Investigation of predictive direct torque control of Double Star permanent magnet synchronous machine (DSPMSM)

Investigação do controle preditivo de torque direto da máquina síncrona de ímã permanente Double Star (DSPMSM)

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Mohamed Ghibeche
PhD Student in Electrical Engineering
Institution: Department of Electrical Engineering, University of Laghouat
Address: 37G Ghardaia Road – Laghouat, 03000 Laghouat, Algeria
E-mail: m.ghibeche@lagh-univ.dz

Katia Kouzi
Doctor in Electrical Engineering
Institution: Department of Electrical Engineering, University of Laghouat
Address: 37G Ghardaia Road – Laghouat, 03000 Laghouat, Algeria
E-mail: k.kouzi@lagh-univ.dz

Djamel Difi
Doctor in Electrical Engineering
Institution: Department of Electrical Engineering, National Polytechnic School
Address: 10 OUDEK Brothers Road, El Harrach 16200 Algiers, Algeria
E-mail: d.difi@yahoo.fr

Abdesslam Ouanouki
PhD Student in Electrical Engineering
Institution: Department of Electrical Engineering, University of Laghouat
Address: 37G Ghardaia Road – Laghouat, 03000 Laghouat, Algeria
E-mail: ouanouki81@yahoo.fr

ABSTRACT
In order to enhance the performance of Direct Torque Control (DTC) applied to a double-star permanent magnet synchronous machine (DSPMSM) in terms to reduce the ripples of torque and current, in this work we propose a Predictive DTC Control for DSPMSM. The primary objective of this control approach is to eliminate the hysteresis controllers and vector selection table commonly found in conventional DTC, addressing associated issues. This innovative strategy relies on Proportional-Integral (PI) controllers and Predictive Control, with both inverters operating at a constant frequency. In the proposed Predictive DTC Control, the predictive model is used to forecast the future behavior of the machine’s torque and current. This allows the control system to make more informed decisions regarding the optimal voltage vectors to apply, minimizing ripples and enhancing
the dynamic response. The simulation results, obtained from Matlab/Simulink, demonstrate a significant improvement in the performance of the DSPMSM when using the proposed method. Key metrics such as torque ripple, current ripple, and overall system efficiency were analyzed, showing favorable outcomes compared to conventional DTC methods. The study underscores the potential of predictive control in advancing the performance of DTC systems for DSPMSMs. By leveraging the capabilities of predictive modeling and PI controllers, the proposed method not only addresses the limitations of conventional DTC but also paves the way for more advanced and reliable control strategies in electric drive applications. The findings suggest that the implementation of Predictive DTC Control could lead to more robust and efficient motor drives, which are critical for various industrial applications requiring precise and stable torque control.

**Keywords:** DTC, predictive control, double star permanent magnet synchronous machine, cost function.

**RESUMO**
Com o objetivo de melhorar o desempenho do Controle Direto de Torque (DTC) aplicado a uma máquina síncrona de ímã permanente de estrela dupla (DSPMSM) no sentido de reduzir as ondulações de torque e corrente, neste trabalho propomos um Controle Preditivo de DTC para DSPMSM. O objetivo principal desta abordagem de controle é eliminar os controladores de histerese e a tabela de seleção vetorial comumente encontrados no DTC convencional, abordando os problemas associados. Esta estratégia inovadora conta com controladores Proporcionais-Integrais (PI) e Controle Preditivo, com ambos os inversores operando em frequência constante. No Controle Preditivo DTC proposto, o modelo preditivo é utilizado para prever o comportamento futuro do torque e da corrente da máquina. Isto permite que o sistema de controle tome decisões mais informadas em relação aos vetores de tensão ideais a serem aplicados, minimizando as ondulações e melhorando a resposta dinâmica. Os resultados da simulação, obtidos no Matlab/Simulink, demonstram uma melhoria significativa no desempenho do DSPMSM ao utilizar o método proposto. As principais métricas, como ondulação de torque, ondulação de corrente e eficiência geral do sistema, foram analisadas, mostrando resultados favoráveis em comparação com métodos DTC convencionais. O estudo ressalta o potencial do controle preditivo no avanço do desempenho dos sistemas DTC para DSPMSMs. Ao aproveitar os recursos de modelagem preditiva e controladores PI, o método proposto não apenas aborda as limitações do DTC convencional, mas também abre caminho para estratégias de controle mais avançadas e confiáveis em aplicações de acionamento elétrico. As descobertas sugerem que a implementação do Controle Preditivo DTC poderia levar a acionamentos de motores mais robustos e eficientes, que são críticos para diversas aplicações industriais que exigem controle de torque preciso e estável.

