A new predictive DTC strategy for a DC/AC inverter-fed Permanent Magnet Synchronous Machine

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Abstract
This paper presents a new Direct Torque Control of PMSM drive with a novel non-linear predictive torque and flux controller. The method is based on the prediction of the torque and flux error vector in order to minimize the torque ripple and ensure the constant switching frequency. Instead of using a single voltage vector during a sampling period of the controller, as is done in standard DTC strategy, an appropriately selected sequence of voltage vectors are used. The goal of the predictive control is to calculate optimal vectors application times, in order to minimize the torque and flux ripples. Furthermore, the use of the pulse width modulation provides a constant switching frequency for the voltage source inverter that feeds the motor.

The new control algorithm, presented in this paper, eliminates the disadvantages of the standard DTC method (high torque ripples) without deterioration of the dynamic properties of DTC, which constitute major advantages of non-linear control methods.

The correctness of the theoretical analysis and main assumptions of the proposed control method have been experimentally verified.

1. Introduction
The Direct Torque Control method was proposed in the mid 80’s by Takahashi and Noguchi [1]. It was a new approach to torque and flux control of the induction machine based on decoupled control of torque and flux. The control scheme of the DTC method proposed by Takahashi and Noguchi is shown in Fig. 1.

Torque and flux errors are the inputs of a three and two level hysteresis comparators respectively. The selection of appropriate voltage vector is based on the switching table. The input quantities are the outputs of the two hysteresis comparators and the stator flux vector.

The DTC method is widely researched and commercialized, because it is very simple in concept and easy to be implement (lack of coordinate transformation and current control loop).

In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. On the other hand, DTC also have some disadvantages. The major drawback is relatively high torque ripple and variable switching frequency, that depends on motor speed.

High torque ripples in the DTC method are caused by limited number of available voltage vectors and the presence of hysteresis comparators.

In recent years, a large number of modifications and improvements of the DTC have been done to eliminate the drawbacks of the standard method.

There are several ways to solve these problems. One of the methods that significantly reduces the torque ripples and ensures the constant switching frequency is direct torque and flux control with linear controllers and PWM modulators (DTC-SVM) [2]-[3]. Another alternative to increase the number of available voltage vectors is to use more than one voltage vector in one sampling period. Romeral et al. [4] proposed a method in which an on-line modulation between active and null vectors are applied. Vector application times calculation is based on rms torque-ripple equation minimization. In Casadei et al. [5] a simple switching table is replaced by several switching tables, obtaining a combination of three voltage vectors in the same switching period.
The new control algorithm, presented in this paper, ensures both the elimination of disadvantages of the standard DTC and very good dynamic properties of DTC, which are the major advantage of non-linear control methods. The proposed methods are based on torque and flux error vector minimization criteria. The control algorithm selects two or three voltage vectors per sampling time. The goal of the predictive control is to calculate optimal vector application times, in order to minimize the torque and flux error vector.

In practice this modulation is performed by using an inverter that supports SVM, which minimizes torque ripple by keeping constant switching frequency.

2. DTC method analysis

The DTC and the FOC methods have some similarities. In both cases the flux and torque are controlled, directly (DTC) or indirectly (FOC) by current components: \( I_{sd} \) (flux) and \( I_{sq} \) (torque). As a result, the analysis of the standard DTC method as well as the one proposed in this paper can be made by observing the behaviour of the current vector components and their influence on torque and flux error vector.

2.1 Machine equations

The equations used to model PMSM in stator-flux-oriented rotating reference frame are as follows:

\[
U_s = R I_s + \frac{d\Psi_s}{dt} + j p_b \omega_s \Psi_s
\]  
\[\Psi_s = L_s I_s + \Psi_{PM}
\]
\[T = \frac{3}{2} p_b \text{Im}(\Psi_s^* \cdot I_s)
\]

where \( U_s \) and \( I_s \) are stator voltage and current complex vectors, \( p_b \) is the number of pole pairs, \( L_s \) is synchronous inductance, \( \Psi_s \) is stator flux vector and \( \Psi_{PM} \) is permanent magnet rotor flux vector respectively.

