A SIMPLE METHOD OF TORQUE RIPPLE REDUCTION FOR DIRECT TORQUE CONTROL OF PWM INVERTER-FED INDUCTION MACHINE DRIVES

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***Abstract* – In conventional Direct Torque Control (DTC), a single stator voltage vector of the inverter standard topology is selected every control sampling period, and it is maintained for the whole period. This makes the torque and stator flux reference values to be reached quickly, with a small number of inverter switchings, resulting in a very good dynamic response. However, by this switching technique, based on hysteresis, large and small torque and flux errors are not distinguished, which cause an extra torque ripple in motor steady state operation. To overcome this problem, this paper proposes a simple solution, which consists in the modulation of the nonzero voltage vector duration over a sampling period, according to the instant values of the torque and stator flux errors. The introduced duty ratio is calculated using a relation containtaining terms proportional to these errors. The presented results show the torque, flux and current ripple reduction obtained by using the proposed method. Its main advantage is that it requires an insignificant additional computation, preserving the simplicity of the conventional DTC.**

Keywords: *Direct torque control, induction motor drives, torque ripple, pulsewidth modulation*

1. INTRODUCTION

Direct Torque Control (DTC) was introduced about twenty years ago by I. Takahashi and T. Noguchi [1] as a new performant control strategy for induction motor drives fed by Voltage Source Inverters (VSI). In 1996, DTC was introduced on the market by ABB [2], which consider it a viable alternative to Vector Flux Oriented Control (FOC).

The main advantages of DTC are the simple control scheme, a very good torque dynamic response, as well as the fact that it does not need the rotor speed or position to realize the torque and flux control (for this reason DTC is considerred a ”sensorless” control strategy). These advantages can be fully exploited in those electric drives where not the speed, but only the torque is to be controlled, for example in electric traction, where the torque reference is provided directly by the operator. For this kind of applications, DTC can be a very attractive option, because it is able to provide high dynamic performance at convenient costs.

However, the classical DTC has some drawbacks, and one of these is the significant torque and current ripple generated in steady state operation. Taking into account the large slopes of the resulted torque and the fact that only a single voltage vector is applied to the inverter in a control sampling period, the classical DTC needs high sampling frequencies (above 40 kHz [2]) to obtain a good steady state behavior. This requires high performance controllers, like the DSP, which rises the overall cost of the drive.

The problem of reducing the torque ripple in conventional DTC has been studied by many researchers, which have proposed solutions for it. One approach is to increase the number of voltage vectors applied in a sampling period, using some sorts of pulsewidth modulation (PWM). Among the possible choices, a simpler one is to use two voltage vectors: a nonzero one, applied for a fraction of the sampling period, and the null vector for the rest. The duty ratio (the ratio of active vector duration to the whole period) must be calculated each sample period, and by varying it between its extreme values, it is possible to apply more voltage levels to the motor, according to the desired torque variation. In [5], an analytical online algorithm calculates the optimum duty ratio each sampling period, by using a torque ripple minimization condition, wich is based on ripple equations. However, this algorithm requires high computational effort and additional motor parameters to be known. În [6] the duty ratio value is provided by a new fuzzy logic module, whose inputs are the stator flux position, the electromagnetic torque and an input defining the motor operating point, given by the speed and the torque values. This algorithm involves expert knowledge and needs the rotor speed.

This paper proposes a simple solution for reducing the torque ripple in classical Direct Torque Control, while preserving the good dynamic and structural simplicity of this scheme. The proposed method consists in the modulation of the nonzero voltage vector duration over a sampling period, according to the torque and stator flux errors. The algorithm for duty ratio calculation requires only a few arithmetic operations and is very easy to implement on a fixed point digital processor. There results are presented

for several motor operating points, to show the improved steady state operation as compared to conventional DTC.

2. DIRECT TORQUE CONTROL

The basic model of the classical DTC induction motor scheme is shown in Figure 1. It consists of torque and stator flux estimators, torque and flux hysteresis comparators, a switching table and a voltage source inverter (VSI). The configuration is much simpler than that of the FOC system where frame transformation, rotor position or speed sensors are required. The basic idea of DTC is to choose the best voltage vector in order to control both stator flux and electromagnetic torque of machine simultaneously [1].

At each sample time, the two stator currents i_{SA} and i_{SB} and DC-bus voltage U_{DC} are sampled.

