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Direct Torque Control for Matrix Converter Driven PMSM

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ABSTRACT

This paper carries work on application of direct torque control for Five-Phase permanent magnet synchronous motor drives. In recent years, only voltage source inverters (VSIs) have been used to supply five-phase drives, but Matrix converters (MCs) pose many advantages over conventional VSIs, such as lack of dc bulk capacitors, high quality power output waveform and higher number of output voltages. Due to some special applications of multiphase machines such as ship propulsion and aerospace, the volume of these drives is an important challenging problem. In this paper, direct torque control (DTC) algorithm using a three-to-five phase Matrix Converter is proposed for five-phase permanent magnet synchronous motors (PMSMs). Because of higher number of output voltages in MCs, there is a greater degree of freedom to control the torque and flux. In other words, this proposed method use the advantages of both DTC method and MCs. Simulation results show the effectiveness of presented method.

Keywords - DTC, matrix converter, five-phase PMSM, Switching Vector

I. INTRODUCTION

Permanent magnet machines have been used in the last three decades. They appear in several different stator and rotor structures and can be used in almost all kinds of application where traditional machines are used. Their main features and advantages are : higher efficiency, high torque/volume relationship. Unfortunately, some of these advantages refer only to machines built with high energy magnets, which are still expensive, despite the introduction of new materials and improved production techniques[1]. This feature has restricted the use of permanent magnet machines built with rare earth magnets to applications where cost is of secondary concern High phase number drives possess several advantages over conventional three phase drives such as: reducing the amplitude and increasing the frequency of torque pulsations, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, lowering the dc link current harmonics and higher reliability Since adjustable speed AC drives application requires a power electronic converter for their supply, the number of machine phases is essentially unlimited in drive applications . this has led to an increase in interest in multiphase AC drives applications[4] , especially in conjunction with traction , and ship propulsion .The first proposal for using a five phase induction motor drive system dates back to 1969[16] . Multiphase machines are therefore often considered for and applied in high power applications .The main driving forces behind this accelerated development have been three specific application areas, namely ship propulsion, “more-electric” aircraft, and traction (railway, electric vehicles, and hybrid electric vehicles).source inverters (VSIs), in the literatures related to the multiphase motor drives, only VSIs have been used to feed these motors.

In this paper, a new DTC of five-phase PMSM using three-to-five phase matrix converter is proposed. Input power factor is controlled to be kept close to unit. In the other word, the advantages of both DTC scheme and MC are used in this presented method. All of output voltage vectors of a three-to-five phase MC are obtained and the effects of these vectors on torque and flux variations are investigated and also a proper switching table is proposed. Simulation results show that using this presented switching pattern table, besides the control of input power factor, good and precise control in electromagnetic torque and flux is achieved.

II. BASIC DIRECT TORQUE FOR FIVE-PHASE PERMANENT MAGNET SYNCHRONOUS MOTOR

A five-phase VSI is illustrated in Figure 1. DTC is a vector control method used to control the torque and therefore the speed of the motor by controlling the switching sequence of the inverter transistors. Figure 3 shows the DTC for a PMSM block diagram. It can be seen that once one has the estimated and reference instantaneous values of electromagnetic torque and stator flux, we proceed to calculate the error between them; these errors are used as inputs for the hysteresis controllers, which aim to maintain the torque and flux errors within upper and lower limits allowed, so that when evaluating within these limits an output level is obtained to know the status of the variable. The output levels achieved in this stage of the control are input signals to the block that is responsible for finding the right vector to get rid of the speed error. This procedure is made for each sampling instant to drive the PMSM to the desired speed value[6]. Five-phase VSI inherently produce 32 output voltage space vectors with two zero vectors and thirty active voltage vectors as it shown in Figure 2. In a five phase system there are two orthogonal subspaces namely $D-Q$ subspace and $Z_1 - Z_2$ subspaces which are shown in Figure 3. As can be seen in this figure, these 32 voltage vectors are composed of three sets of different amplitudes namely small, medium and large vectors, respectively[7]. From the following equation, the output voltage vectors in $D-Q$ and $Z_1 - Z_2$ subspaces are obtained. If the upper switches of converter are closed, S is considered to be 1 and on contrary, if the lower switches are closed, S is 0.

