IJRCS

International Journal of Robotics and Control Systems
Vol. 6, No. 1, 2026, pp. 190-203
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

ASCEE

Advanced Predictive DTC for Double-Star PMSM Using PI-Regulated Switching

Mohamed Ghibeche [a,1], Katia Kouzi [a,2], Abdesslam Ouanouki [a,3], Djamel Difi [b,4], Bachir Nail [c,5], Imad Eddine Tibermacine [d,6,*], Alfian Ma'arif [e,7]

[a] Department of Electrical Engineering, University of Laghouat, 37G Ghardaia Road Laghouat, Laghouat 03000, Algeria
[b] Department of Electrical Engineering, National Polytechnic School, 10 OUDEK Brothers Road El Harrach, Algiers 16200, Algeria
[c] Renewable Energy Systems Applications Laboratory (LASER), Faculty of Sciences and Technology, Ziane Achour University, Djelfa, Algeria
[d] Department of Computer, Automation and Management Engineering, Sapienza University of Rome, Via Ariosto, 25, 00185 Roma (RM), Rome, Italy
[e] Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[1] m.ghibeche@lagh-univ.dz; [2] k.kouzi@lagh-univ.dz; [3] a.ouanouki@lagh-univ.dz; [4] d.difi@yahoo.fr;
[5] b.nail@univ-djelfa.dz; [6] tibermacine@diag.uniroma1.it; [7] alfian.maarif@te.uad.ac.id
* Corresponding Author

ARTICLE INFO

Article history
Received October 01, 2025
Revised November 22, 2025
Accepted January 03, 2025

Keywords
Underactuated Mechanical System UMS;
Fractional-Order;
Sliding Mode Control;
Adaptive Fuzzy Type-3

ABSTRACT

This paper proposes an improved Predictive Direct Torque Control (DTC) strategy for Double-Star Permanent Magnet Synchronous Machines (DSPMSMs). Conventional DTC exhibits torque and flux ripples and variable switching frequency due to the use of hysteresis comparators and switching tables. To address these limitations, a hybrid predictive DTC approach is developed by integrating model-based prediction with Proportional–Integral (PI) regulators to maintain constant switching frequency in both inverters. The novelty of this work lies in the real-time coordination of the dual-inverter DSPMSM structure while simultaneously suppressing torque ripple and improving current waveform quality. The proposed control scheme is implemented in MATLAB/Simulink and evaluated under speed reversal and load disturbance conditions, and the obtained results demonstrate significant improvements in torque ripple suppression, current quality, and overall machine performance. These improvements demonstrate the effectiveness of the approach for high-performance electric drive applications. The study is currently limited to simulation validation, and future work will focus on real-time implementation and robustness evaluation under practical machine and inverter parameter uncertainties.

1. Introduction

Model Predictive Control (MPC) and Direct Torque Control (DTC) have become central strategies for high-performance electrical drives due to their fast dynamic response, direct manipulation of torque and flux, and suitability for modern power converters. Recent contributions in predictive torque and current control span a wide range of machine types, including switched

http://dx.doi.org/10.31763/ijrcs.v6i1.2255

reluctance motors (SRM), PMSMs, induction motors, multiphase machines, and dual-stator architectures. Early foundations in predictive torque control for SRM and PMSM highlighted efficiency and measurement reduction through optimized voltage-vector prediction [1], [2], with further developments demonstrating robust implementations in multi-machine systems such as series-connected five-phase PMSMs [3]. Model-free, data-driven, and multiphase predictive current control techniques have also emerged to reduce measurement burdens and improve adaptability in dual three-phase PMSMs, five-phase PMSMs, and multiphase drives [4]-[7].

A key evolution in MPC research concerns robustness against parameter variations, disturbances, and dead-time effects. Several works propose inductance/flux-linkage extraction algorithms, disturbance observers, sliding-mode observers, and optimized dead-time voltage-vector compensation [8]-[15]. These methods improve the reliability of predictive controllers in uncertain environments, while deadbeat predictive torque control and discrete SVM-based MPC schemes significantly enhance steady-state accuracy and transient response in PMSM drives [11], [12], [16]. Complementary research introduces dual-channel feedback MPC [13], robust sliding-mode predictive torque control for induction motors [14], and optimized-sector predictive torque control for SRM [15].

In recent years, attention has shifted toward torque- and flux-ripple reduction using multi-vector, three-vector, or weighting-factor-free predictive control strategies. Multi-vector predictive current control has shown strong ripple suppression in five-phase and six-phase machines using virtual vectors [6], [7], whereas advanced three-vector MPC methods for dual three-phase PMSMs reduce ripple and improve harmonic behavior [17]. Multi-vector finite-control-set MPC has been further refined in low-complexity versions for SPMSM and multiphase machines [18]-[20]. Additional contributions explore discrete SVM enhancements [16], weighting-factor-free DTC strategies [21], lookup-table-based MPC [22], and nonlinear efficiency-optimal MPC for induction machines [23]. Intelligent and hybrid schemes incorporating fuzzy logic, adaptive observers, immune chaotic PSO, and metaheuristic optimization also contribute to performance improvements in PMSM and SRM predictive control [10], [25]-[29].