**Palavras-chave:** DTC, controle preditivo, máquina síncrona de ímã permanente de estrela dupla, função de custo.
1 INTRODUCTION

In recent times, double star permanent magnet synchronous motors have experienced a surge in demand due to their significant advantages over conventional three-phase machines. These benefits include high reliability, the capability to function in one or two phases in the event of a fault, reduced capacity, and increased frequency [5] [12] [13]. Additionally, these motors, by mitigating pulsing torque and reducing current per phase, find extensive use in numerous high-power applications, notably in the realms of high-power hybrid electric vehicles, aviation, as well as the propulsion systems of electric locomotives and ships [4] [7].

The conventional Direct Torque Control (DTC) strategy provides a viable solution to the issues associated with vector control. It stands out for its efficiency and straightforward implementation [6]. In this approach, inverter commutations are determined based on the output information of two hysteresis regulators (torque and flux) and the position of the stator flux. However, due to these regulators, the frequency of power switch control is not constant these results in a spectrum with rich harmonic content, leading to increased losses in the machine [10] [9].

To address the primary drawbacks of DTC stemming from variable frequency, an enhancement has been introduced through the implementation of Predictive Direct Torque Control (DTC) [2] [18]. This novel approach centers on achieving a consistent frequency for the inverters while minimizing torque ripple and flux. Additionally, it assesses the cost function for each available conversion state in the two-level inverters. This technique, known as Predictive DTC, serves as an alternative solution to mitigate the drawbacks associated with conventional DTC [14] [16].

The objective of this article is to implement the Predictive Direct Torque Control (DTC) approach for torque regulation of the double star permanent magnet synchronous machine (DSPMSM). This includes presenting the mathematical model of the synchronous machine and detailing the proposed control principle. Finally, the article aims to provide simulation results to assess the performance of this control strategy.
2 DOUBLE STAR PERMANENT MAGNET SYNCHRONOUS MACHINE (DSPMSM)

The double star permanent magnet synchronous machine features two stator windings, each displaced by an electrical angle of $\pi/6$ radians. Each stator consists of three identical windings with an equal number of poles. These windings have axes that are spatially separated by an electrical angle of $2\pi/3$, as illustrated in Figure 1 [02] [04].

![Figure 1: The presentation of DSPMSM](image)

Source: Authors.

2.1 DSPMSM DYNAMIC MODEL

The electrical model of double star PMSM in the reference (dq) is given by the following equations:

\[
\begin{align*}
    v_{d1} &= R_{s1}i_{d1} + L_{d1} \frac{dt}{dt}i_{d1} - \omega L_{q1}i_{q1} + M \frac{dt}{dt}i_{d2} - M\omega i_{q2} \\
    v_{q1} &= R_{s1}i_{q1} + L_{q1} \frac{dt}{dt}i_{q1} + \omega L_{d1}i_{d1} + M \frac{dt}{dt}i_{q2} + M\omega i_{d2} + \frac{3}{2}\omega f \\
    v_{d2} &= R_{s2}i_{d2} + L_{d2} \frac{dt}{dt}i_{d2} - \omega L_{q2}i_{q2} + M \frac{dt}{dt}i_{d1} - M\omega i_{q1} \\
    v_{q2} &= R_{s2}i_{q2} + L_{q2} \frac{dt}{dt}i_{q2} + \omega L_{d2}i_{d2} + M \frac{dt}{dt}i_{q1} + M\omega i_{d1} + \frac{3}{2}\omega f
\end{align*}
\]