$$\overline{V_0^{D-Q}} = \frac{2}{5} V_{dc}\left(S_A + S_B e^{j\frac{2\Pi}{5}} + S_C e^{j\frac{4\Pi}{5}} + S_D e^{-j\frac{4\Pi}{5}} + S_E e^{-j\frac{2\Pi}{5}}\right) \tag{1}$$

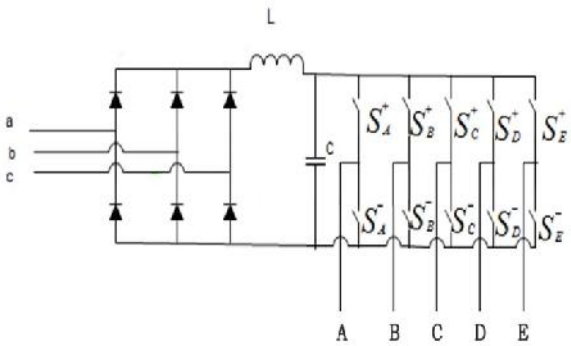

Fig 1. Five-phase voltage source inverter

The principle of selecting a voltage space vector in the conventional DTC of five-phase drive is similar as that in DTC of three-phase drives. It is shown in [7] that, for three-phase PMSM with uniform air gap, electromagnetic torque is

$$T_e = \left(\frac{3p}{2}\right)\left(\frac{1}{L}\right)\phi_{r\max}\left|\phi_s(t)\right|\sin\delta \tag{2}$$

Where, $|\phi_S(T)|$ presents the amplitude of stator flux, $\phi_{r\ max}$ is explanatory of rotor flux permanent magnet, p is the number of poles and δ is angle between stator flux and rotor flux.

For a five-phase motor equation (2) can be rewritten as

$$T_e = \left(\frac{5p}{2}\right)\left(\frac{1}{L}\right)\phi_{rD-Q}\left|\phi_{sD-Q}(t)\right|\sin\delta \tag{3}$$

As it is shown in Figure 2, the switching pattern plane is divided to ten sectors. Each voltage vector has a radial component and a tangential component. The variation of radial component is related to stator flux variation and the variation of tangential component is related to variation of electromagnetic torque

According to aforementioned analysis, a switching table has been proposed in [10] which is shown in table.1. It should be noted that, $d\phi = -1$($d\phi = 1$), show that the stator flux linkage has to be decreased (increased). On the other hand, $dTe = -1$($dTe = 1$) is the explanatory of this fact that the electromagnetic torque has to be decreased (increased).

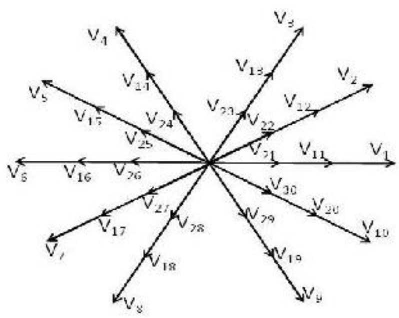

Fig 2. Thirty two voltage vector of a five-phase VSI

The block diagram of DTC of five-phase PMSM is illustrated in Figure 3. As it can be seen, the measured stator voltages and currents are transformed to stationary reference frame. In the next step, torque and flux are estimated by measured voltages and currents and will be compared with their corresponding target values. Then, the errors between target and actual values will be sent to hysteresis comparators[7]. By the outputs of hysteresis controllers and stator flux angle, a switching state will be selected from an offline switching table and command will be sent to the inverter.

Electromagnetic torque and stator flux are obtained using stator voltages and currents in stationary reference frame. Stator flux angle also can be achieved using equation (6).

$$T_e = \left(\frac{5}{2}\right)\left(\frac{p}{2}\right)\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right)$$

$$\psi_\alpha = \int \left(V_\alpha - R_s I_\alpha\right) dt$$

$$\psi_\beta = \int \left(V_\beta - R_s I_\beta\right) dt$$

$$\psi_s = \sqrt{\left(\psi_\alpha^2 + \psi_\beta^2\right)}$$

$$\angle \psi_s = tg^{-1} \frac{\psi_\beta}{\psi_\alpha} \tag{7}$$

Where, α is the direct axis and β is the perpendicular axis.