2.2 Current vector derivatives

By substituting (2) into (1), current vector derivative can be obtained as:

\[
L_s \frac{di_s}{dt} = -(R_i I_s + j p_b \omega_s \Psi_s) + U_s
\]
\[D_{ixxx} = L_s D_{ixxx} = L_s \frac{di_s}{dt} = -U^* + U_s
\]

where \( L_s \) and \( R_i \) are synchronous inductance and stator resistance respectively. \( U \) is the set voltage vector. \( U \) is the input voltage vector of the inverter and is given by:

\[
U_s = \begin{cases} \frac{2}{3} U_d e^{j((n-1)\frac{\pi}{3} - \omega_s t)} & \text{"0"} \end{cases}
\]

where: \( U_d \) – DC link voltage.

The equation (5) describes the derivatives of the PMSM stator current vector [6]. The derivatives are caused by the application of the inverter voltage vectors.

Graphical illustration of formula (5) is shown in Fig 2. The derivatives of the current vector \( D_{ixxx} \) determine the direction and rate of changes of the current vector components and thus the direction and dynamics of the torque and flux changes.
3. Predictive DTC-3V strategy

3.1 Torque and flux error vector

Flux \( \varepsilon_\Psi \) and torque \( \varepsilon_T \) control errors are the components of complex error vector \( \varepsilon_{\Psi T} \). This vector should be standardized proportionally to a common reference frame, related with current:

\[
\varepsilon_{\Psi T} = \varepsilon_{\Psi} + j\varepsilon_T = c_\Psi \varepsilon_{\Psi} + j c_T \varepsilon_T
\]

(6)

After standardization of the error vector the analysis of the influence of the changes of current vector components on the error vector \( \varepsilon_{\Psi T} \) can be made.

The \( c_T \) and \( c_\Psi \) coefficients are defined as follow [7]:

\[
c_T = \frac{I_{qN}}{T_N}, \quad c_\Psi = \frac{1}{L_s}
\]

(7)

where: \( T_N \) – nominal torque, \( I_{qN} \) – nominal q-axis stator current.

Using equation (5) the predicted error vector in the next sampling period can be written as [7]:

\[
\varepsilon_{n+1} = \varepsilon_n + T_p (-D_{xxx}) = \varepsilon_n + T_p D_{xxx}
\]

(8)

where: \( T_p \) – sampling period.

3.2 Error vector minimization strategy

In the standard DTC method only one voltage vector is selected during sampling period \( T_p \), so the possibilities of minimizing the error vector are limited. Fig.3. shows the situation when one vector is used (a) and when the three voltage vector are applied (b).

In the first case the error vector can be moved to one of three points that are the vertices of an equilateral triangle. Therefore, to reduce the torque ripples, the control algorithm should work with short sampling time below 25\( \mu \)s.

In the second case, the error vector can be moved to any point lying inside the triangle (Fig. 3b). It can even be reduced to zero, if the origin of the

reference frame lies inside the triangle. If the last condition is true (which should be verified), we can use the DTC-3V algorithm.

The idea of the DTC-3V method is shown in Fig. 4. (for sector \( N=1 \)). Depending on sector number three appropriate voltage vector are selected. In sector \( N=1 \) there are 110, 010 and “0” vectors.

Zero voltage vector (111 or 000) is used during time \( t_{010} \) and 010 during time \( t_{010} \). Finally, vector 110 is used during time \( t_{110} \). The sum of these three time periods is equal to sampling period \( T_p \).

![Fig. 4. The idea of the predictive DTC-3V method.](image)

The predicted error vector at the end of sampling period is expressed as follows:

\[
\varepsilon_{n+1} = \varepsilon_n + t_{110} \cdot D_{110} + t_{010} \cdot D_{010} + t_{000} \cdot D_{000} = 0
\]

(7)

The Fig. 4 shows that, if the voltage vector application times are properly calculated, the predicted error vector is equal to zero, which means that the torque and flux errors have been exactly compensated. The main goal of this predictive control is to calculate optimal vector application times.