The electromagnetic and mechanical torque equations are given by:
\[
\begin{align*}
T_e &= \frac{3}{2} p \left( (\varphi_{d1} l_{q1} - \varphi_{q1} l_{d1}) + (\varphi_{d2} l_{q2} - \varphi_{q2} l_{d2}) \right) \\
J \frac{d\Omega}{dt} + f\Omega &= T_e - T_r
\end{align*}
\]

(2)

2.2 VOLTAGE SOURCE INVERTER

The DSPMSM is powered by two three-phase two-level inverters, the mathematical model of VSI can be expressed as follows: [12]

\[
\begin{bmatrix}
v_{a1} \\
v_{b1} \\
v_{c1}
\end{bmatrix} =
\begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix}
\begin{bmatrix}
S_{a1} \\
S_{b1} \\
S_{c1}
\end{bmatrix}
\] (3)

\[
\begin{bmatrix}
v_{a2} \\
v_{b2} \\
v_{c2}
\end{bmatrix} =
\begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix}
\begin{bmatrix}
S_{a2} \\
S_{b2} \\
S_{c2}
\end{bmatrix}
\] (4)

Each inverter comprises three branches, with each branch housing two pairs of switches assumed to be ideal, operating independently and in a complementary manner. Within each inverter, there are eight distinct switching states, illustrated in Figure 2 (comprising six active vectors and two null vectors) [16].

![Figure 2: Two-level inverter Voltage vector selection](image)

Source: Authors.

3 DOUBLE STAR PMSM DIRECT TORQUE CONTROL STRATEGY

The Direct Torque Control (DTC) principle for a permanent magnet synchronous machine revolves around the direct manipulation of stator flux and torque without the need to control stator current. This is accomplished by directly
determining the command sequence applied to the switches of the inverters. Each inverter provides access to seven unique positions in the phase plane, which corresponds to the eight sequences of voltage vectors at the output of each inverter. The control of these voltage vectors is managed through a pre-calculated table [06].

3.1 STATOR FLUX ESTIMATION

The stator flux is expressed by the following equations:

\[
\begin{align*}
\phi_{s\alpha i} &= \int (v_{\alpha i} - R_{si}i_{\alpha i}) dt \\
\phi_{s\beta i} &= \int (v_{\beta i} - R_{si}i_{\beta i}) dt
\end{align*}
\]

\[i = 1, 2\] (5)

The modulus of the amplitude of the estimated stator flux is determined from the two components of the reference flux (α, β) by:

\[
\phi_{si} = \sqrt{\phi_{s\alpha i}^2 + \phi_{s\beta i}^2}
\] (6)

Where the rated voltage \(V_{s\alpha i}\) and \(V_{s\beta i}\) are obtained in the fixed reference frame (α, β) using the inverter model.

3.2 ELECTROMAGNETIC TORQUE ESTIMATION

Once the two components of flux and current are obtained, we can estimate the electromagnetic torque only according to the components (α, β), the torque can be put in the form:

\[
T_e = \frac{3}{2} p \left( (\varphi_{a1}l_{\beta 1} - \varphi_{\beta 1}l_{a1}) + (\varphi_{a2}l_{\beta 2} - \varphi_{\beta 2}l_{a2}) \right)
\] (7)

3.3 PREDICTIVE DTC CONTROL

In essence, the predictive model represents an extension of DTC, as it replaces the static DTC table with an online optimization process for controlling the torque and flux of the machine. In predictive control, the vector selection principle relies on the assessment of a predefined cost function. This means that the voltage vector chosen from the conventional switching table in DTC may not necessarily be the most effective in terms of reducing torque and flux ripples. Consequently, it
becomes possible to evaluate the effects of each voltage vector and select one that minimizes the cost function [13] [1].

