions as represented in Figure 2. However, Group III is not useful. Only 18 non-zero space vectors in Group I (±1, ±2, …, ±9) and 3 zero space vectors in Group II (0a, 0b, 0c) can be usually employed in the modern control techniques for the matrix converter (such as the Space Vector Modulation, DTC methods, etc.)



a) Output line-to-neutral voltage vectors

b) Input line current vectors

Table2. Possible Switching Configurations of MC

Group	Vector	A	B	C	v_s	α_0	i_i	β_i
I	$+1_{MC}$	a	b	b	$2/3v_{ab}$	0	$2/\sqrt{3}i_{sa}$	-π/6
	-1	b	a	a	-2/3v	0	$-2/\sqrt{3}i$	-π/6
	$+2_{MC}$	b	c	c	$2/3v_{bc}$	0	$2/\sqrt{3}i_{sa}$	π/2
	-2_{MC}	c	b	b	$-2/3v_{bc}$	0	$-2/\sqrt{3}i_{sa}$	π/2
	$+3_{MC}$	c	a	a	$2/3v_{ca}$	0	$2/\sqrt{3}i_{sa}$	7π/6
	-3_{MC}	a	c	c	$-2/3v_{ca}$	0	$-2/\sqrt{3}i_{sa}$	7π/6
	$+4_{MC}$	b	a	b	$2/3v_{ab}$	2π/3	$2/\sqrt{3}i_{sb}$	-π/6
	-4_{MC}	a	b	a	$-2/3v_{ab}$	2π/3	$-2/\sqrt{3}i_{sb}$	-π/6
	$+5_{MC}$	c	b	c	$2/3v_{bc}$	2π/3	$2/\sqrt{3}i_{sb}$	π/2
	-5_{MC}	b	c	b	$-2/3v_{bc}$	2π/3	$-2/\sqrt{3}i_{sb}$	π/2
	$+6_{MC}$	a	c	a	$2/3v_{ca}$	2π/3	$2/\sqrt{3}i_{sb}$	7π/6
	-6_{MC}	c	a	c	$-2/3v_{ca}$	2π/3	$-2/\sqrt{3}i_{sb}$	7π/6
	$+7_{MC}$	b	b	a	$2/3v_{ab}$	4π/3	$2/\sqrt{3}i_{sc}$	-π/6
	-7_{MC}	a	a	b	$-2/3v_{ab}$	4π/3	$-2/\sqrt{3}i_{sc}$	-π/6
	$+8_{MC}$	c	c	b	$2/3v_{bc}$	4π/3	$2/\sqrt{3}i_{sc}$	π/2
	-8_{MC}	b	b	c	$-2/3v_{bc}$	4π/3	$-2/\sqrt{3}i_{sc}$	π/2
	$+9_{MC}$	a	a	c	$2/3v_{ca}$	4π/3	$2/\sqrt{3}i_{sc}$	7π/6
	-9_{MC}	c	c	a	$-2/3v_{ca}$	4π/3	$2/\sqrt{3}i_{sc}$	7π/6
II	0_a	a	a	a	0	-	0	-
	0_b	b	b	b	0	-	0	-
	0_c	c	c	c	0	-	0	-
III	x	a	b	c	x	x	x	x
	x	a	c	b	x	x	x	x
	x	b	c	a	x	x	x	x
	x	b	a	c	x	x	x	x
	x	c	a	b	x	x	x	x
	x	c	b	a	x	x	x	x

A. *DTC Principles Using Matrix Converter*

According to [9] , the basic DTC principles using matrix converters can be briefly described as follows: at each sampling period, the proper switching configuration, which allows the compensation of instantaneous errors in the stator flux magnitude and torque, is selected under the constraint of unity input power factor. This last requirement of the input side of the matrix converter is intrinsically satisfied if the average value of sin (ψ_i) is maintained close to zero, where ψ_i is the displacement angle between the input line voltage and input line current. The hysteresis comparator shown in figure 2a directly controls this variable and the average value of sin (ψ_i) is obtained by applying a low-pass filter to its instantaneous value. The average value of sin (ψ_i) is controlled close to zero because the input power factor is aimed close to unity.