Predictive torque control for multiphase and dual-stator systems has gained increased interest due to intrinsic benefits such as fault tolerance, reduced torque pulsations, and improved power density. Recent works investigate three-vector predictive torque control for dual three-phase machines [17], finite-set MPC for PMSG-based wind systems [30], and continuous-set MPC for electrically excited synchronous motors [31]. Several studies address the control challenges of SRMs with multi-leg inverters [25], voltage-vector parallel optimization for PMSMs [32], sliding-mode-observer-assisted MPC [26], and dual-torque duty-cycle MPC for PMSMs [33]. Open-end winding and nine-phase PMSM systems have been addressed using cost-free function MPC, fuzzy MPC, and zero-sequence current suppression techniques [34], [24].

Classical and advanced DTC research continues to serve as the primary benchmark for torque-regulation performance. Enhancements include load-capacity-aware five-phase PMSM DTC [36], hybrid DTC-SVM for multiphase machines [35], analytical torque-ripple modeling for PMSM [36], low-ripple DTC for IPMSM [37], optimized DTC-SVM using metaheuristics [38], and torque-ripple-suppression predictive strategies for induction machines [39]. Foundational contributions in predictive DTC further support modern developments [40]. Dual-stator and multi-stator research highlights specific challenges in harmonic-current mitigation, circulating-current suppression, and fault-tolerant control, with optimized synergetic control, sliding-mode approaches, and diagnostic methods developed for DSIM and DSPMSM systems [41]-[45]. Studies on DSPMSM behavior under nonlinear coupling, aerodynamic loading, and inter-turn-short faults emphasize the complexity of modeling and controlling dual-stator PMSMs [45]-[49]. Meanwhile, DSPMSM system identification, slot-number optimization, and magnetic-coupling analysis provide important insights for ripple minimization and machine design [47], [49].

Additional recent work highlights predictive control challenges in fault-tolerant operations, variable control periods, genetic-algorithm-based torque optimization, and flying-capacitor balance in multilevel inverters [27]-[29], [32], [50]. Advances in fuzzy FOC for seven-phase machines and synergetic control for dual-stator induction motors further reinforce the diversity of high-performance control methods applicable to multi-winding and dual-star drives [51], [52]. Classical modeling of dual-stator windings also remains fundamental to minimizing circulating harmonics and improving inverter compatibility [53].

Despite this extensive progress, several gaps remain. Most predictive DTC and MPC strategies have been optimized for conventional three-phase PMSM drives, while the DSPMSM-characterized by inter-stator coupling, potential circulating currents, and complex harmonic behavior-has received significantly less attention. Only a limited number of studies explore predictive control explicitly tailored to DSPMSM behavior [45]-[48]. Moreover, consistent switching-frequency control, low computational cost, and robustness against parameter variations remain open challenges, especially in industrial scenarios requiring real-time implementation. Finally, comparative studies between predictive DTC, MPC-SVM, and hybrid intelligent schemes for DSPMSM remain scarce, hindering unified assessment of performance versus computational complexity. Motivated by these gaps, the present work proposes a predictive DTC strategy specifically designed for DSPMSM drives. This positions the proposed method at the intersection of predictive control advances [54]-[58] and DSPMSM-specific requirements [40], [42], [59], [60].

The proposed strategy eliminates the need for hysteresis controllers and lookup tables while ensuring constant inverter switching frequency. Furthermore, a Proportional–Integral (PI) regulator is integrated with the predictive model to enhance steady-state performance and minimize torque and flux errors. This hybrid predictive–PI approach effectively reduces torque ripple, improves current waveform quality, and enhances the drive's overall stability and efficiency. The main contributions of this work are as follows:

1. Development of a predictive DTC framework tailored for DSPMSMs that removes hysteresis controllers and static lookup tables.
2. Integration of PI regulators within the predictive control loop to achieve constant switching frequency and superior torque–flux regulation.
3. Comprehensive simulation validation in MATLAB/Simulink, demonstrating significant reductions in torque ripple and harmonic distortion, and confirming the feasibility of the proposed control for high-performance DSPMSM applications.

The remainder of the paper is organized as follows. Section 2 is the methodology section and it is divided into two main subsections, the first one introduces the mathematical model of the DSPMSM, while the second one describes the proposed advanced predictive DTC methods. Section 3 discusses simulation results and performance analysis. Finally, Section 4 concludes the paper and outlines future research directions.