### 3.4 PREDICTIVE MODEL FOR STATOR CURRENTS

According to model (1) for a double star PMSM, the prediction of the stator currents at the sampling time T is expressed in the following form:

$$\begin{align*}
    \frac{d}{dt} i_{d1(k+1)} &= i_{d1(k)} + \frac{T_s}{L_{d1}} (v_{d1} - R_{s1} i_{d1(k)} + \omega L_{q1} i_{q1(k)} - M \frac{d}{dt} i_{d2(k)} + M \omega i_{q2(k)}) \\
    \frac{d}{dt} i_{q1(k+1)} &= i_{q1(k)} + \frac{T_s}{L_{q1}} (v_{q1} - R_{s1} i_{q1(k)} - \omega L_{d1} i_{d1(k)} - M \frac{d}{dt} i_{q2(k)} - \omega M i_{d2(k)} - \sqrt{2} \sqrt{3} \omega \phi_f) \\
    \frac{d}{dt} i_{d2(k+1)} &= i_{d2(k)} + \frac{T_s}{L_{d2}} (v_{d2} - R_{s2} i_{d2(k)} + \omega L_{q2} i_{q2(k)} - M \frac{d}{dt} i_{d1(k)} - \omega M i_{q1(k)}) \\
    \frac{d}{dt} i_{q2(k+1)} &= i_{q2(k)} + \frac{T_s}{L_{q2}} (v_{q2} - R_{s2} i_{q2(k)} - \omega L_{d2} i_{d2(k)} - M \frac{d}{dt} i_{q1(k)} - \omega M i_{d1(k)} - \sqrt{2} \sqrt{3} \omega \phi_f)
\end{align*}$$

Ts: the sampling period

### 3.5 PREDICTED FLUX AND TORQUE ESTIMATION

The prediction of stator flux and torque is obtained based on the estimation in relation 5 as follows:

$$\begin{align*}
    \phi_{sai(k+1)} &= \phi_{sai(k)} + T_s (v_{ai} - R_s i_{ai(k+1)}) \\
    \phi_{sbi(k+1)} &= \phi_{sbi(k)} + T_s (v_{bi} - R_s i_{bi(k+1)})
\end{align*}$$

The expected electromagnetic moment in the system (α-β) can be given by the following formula:

$$T_e(k+1) = \frac{3}{2} p \left( (\varphi_{\alpha 1(k+1)} l_{\beta 1(k+1)} - \varphi_{\beta 1(k+1)} l_{\alpha 1(k+1)}) + (\varphi_{\alpha 2(k+1)} l_{\beta 2(k+1)} - \varphi_{\beta 2} l_{\alpha 2(k+1)}) \right)$$

### 3.6 MINIMIZATION OF THE COST FUNCTION

To evaluate the effect of each voltage vector when applied to the motor torque and stator flux the minimum value of the cost function is defined as follows[16]

$$F = |T_{er ef} - T_e(k+1)| + k|\varphi_{sire f} - \varphi_{sir(k+1)}|$$
K is the weighting factor. Where $T_{\text{eref}}$ and $\varphi_{\text{siref}}$ are the reference values of torque and flux respectively, $T_e(k+1)$ and $\varphi_s(k+1)$ are values of predicted torque and flux respectively.