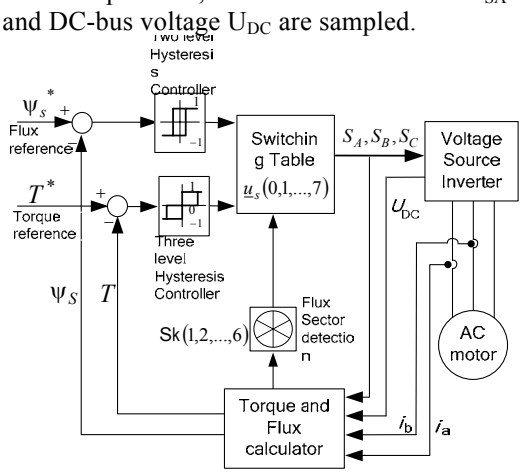


Figure 1: Block diagram of the conventional DTC

The $\alpha-\beta$ components of the stator voltage space vector in the stationary reference frame are calculated as shown in (1) and (2) [3].

$$u_{s\alpha} = \frac{2}{3}U_{DC}\left(S_A - \frac{S_B - S_C}{2}\right) \quad (1)$$

$$u_{s\beta} = \frac{2}{3}U_{DC}\frac{S_B - S_C}{\sqrt{3}} \quad (2)$$

where: S_A, S_B, S_C denote the inverter switching states, in which $S_i = 1\ (i = A, B, C)$, if the upper leg switch is on and $S_i = 0$, if the upper leg switch is off.

The $\alpha-\beta$ components of the stator current space vector are calculated using equations (3) and (4), supposing the motor has the star connection.

$$i_{s\alpha} = i_{sA} \quad (3)$$

$$i_{s\beta} = \frac{i_{sA} + 2i_{sB}}{\sqrt{3}} \quad (4)$$

Using the equations (1) – (4) and the stator resistance, the $\alpha-\beta$ components of the stator flux are calculated in (5) and (6):

$$\psi_{s\alpha} = \int (u_{s\alpha} - R_s i_{s\alpha})dt \quad (5)$$

$$\psi_{s\beta} = \int (u_{s\beta} - R_s i_{s\beta})dt \quad (6)$$

The circular trajectory of stator flux is divided into six symmetrical sections ($S_1 - S_6$) referred to inverter voltage vectors, as shown in Figure 2. The $\alpha-\beta$ components of the stator flux are used to determine the sector in which the flux vector are located.

Then using equations (3) – (6), the magnitude of the stator flux and electromagnetic torque are calculated in (7) and (8).

$$|\psi_s| = \sqrt{\psi^2{}_{s\alpha} + \psi^2{}_{s\beta}} \quad (7)$$

$$T_e = \frac{3}{2}P(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \quad (8)$$

where: P is the number of pole pairs
Rs is the Stator resistance.

The calculated magnitude of stator flux and electromagnetic torque are compared with their reference values in their corresponding hysteresis comparators, as are shown in Figure 1. Finally, the outputs of the comparators and the number of sector at which the stator flux space vector is located are fed to a switching table to select an appropriate inverter voltage vector [3]. As shown in Figure 2, eight switching combinations can be selected in a two-level voltage source inverter, two of which determine zero voltage vectors and the others generate six equally spaced voltage vectors having the same amplitude.

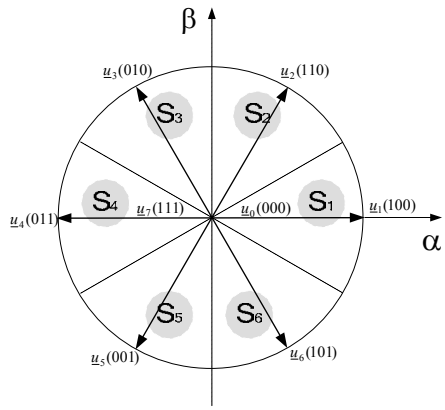


Figure 2: The inverter voltage vectors and the stator flux sectors

The selected voltage vector will be applied to the induction motor at the end of the sample time.

3. TORQUE RIPPLE REDUCTION

In conventional DTC, the voltage vector selection is based on the torque and flux errors, but small and large errors are not distinguished by the hysteresis controllers. The voltage vectors are applied for the entire sample period, even for small errors, resulting large torque overshoots in steady-state regime.