As a facultative example, after calculation at the first time of each sampling period and considering the stator flux vector lying in sector 1, the input voltage vector lying in sector 2, the output of the torque hysteresis comparator, the flux hysteresis comparator and the hysteresis comparator of the average value of sin (ψi) are respectively $c_T = +1$, $c_\varphi = 0$ and $c_\psi = +1$. As shown in Figure 4, first with $c_T = +1$, $c_\varphi = 0$ and the stator flux in sector 1, the suitable voltage vector $V_{6\text{-vsi}}$ is the VSI output voltage vector by the DTC algorithm in a given switching period from Table 2. Then, with the chosen VSI voltage vector $V_{6\text{-vsi}}$, $c_\psi = +1$ and the input voltage vector in sector 2, the opportune matrix converter voltage vector is finally selected as V_{-5MC} from Table 3.The schematic of the DTC method using the matrix converter fed induction motor is represented in Figure 4. The reference values of the torque and the stator flux are compared with the estimated values and coordinate with the average value of the sin (ψ_i) hysteresis comparator. In the lower part of the block diagram, the estimators of the electromagnetic torque, stator flux and the average value of sin (ψ_i) are represented. These estimators require the knowledge of input and output of voltages and currents for the matrix converter. However, only the input voltages and the output currents of the matrix converter module are measured by sensors, while other quantities such as the input voltages of the induction motor and the input currents of the matrix converter module are calculated from the previous switching states, the input voltages and the output currents of the matrix converter module.

Table 3 DTC Switching Table Using MC

Sector of v_i	1		2		3		4		5		6	
c_Ψ	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
$V_{1\text{-vsi}}$	-3_{MC}	$+1_{MC}$	$+2_{MC}$	-3_{MC}	-1_{MC}	$+2_{MC}$	$+3_{MC}$	-1_{MC}	-2_{MC}	$+3_{MC}$	$+1_{MC}$	-2_{MC}
$V_{2\text{-vsi}}$	$+9_{MC}$	-7_{MC}	-8_{MC}	$+9_{MC}$	$+7_{MC}$	-8_{MC}	-9_{MC}	$+7_{MC}$	$+8_{MC}$	-9_{MC}	-7_{MC}	$+8_{MC}$
$V_{3\text{-vsi}}$	-6_{MC}	$+4_{MC}$	$+5_{MC}$	-6_{MC}	-4_{MC}	$+5_{MC}$	$+6_{MC}$	-4_{MC}	-5_{MC}	$+6_{MC}$	$+4_{MC}$	-5_{MC}
$V_{4\text{-vsi}}$	$+3_{MC}$	-1_{MC}	-2_{MC}	$+3_{MC}$	$+1_{MC}$	-2_{MC}	-3_{MC}	$+1_{MC}$	$+2_{MC}$	-3_{MC}	-1_{MC}	$+2_{MC}$
$V_{5\text{-vsi}}$	-9_{MC}	$+7_{MC}$	$+8_{MC}$	-9_{MC}	-7_{MC}	$+8_{MC}$	$+9_{MC}$	-7_{MC}	-8_{MC}	$+9_{MC}$	$+7_{MC}$	-8_{MC}
$V_{6\text{-vsi}}$	$+6_{MC}$	-4_{MC}	-5_{MC}	$+6_{MC}$	$+4_{MC}$	-5_{MC}	-6_{MC}	$+4_{MC}$	$+5_{MC}$	-6_{MC}	-4_{MC}	$+5_{MC}$

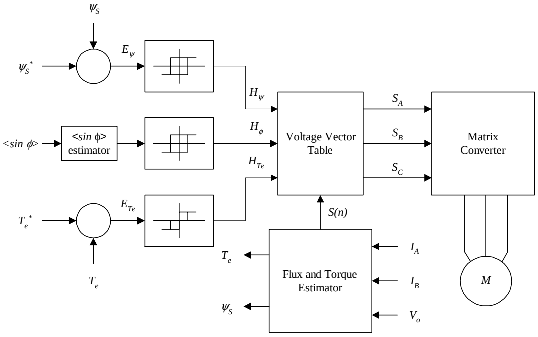


Figure 4. Block diagram of the DTC with MC

III. SIMULATION RESULTS

The classical DTC and DTC-MC are simulated and the comparison between the results is performed.

Stator flux linkage comparing curves are shown in Figure 5 and Figure 6.

Compared with two groups of flux waveform, the flux track amplitude of traditional DTC model is volatile. At certain parts, there is a clear deviation, flux required for a longer time to reach steady-state, the DTC Matrix Converter flux track has always maintained a very good round, flux is required for a short time to reach steady-state, and flux amplitude fluctuation is small.