The \( t_{010}, t_{110} \) and \( t_{110} \) can be expressed as:

\[
t_{110} = a_{110} \cdot T_p, \quad t_{010} = a_{010} \cdot T_p, \quad t_{000} = a_{000} \cdot T_p
\]

(8)

where \( a_{xxx} \) are the relative voltage vector application times (in the range from 0 to 1). Their exact values are determined by the geometric relationship occurring in the equilateral triangle shown in Figure 4. It was theoretical proved that the equation (8) is satisfied if the \( a_{110}, a_{010} \) and \( a_{000} \) coefficients are given as follows:

\[
a_{110} = \frac{d_{110}}{h}, a_{010} = \frac{d_{010}}{h}, a_{000} = \frac{d_{000}}{h}
\]

(9)
where \( h \) is the height of the equilateral triangle and is expressed as:

\[
h = \frac{\sqrt{3}U_d}{3L_s}
\]  

(10)

The \( d_{xx} \) are the distances from the origin of the reference frame to each of the three lines containing a side of the triangle.

The control scheme of the presented method is shown in Fig. 5.

Torque and flux values are compared with the reference values. Next, the error vector is created and standardized proportionally to a common reference frame related with current (6),(7).

The proposed control strategy can be described as follows:

- Set voltage vector \( U^* \) is calculated from (4),
- Derivatives of the current vector are calculated from (5),
- The control algorithm verifies if the origin of the error reference frame lies inside the equilateral triangle from Fig. 4. If the condition is true then we use the DTC-3V control strategy. Otherwise, the transient state strategy (described in more detail in [7]) is used,
- The voltage vector application times are obtained from (8) and (9).

4. Experimental results

The effectiveness of the proposed control strategy is experimentally tested with a four-pole 2.8-kW PMSM drive, which is characterized by the nominal parameters: \( T_N=36 \text{ Nm}, n_N=750 \text{ rpm}, U_{DC}=350 \text{ V}, R_s=1.35 \Omega, L_s=0.01325H, \Psi_{PM}=0.56 \text{ Wb}. \)

All control algorithms are programmed in a ADSP-21262 32-bit floating point SHARC DSP. A three phase inverter of IGBT’s is used to feed the PM synchronous machine. Hall-effect sensors (LEM LA-55P and LV-25P) are used for current and voltage measurements, respectively. It should be noted that all current waveforms in the figures below show the real currents (not the sampled ones) measured by current probe connected to the scope.

The proposed DTC-3V strategy was compared with the conventional DTC.

The sampling time is equal \( T_p=50\mu s \) for the conventional DTC method and \( T_p=200\mu s \) for the proposed one, which means that the average switching frequency of both methods is comparable.

Figs. 11 and 12 show the motor torque, flux and phase current obtained with a rotor angular velocity of 50 rad/s for standard DTC (Fig. 10.) and the DTC-3V (Fig. 11.), respectively. In Figs. 13 and 14 the angular speed of the rotor is equal to 15 rad/s. It can be seen, especially at low motor speed, that the proposed predictive strategy brings less current and torque ripples, and the phase current shows good
The DTC-3V exhibits better steady state performance that is needed for servo drives with synchronous motors. The current THD coefficient is much lower in the DTC-3V (2%) than in standard DTC (6.4%).

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5. Conclusions

This paper has introduced the new predictive DTC-3V strategy that ensures the torque ripple minimization and constant switching frequency. With this proposed control scheme, it is possible to obtain a similar dynamic performance as with the conventional DTC. Instead of torque and flux comparators and a standard switching table a new, specific vector modulation is used. This approach allows us to combine the dynamic performance of DTC method with the advantages of the methods based on space vector modulation such as constant switching frequency and low torque ripples.

The torque ripples in the predictive DTC-3V method are much lower than in standard DTC in spite of the fact that the sampling time in the proposed method is four times longer than in standard DTC.

Moreover, the presented method is universal. It can be adopted to control the inverters fed PMSM, Induction Motors or to control the AC/DC converters [8],[9].

**Bibliography**


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