The proposed method for torque ripple reduction, presented in this paper, consists in the modulation of the nonzero voltage vector duration over a sampling period, according to the torque and stator flux errors, using simmetric PWM. The nonzero voltage vectors are selected using a switching table, like in classical DTC. The null vectors are automatically inserted by using PWM, so they are no more needed in the switching table. Consequently, in the proposed control scheme, shown in Figure 3, simple comparators, with no hysteresis, are used. A duty ratio calculator and a PWM block have been added to the classical scheme.

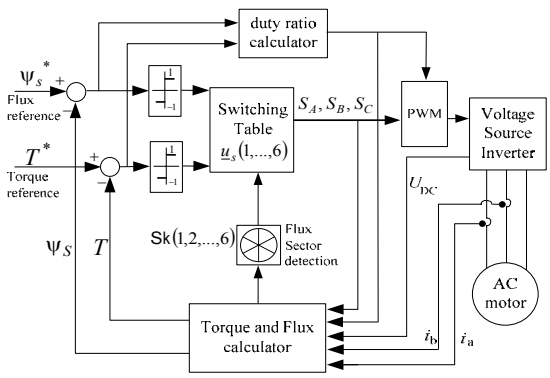


Figure 3: Block diagram of the proposed control

Every sample time, one of the six nonzero voltage vectors are selected from the switching table, and it is applied to the inverter using simmetric PWM switching strategy. The PWM period is considerred equal to the control sample period.

To apply to the inverter the selected voltage vector (denoting the corresponding inverter switching states S_i, $i = A, B, C$), with a given duty ratio, it was adopted the following method: for $S_i = 0$, the pulse duty ratio of the corresponding inverter leg takes zero value, otherwise it takes the calculated value. The calculation procedure of the duty ratio is presented below.

In order to preserve the very good dynamic response of the classical DTC, the proposed method for reducing the torque ripple is applied only when the actual torque value is located in a "proximity" zone, arround the reference value. This zone, whose width is denoted by Z_T, is similar to the torque hysteresis band of the classical DTC torque comparator. In other words, only for torque errors between $-Z_T$ and Z_T the voltage duty ratio is modified, otherwise it is kept at 100%.

For a preliminar approach, the duty ratio was taken equal to the normalized torque error – which means the ratio of the torque error, ε_T, to the zone width, Z_T – as shown in (9).

$$\delta_T = \left|\frac{\varepsilon_T}{Z_T}\right| \le 1 \qquad (9)$$

where: $\left|\frac{\varepsilon_T}{Z_T}\right|$ is the normalized value of the torque error

δ_T is the duty ratio corresponding to the torque error.

This first approach was tested and it was revealed that if only the torque error is taken into account, small values of the duty ratio conduce to stator flux decrease at low frequencies, when the voltage drop on the stator resistance becomes significant. The flux decrease determines the torque decrease, which consequently enlarges the duty cycle. However, this compensation is slow, generating flux oscillations. In order to avoid the flux decrease at low frequencies, the method was improved by taking into account also the flux error, which is normalized in the same manner as the torque error. The duty ratio corresponding to the flux error is considerred as a ratio of the rest of the sampling period, $(1-\delta_T)$, as in equation (10).

$$\delta_F = \left|\frac{\varepsilon_F}{Z_F}\right|(1-\delta_T) \qquad (10)$$

where: $\left|\frac{\varepsilon_F}{Z_F}\right|$ is the normalized value of the flux error

δ_F is the duty ratio corresponding to the flux error.

The final value of the duty ratio, which takes into account both errors is calculated in (11), so that it will be a fractionar value.

$$\delta = \delta_T + \delta_F = \left|\frac{\varepsilon_T}{Z_T}\right| + \left|\frac{\varepsilon_F}{Z_F}\right|\left(1 - \left|\frac{\varepsilon_T}{Z_T}\right|\right) \le 1 \qquad (11)$$

In Figure 4 is represented the duty ratio as function of normalized torque error $\left|\frac{\varepsilon_T}{Z_T}\right|$, for different constant values of normalized flux error $\left|\frac{\varepsilon_F}{Z_F}\right|$ (characteristics (a), (b) and (c)). The duty ratio δ is limitted to a minimum value, $\delta_{\min}$, in order to consider the maximum inverter switching frequency.