III. DIRECT TORQUE CONTROL USING MATRIX CONVERTER

Three-phase to Five-phase Matrix Converter

The power circuit topology of a three-phase to five-phase matrix converter is illustrated in Figure.4. As can be seen, there are five legs which each leg have three bidirectional switches in series[3].

Switching constraint is $S_{ka} + S_{kb} + S_{kc} = 1$. Where, $k = \{A, B, C, D, E\}$ is the output phase of the converter and $j = \{a,b,c\}$ is the input phase of the converter, S is the status of switches which 1 denotes that the switch is closed and 0 implies that the switch is open.

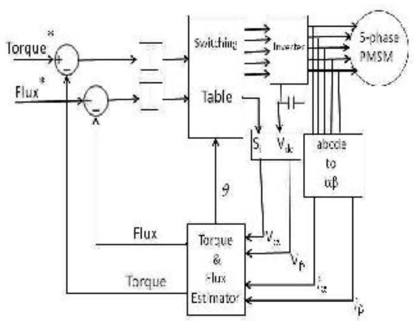

Fig 3. DTC of five-phase PMSM using standard VSI

The state of converter can be represented using following transformation matrix.

$$T = \begin{bmatrix} S_{Aa}(t) & S_{Ab}(t) & S_{Ac}(t) \\ S_{Ba}(t) & S_{Bb}(t) & S_{Bc}(t) \\ S_{Ca}(t) & S_{Cb}(t) & S_{Cc}(t) \\ S_{Da}(t) & S_{Db}(t) & S_{Dc}(t) \\ S_{Ea}(t) & S_{Eb}(t) & S_{Ec}(t) \end{bmatrix} \tag{4}$$

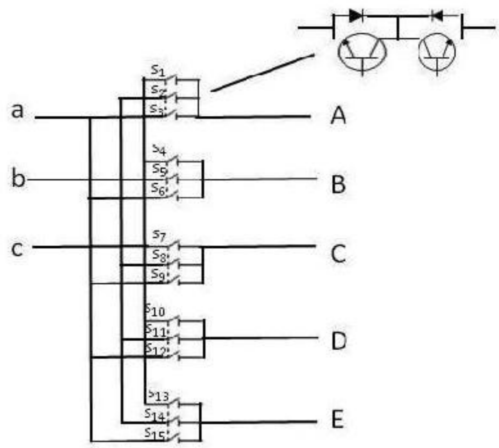

Fig 4. Schematic diagram of a three-phase to five-phase matrix converterUsing transformation matrix, we will obtain

$[V_0(t)] = [T][V_i(t)]$ (8)

$[T_i(t)] = [T^T][I_0(t)]$ (9)

Where, V_o and I_o are output voltage and output current vectors, respectively. Also, Vi and I_i are input voltage and input current vectors.

A three-phase to five-phase MC produce 3^5 = 243output voltage space vectors. Among these vectors, 93 vectors have fixed direction and called stationary vectors group[5]. As aforementioned for conventional five-phase VSIs, for a five-phase matrix converter, 30 output voltage space vectors are large vectors, 30 vectors are medium and the last 30 vectors are small vectors. It should be noted that three vectors are zero voltage space vectors. These 93 vectors consist of configuration which connects 4 of the output phases to one of the input phases and the fifth phase of output side is connected to another input phase (medium vectors). The other configuration of stationary vectors group connects 3 of the output phases to one of the input phases and the 2 other output phases to another input phase (Large and small vectors). If all of output phases are connected to a same input phase, zero voltage vectors will be produced[11]. As it has been mentioned in previous sections, using medium and small vectors in $D-Q$ plane, leads to large harmonics in stator current. Thus, in this paper authors only will use large voltage vectors of $D-Q$ subspace.

The space vector of output voltages can be expressed as follow

$$\overline{V}_0 = \frac{2}{5}\left(V_A + V_B e^{j\frac{2\Pi}{5}} + V_C e^{j\frac{4\Pi}{5}} + V_D e^{-j\frac{4\Pi}{5}} + V_E e^{-j\frac{2\Pi}{5}} \right) \tag{10}$$

Where V_A ,V_B ,V_C ,V_D and V_E are output line-to-neutral voltage vectors of five phase A,B ,C ,D and E , respectively.