2. Methodology

This section presents the modeling and control design of the proposed Predictive Direct Torque Control (PDTC) strategy for the Double Star Permanent Magnet Synchronous Machine (DSPMSM). The main contribution lies in extending Model Predictive DTC (MP-DTC)-originally introduced by Geyer (2009) [40] for conventional PMSMs-to a dual-inverter DSPMSM configuration that explicitly considers magnetic coupling between the two stator windings. Unlike Mesloub (2016) [57], who applied predictive-PI control to a single-stator PMSM, the proposed method integrates a lightweight PI regulator directly within the predictive loop to achieve constant switching frequency while preserving dynamic torque and flux accuracy. The following subsections describe the modeling, estimation, predictive control, and implementation details. To provide a clear overview of the research workflow, Fig. 1 illustrates the sequence of operations in the proposed PDTC system. The flowchart summarizes the entire methodology from signal acquisition to torque control and inverter actuation. This diagram provides a concise roadmap that links all subsequent subsections, making the methodology easier to follow.

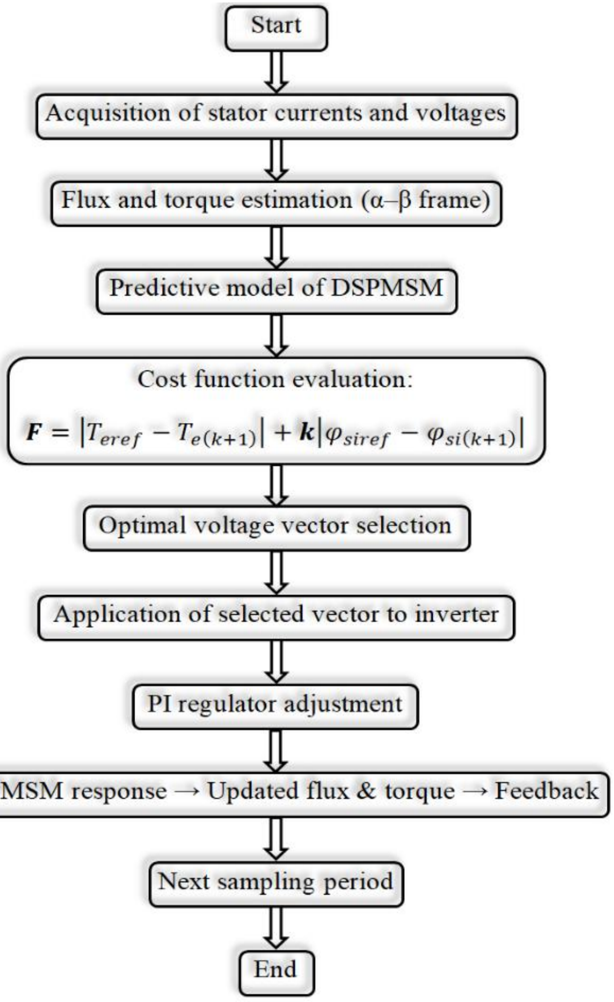

Fig. 1. Flowchart of the proposed predictive DTC strategy for DSPMSM

2.1. 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 π/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 2π/3, as illustrated in Fig. 2 [39], [41].

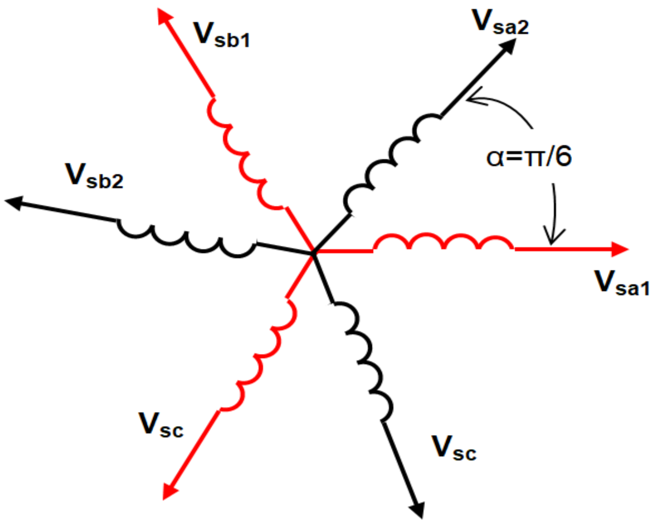

Fig. 2. The presentation of DSPMSM

2.1.1. DSPMSM Dynamic Model

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

$$\begin{cases} v_{d1} = R_{s1}i_{d1} + L_{d1}\dfrac{d}{dt}i_{d1} - \omega L_{q1}i_{q1} + M\dfrac{d}{dt}i_{d2} - M\omega i_{q2} \\ v_{q1} = R_{s1}i_{q1} + L_{q1}\dfrac{d}{dt}i_{q1} + \omega L_{d1}i_{d1} + M\dfrac{d}{dt}i_{q2} + M\omega i_{d2} + \sqrt{\dfrac{3}{2}}\omega\phi_f \\ v_{d2} = R_{s2}i_{d2} + L_{d2}\dfrac{d}{dt}i_{d2} - \omega L_{q2}i_{q2} + M\dfrac{d}{dt}i_{d1} - M\omega i_{q1} \\ v_{q2} = R_{s2}i_{q2} + L_{q2}\dfrac{d}{dt}i_{q2} + \omega L_{d2}i_{d2} + M\dfrac{d}{dt}i_{q1} + M\omega i_{d} + \sqrt{\dfrac{3}{2}}\omega\phi_f \end{cases} \tag{1}$$