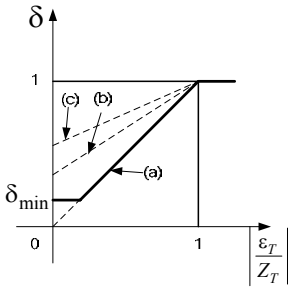


Figure 4: The characteristics of duty ratio (δ) for: (a) $\left|\frac{\varepsilon_F}{Z_F}\right|_{(a)} = 0$, (b) $\left|\frac{\varepsilon_F}{Z_F}\right|_{(b)} \neq 0$, (c) $\left|\frac{\varepsilon_F}{Z_F}\right|_{(c)} > \left|\frac{\varepsilon_F}{Z_F}\right|_{(b)}$

Every sample time, the duty ratio is calculated using the algorithm presented in Figure 5.

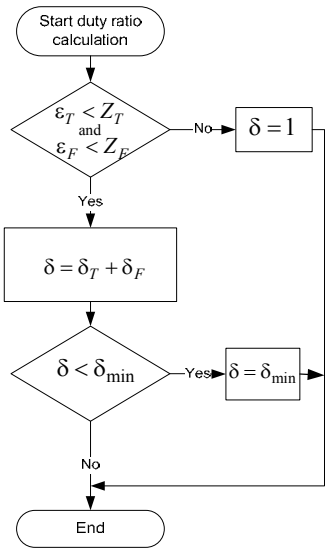


Figure 5: The online algorithm for duty ratio calculation

Considering the voltage duty ratio, the line voltage at the inverter output is given by (12).

$$U_l = \delta \cdot U_{DC} \tag{12}$$

where: U_l is the line voltage at the inverter output

U_{DC} is DC link voltage.

At current sample time, the $\alpha - \beta$ components of the stator voltage are calculated using (13) and (14), based on (1) and (2) respectively.

$$u_{s\alpha} = \frac{2}{3}\delta U_{DC}\left(S_A - \frac{S_B - S_C}{2}\right) \tag{13}$$

$$u_{s\beta} = \frac{2}{3}\delta U_{DC}\frac{S_B - S_C}{\sqrt{3}} \tag{14}$$

where δ is the duty ratio calculated at previous sample time.

4. RESULTS

The control schemes were implemented using Matlab-Simulink environment. Graphical results are presented for few operating points, showing the motor no load start-up and operation, followed by the operation with rated torque, which is applied as step at t=0.2s. The control sampling time was set to 100 μs.

The results obtained by conventional DTC are represented in Figure 6 and 7, for low and respectively high frequency.