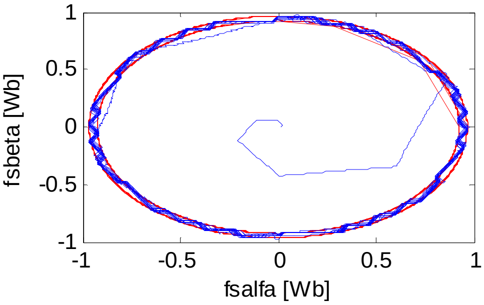


Figure.5. Stator flux circle based Classical DTC

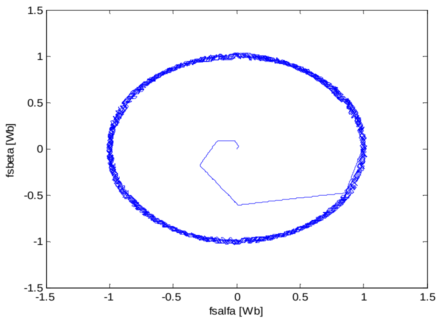


Figure.6. Stator flux circle based DTC Matrix Converter

From these results it can be seen a good torque responses for two methods,

However in DTC Matrix Converter technique shown Figure.8, the ripple of torque in steady state is reduced remarkably compared with Classical DTC (Figure 7).

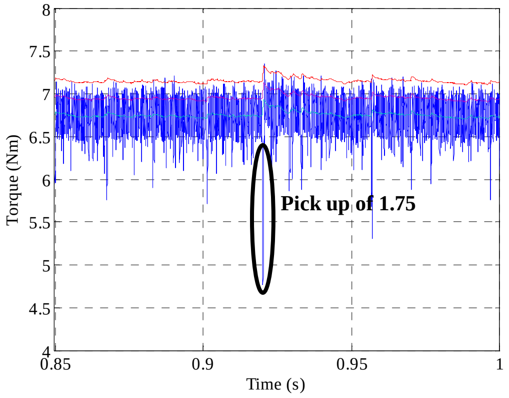


Figure.7. Torque response based Classical DTC

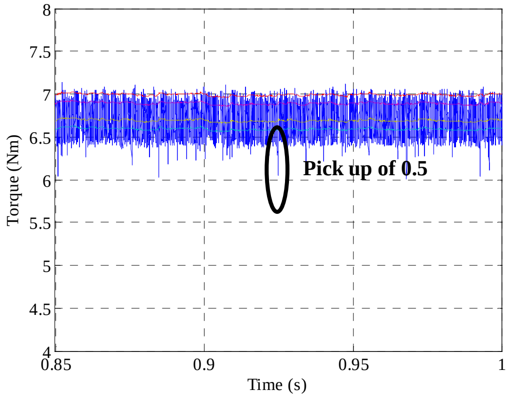


Figure.8. Torque response based DTC Matrix Converter

Figures. 9 and 10 show the steady state and speed signals of the DTC and DTC Matrix Converter, under (w_{ref}=100% rated speed and T_L=100% rated torque).

See figures, a good tracking performances can still be achieved even at the steady state (see Figure.9), and good speed reversal responses for two methods, However DTC Matrix Converter has a better performance; since the speed and steady state response method possesses less ripples in compare classical DTC.

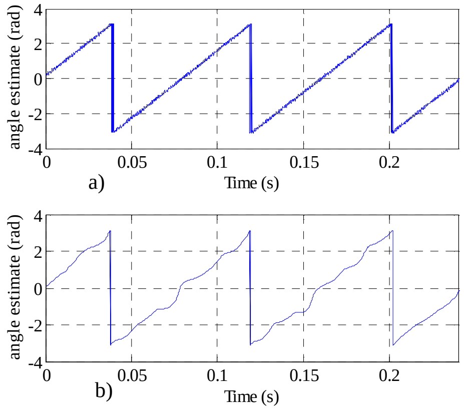


Figure 9. Simulation results of Steady state at 375 rpm :a) Classical DTC, b) DTC Matrix Converter

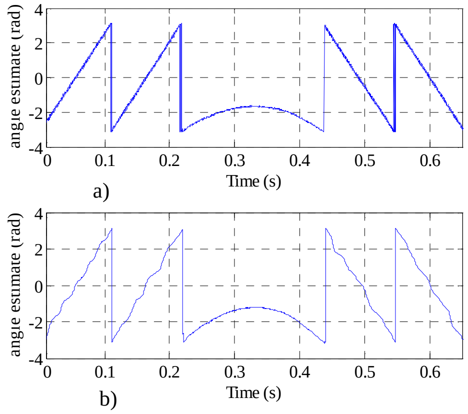


Figure 10. Simulation results of Speed reversal: a) Classical DTC, b) DTC Matrix Converter

IV. CONCLUSIONS

This paper presents a Direct Torque Control with Matrix Converter method for induction motor. The advantages of the DTC method have been successfully combined with the SVM method on matrix converter. The simulation results prove the excellent transient torque response for both proposed methods. The DTC Matrix Converter method has a better performance. Since the torque control and torque ripples reduction was the main goal, the speed and steady response of DTC Matrix Converter method possesses less ripples in compare classical DTC.

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