In the same way, the space vector of input currents can be expressed as follow

$$\overline{I}_i = \frac{2}{3}\left(i_a + i_b e^{j\frac{2\Pi}{3}} + i_c e^{-j\frac{2\Pi}{3}} \right) \tag{11}$$

Where i_a , i_b and i_c are input line currents.

The switching states of a 3x5MC are shown in table 2. It should be noted that, only the large vectors of MC are shown in this table. The medium and small voltage space vectors are shown in tables A and B.

The block diagram of proposed DTC scheme is shown in Figure5. As it can be seen, the basis of this proposed DTC algorithm is as same as classical DTC. But, in each sampling period, in addition to measuring stator voltage and currents, voltage and currents of input side of MC should be measured to specify the sector that input line-to-neutral voltage vector lies in. Also, the current and voltage angle difference is measured and is sent to controller. Controller imposes this displacement angle to be close to zero. Thus, a close to unity input power factor will be obtained.

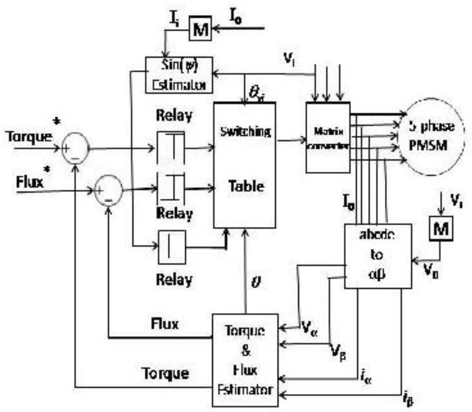

Figure 5: Schematic diagram of proposed DTC using matrix converter

IV. SIMULATION RESULTS AND DISCUSSION

The models of the PMSM, VSI and basic DTC algorithm are developed in Matlab/Simulink in order to examine the complete behavior of the basic DTC. In comparison with basic model, matrix converter driven PMSM was considered with DTC methodology. Various tests have been carried out in order to investigate the drive performance and to characterize the steady-state and transient behavior. The parameters of motor are P=4, d-axis Inductance is 18mH, q-axis inductance is 42mH, Inertia 0.025 Kgm^2, Stator Resistance 0.7 ohms