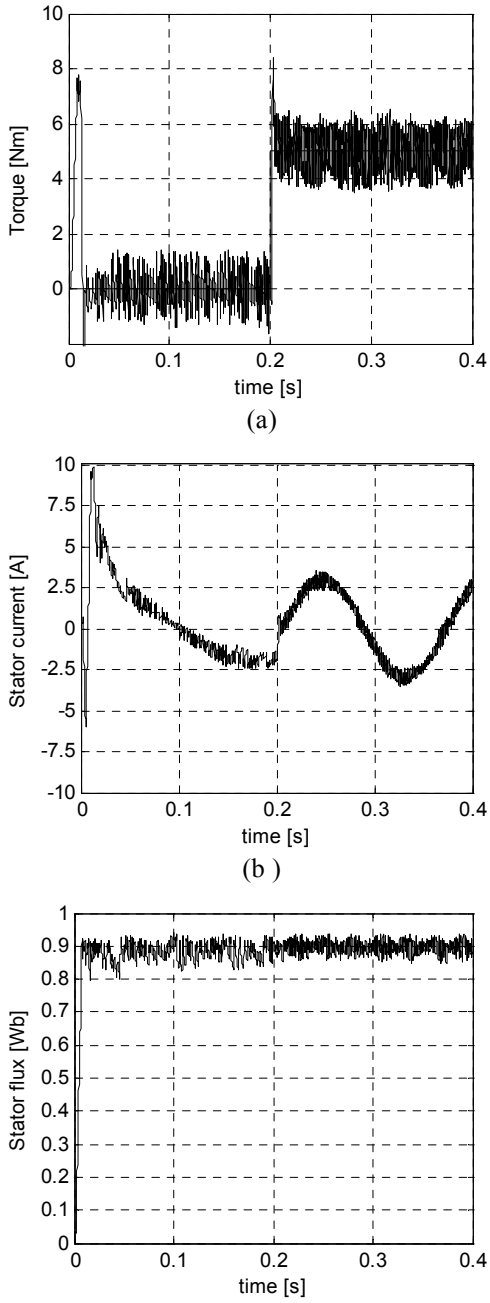
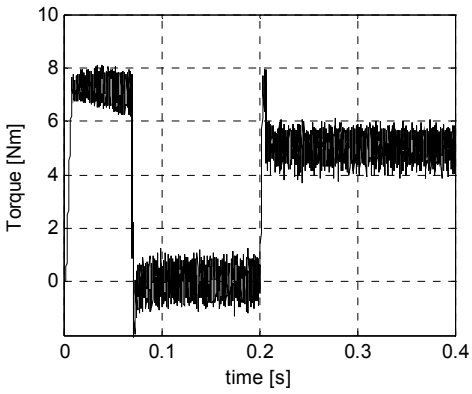
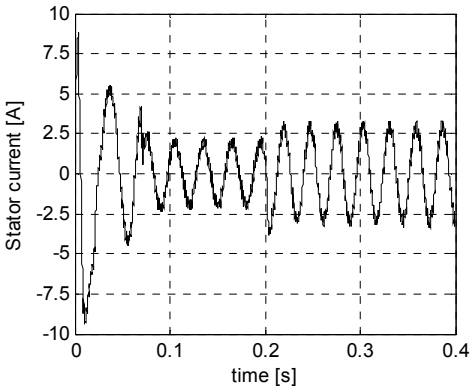


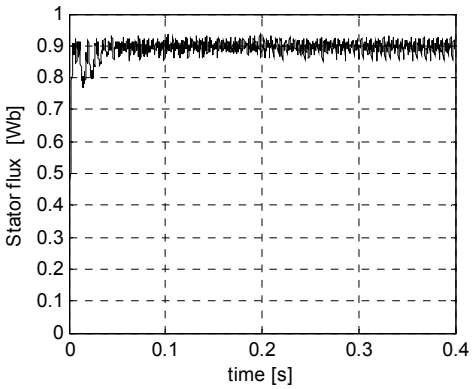
Figure 6: Classic DTC, at 100 rpm: (a) torque, (b) stator current, (c) stator flux magnitude



(a)



(b)



(c)

Figure 7: Classic DTC, at 1000 rpm: (a) torque, (b) stator current, (c) stator flux magnitude

In order to adequately illustrate the comparison between the conventional DTC and DTC with proposed improvement scheme, the torque and flux hysteresis bands widths were set (by trial and error) so that the torque and flux ripple to be as low as possible in conventional DTC:

$$HB_T = 0.11 \cdot T_n \text{ and } HB_F = 0.04 \cdot F_n$$

where: HB_T is the torque hysteresis band width

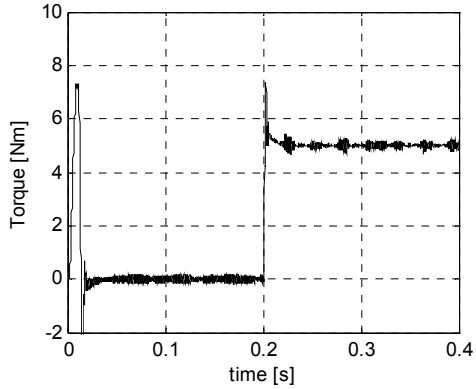
T_n is the motor rated torque,

respectively: HB_F is the flux hysteresis band width

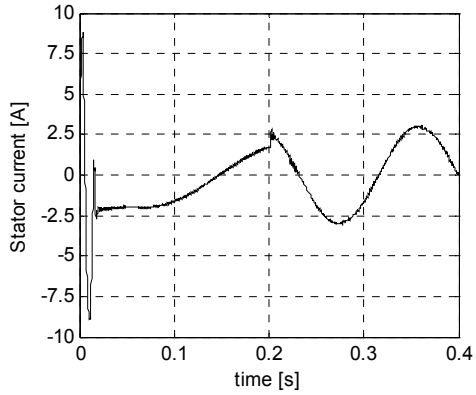
F_n is the rated flux.