This function will be calculated to obtain eight $V_s$ in each inverter from the set of switching states, of which six are active vectors, while the other two are zero. The vector that minimizes the cost function (11) is chosen [6].

$$v_{s1}^k \in \{v_1; v_2; v_3; \cdots v_6\}$$

$$v_{s1}^k \in \{v_1; v_2; v_3; \cdots v_6\}$$

4 SIMULATION AND INTERPRETATION

To assess the performance of Direct Torque Control (DTC) for the Double Star Permanent Magnet Synchronous Machine (DSPMSM) through simulation in the Matlab/Simulink environment, we conducted various robustness tests:

In Figure 3, we observe the DSPMSM's behavior under variable load conditions. Beginning with a no-load start at a reference speed of 100 rad/s, we introduced a variable load torque (10 Nm at $t = 0.5s$). The system exhibited satisfactory responses in terms of electrical and mechanical quantities, as the load variation had minimal influence on their values.

The speed promptly reached its reference, and the electromagnetic torque increased and closely followed its reference. This same trend was observed for the quadrature currents ($i_{q1,2}$).

For the Speed Variation Test, we introduced a load torque $T_r = 20$ Nm after a no-load start at time $t = 0.4s$. Subsequently, we reversed the direction of rotation, shifting from 100 rad/s to -100 rad/s at $t = 0.5$. Figure 4 displays the simulation results, illustrating that the system consistently and promptly adapts to this test across all operating intervals, with a response time nearly identical.
Figure 3: Dynamic and Static Characteristics of the Predictive DTC of the DSPMSM during Load Torque Variation

![Graph 1: Speed (rad/s) vs. Time (S)](image)

![Graph 2: Electromagnetic Torque (N.m) vs. Time (S)](image)

![Graph 3: Current (Iq (A)) vs. Time (S)](image)

![Graph 4: Current (Id (A)) vs. Time (S)](image)

Source: Authors.

Figure 4: Dynamic and Static Characteristics of the Predictive DTC of the DSPMSM when Reversing the Direction of Rotation

![Graph 1: Speed (rad/s) vs. Time (S)](image)

![Graph 2: Electromagnetic Torque (N.m) vs. Time (S)](image)

![Graph 3: Current (Iq (A)) vs. Time (S)](image)

![Graph 4: Current (Id (A)) vs. Time (S)](image)
5 CONCLUSION

In this paper, we investigated the application of DTC-Predictive control to a double star permanent magnet synchronous machine powered by two voltage inverters. Upon analyzing the results obtained with this control strategy, it is evident that the approach has demonstrated remarkable performance, particularly in terms of reducing torque ripple and stator current. Additionally, it exhibited a favorable dynamic response in torque production. This work can offer significant contributions to both society and academia:

Societal Impact: Implementing the Predictive Direct Torque Control (DTC) approach for double star permanent magnet synchronous machines (DSPMSMs) can lead to advancements in various industries, particularly those reliant on high-power electric motors. Applications such as high-power hybrid electric vehicles, aviation, electric locomotives, and ships can benefit from improved efficiency, reduced energy consumption, and enhanced performance. Ultimately, this could lead to a reduction in environmental impact through decreased energy usage and emissions in transportation and industrial sectors.

Academic Contribution: This research provides valuable insights and methodologies for academics and researchers working in the field of electrical engineering, specifically in the area of motor control and power electronics. The detailed presentation of the mathematical model of synchronous machines and the proposed control principle can serve as educational resources for students and professionals alike. Furthermore, the simulation results offer a basis for further studies, experimentation, and refinement of predictive control strategies, fostering ongoing advancements in motor control theory and practice.
By bridging the gap between theoretical research and practical implementation, this work facilitates knowledge transfer from academia to industry, driving innovation and technological progress in the field of electric motor control systems. Additionally, the dissemination of findings through academic publications and conferences can inspire further research, collaboration, and interdisciplinary exploration, ultimately enriching the collective understanding of electric motor control and its applications in society.

Despite its contributions, this research may have limitations that could be addressed in future studies. For instance, the proposed Predictive DTC approach may require further validation through experimental testing on real-world DSPMSM systems to confirm its effectiveness and reliability in practical applications. Moreover, for future researchs, such as investigating the scalability of the proposed approach to different motor sizes and operating conditions could enhance its applicability across a wider range of industrial settings.
REFERENCES