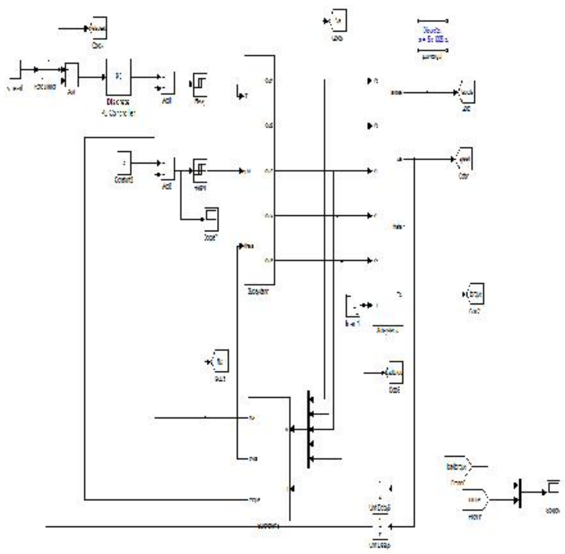

Figure 6: Simulink model of proposed system

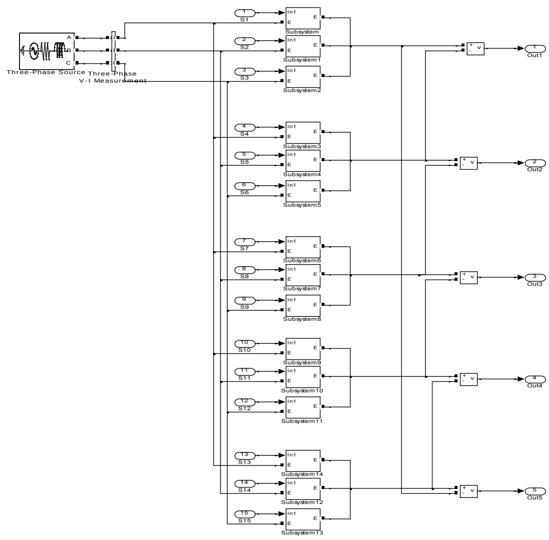

Figure 7: Simulink model for matrix converter

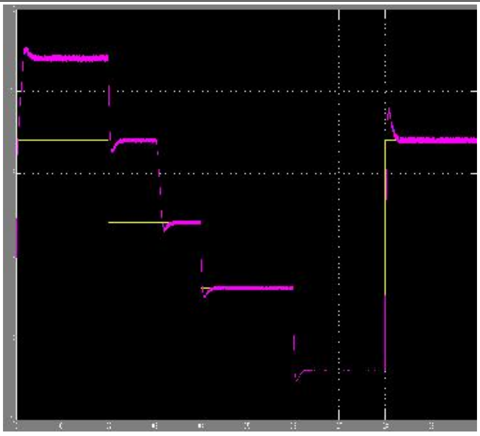

Figure 8: Reference torque and load torque for classical DTC

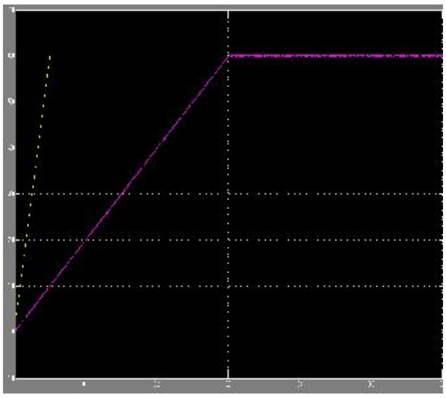

Figure 9: Reference speed and machine speed for classical DTC

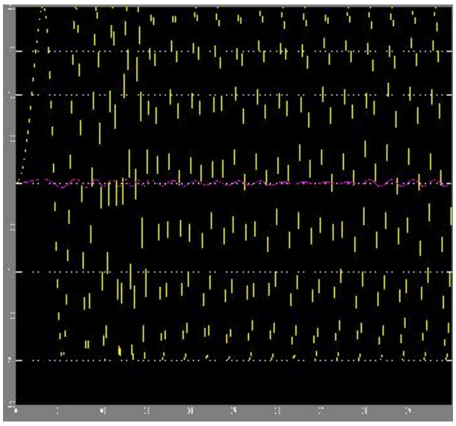

Figure 10: Filtered current and corresponding phase voltage for classical DTC

Figure.8, Figure.9 and Figure.10 show the characteristics of electromagnetic torque, speed , stator current and corresponding phase voltage for classic DTC in rotor speed of 600 rpm respectively. As it is shown in these figures, in classic DTC method electromagnetic torque and stator flux follow their references slowly. Stator current is distorted because of large magnitude of third harmonic currents. The command torque changes from 7 N.m to 2 N.m at 0.2 sec, from 2 N.m to -2 N.m at 0.4 sec , from -2 N.m to -7 N.m at 0.6 sec, from -7 N.m to 7 N.m at 0.8 sec .the load torque is following the command torque slowly and it has an high over shoots and undershoot, high settling time for every command torque change Filtered input line current and its corresponding line-to-neutral voltage are shown in Figure.10.