In Figure 8 and 9 are shown the results obtained by DTC using the proposed solution for torque ripple reduction, for low and respectively high frequency. The voltage duty ratio is related to both the torque and flux errors, according to equation (11).

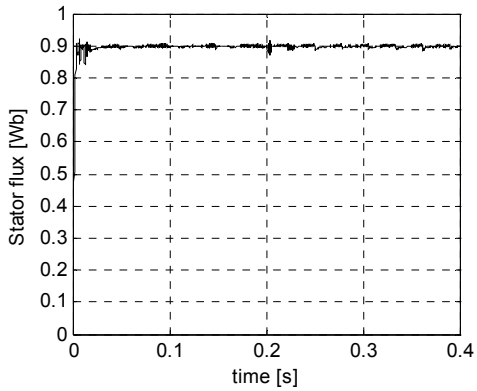
The zone widths Z_T and Z_F, introduced by the proposed method, were set to $0.1 \cdot T_n$ and $0.1 \cdot F_n$ respectively.



(a)

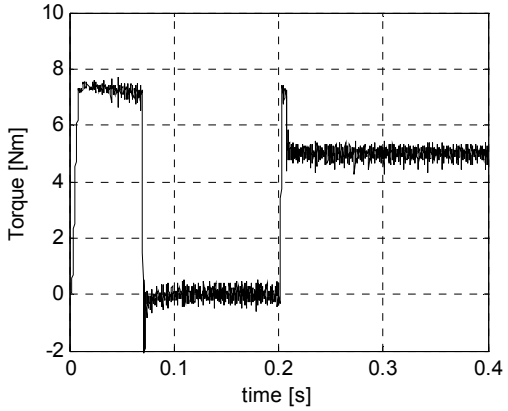


(b)

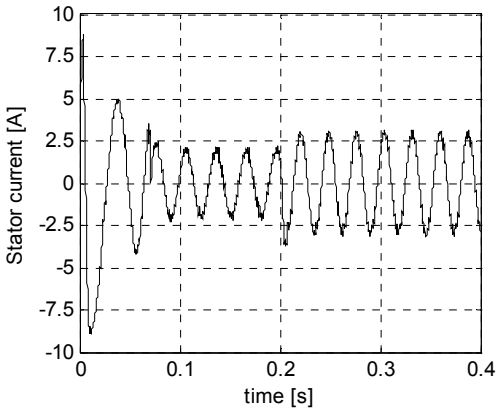


(c)

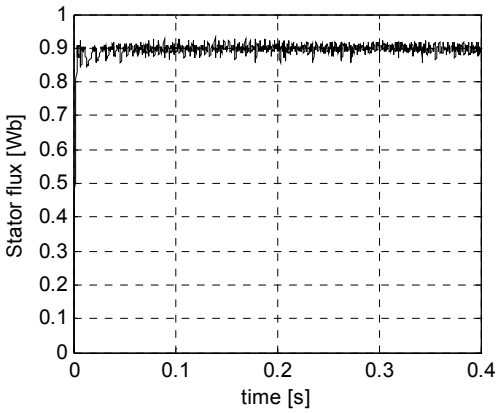
Figure 8: DTC with voltage control using the proposed method, at 100 rpm: (a) torque, (b) stator current, (c) stator flux magnitude



(a)



(b)



(c)

Figure 9: DTC with voltage control using the proposed method, at 1000 rpm: (a) torque, (b) stator current, (c) stator flux magnitude

The results show an important reduction of torque, current and flux ripple obtained when the proposed solution is used, comparing with the conventional DTC.

5. CONCLUSIONS

This paper presents a cost-effective solution for reducing the torque ripple in conventional Direct Torque Control, while preserving the dynamic response and structural simplicity of this control scheme.

The solution proposed uses PWM control of the voltage vector with duty ratio determined using a simple algorithm based on torque and flux errors. The results show that not only the torque ripple was reduced, but also the stator current and flux ripples. Compared with other methods for reducing the torque ripple in DTC, like [5] and [6], the proposed method is much simpler and does not need additional motor parameters or knowledge of the rotor speed.

Taking into account that today many microcontrollers and DSP offer PWM interfaces, the proposed method can be very easily implemented on them, adding very little computation effort to the classical DTC control algorithm.

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