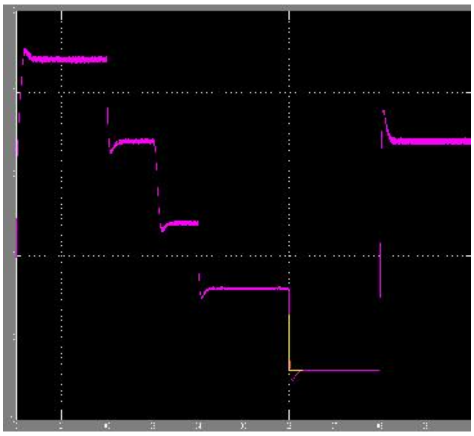

Figure 11:.1laod torque and reference torque for matrix converter based DTC

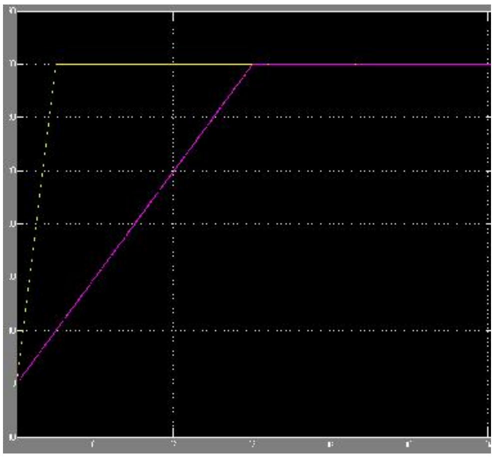

Figure 12: 1machine speed and reference speed for matrix converter based DTC

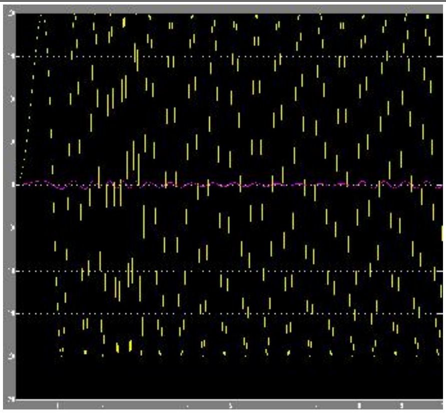

Figure 13: Filtered current and corresponding phase voltage for matrix converter based DTC

Figure.11, Figure12 and Figure.13 show the characteristics of electromagnetic torque, speed , stator current and corresponding phase voltage for matrix converter based DTC in rotor speed of 600 rpm respectively. As it is shown in these figures, the command torque changes from 7 N.m to 2 N.m at 0.2 sec, from 2 N.m to -2 N.m at 0.4 sec , from -2 N.m to -7 N.m at 0.6 sec, from -7 N.m to 7 N.m at 0.8 sec .the load torque is following the command torque very effectiveli and it has low over shoots low undershoot, very good settling time for every command torque change . Figure.13 shows that the Filtered input line current and its corresponding line-to-neutral voltage are very less distorted compared to classical DTC.flux ripples are less in matrix converter based DTC compared with classical DTC.

Figure.14 and Figure.14 shows that the stator flux for matrix converter based DTC and classical DTC

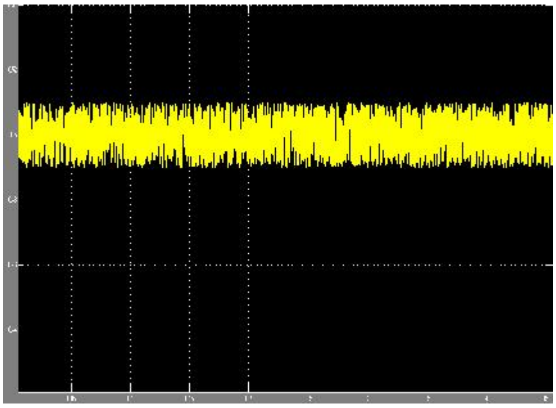

Figure 14: stator flux for matrix converter based DTC

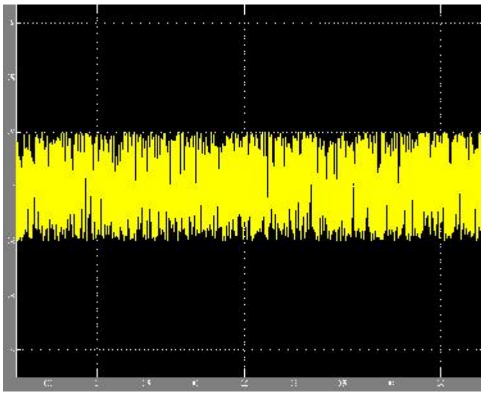

Figure 15: stator flux for classical DTC

V. CONCLUSION

The control of torque and flux is done through DTC algorithm has been proposed for matrix converter fed five-phase PMSMs. All of output voltage space vectors of a three-to-five phase MC have been extracted. It has been shown that, there are 93 output voltage vectors with fixes directions which can be use in DTC method. Moreover the torque and flux control, the input power factor has been controlled and kept close to unit. The presented method has been simulated, steady state situation, and dynamic performance were verified through results. In all of situation, torque and flux followed their reference values as well as VSI-fed (classic) drives and matrix converter drive were verified for input power factor improvement .all the simulation results shows that the matrix converter based DTC shows better results than classical DTC in terms of low ripple content in load torque, less distorted in phase current and corresponding phase voltage.

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