Where $v_{d1}, v_{q1}, v_{d2}, v_{q2}$ are the stator voltages, R_s is the stator resistance, and $i_{d1}, i_{q1}, i_{d2}, i_{q2}$ are the stator currents. L Inductance seen by current aligned/orthogonal to rotor flux, M Represents magnetic coupling between star 1 and star 2 windings. The electromagnetic and mechanical torque equations are given by:

$$\begin{cases} T_e = \dfrac{3}{2}p\left(\left(\varphi_{d1}I_{q1} - \varphi_{q1}I_{d1}\right) + \left(\varphi_{d2}I_{q2} - \varphi_{q2}I_{d2}\right)\right) \\ J\dfrac{d\Omega}{dt} + f\Omega = T_e - T_r \end{cases} \tag{2}$$

φ_d, φ_q are the components of the stator flux linkage vector.

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 [43]:

$$\begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} v_{a2} \\ v_{b2} \\ v_{c2} \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} \tag{4}$$

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 Fig. 3 (comprising six active vectors and two null vectors) [55].

2.3. DSPMSM 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 [7].

2.3.1. Stator Flux Estimation

The stator flux is expressed by the following equations:

$$\begin{cases} \phi_{s\alpha i} = \displaystyle\int (v_{\alpha i} - R_{si}i_{\alpha i})dt \\ \phi_{s\beta i} = \displaystyle\int (v_{\beta i} - R_{si}i_{\beta i})dt \end{cases} \quad i = 1.2 \tag{5}$$

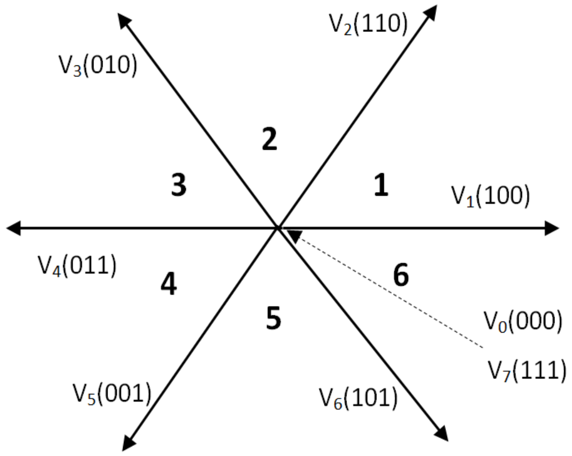

Fig. 3. Two-level inverter voltage vector selection

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

$$\phi_{si} = \sqrt{{\phi_{s\alpha i}}^2 + {\phi_{s\beta i}}^2} \tag{6}$$

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

2.3.2. 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:

$$T_e = \frac{3}{2} p \left(\left(\varphi_{\alpha 1} I_{\beta 1} - \varphi_{\beta 1} I_{\alpha 1} \right) + \left(\varphi_{\alpha 2} I_{\beta 2} - \varphi_{\beta 2} I_{\alpha 2} \right) \right) \tag{7}$$

2.3.3. 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 [6], [38].

2.3.4. 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:

$$\begin{cases} \frac{d}{dt} i_{d(k+1)} = i_{d1(k)} + \frac{T_s}{L_{d1}} \left(v_{d1} - R_{s1} i_{d1(k)} + \omega L_{q1} i_{q1(k)} - M \frac{d}{dt} i_{d2(k)} + M \omega i_{q2(k)} \right) \\ \frac{d}{dt} i_{q1(k+1)} = i_{q1(k)} + \frac{T_s}{L_{q1}} \left(v_{q1} - R_{s1} i_{q1(k)} - \omega L_{d1} i_{d1(k)} - M \frac{d}{dt} i_{q2(k)} - M \omega i_{d2(k)} - \sqrt{\frac{3}{2}} \omega \phi_f \right) \\ \frac{d}{dt} i_{d2(k+1)} = i_{d2(k)} + \frac{T_s}{L_{d2}} \left(v_{d2} - R_{s2} i_{d2(k)} + \omega L_{q2} i_{q2(k)} - M \frac{d}{dt} i_{d1(k)} - M \omega i_{q1(k)} \right) \\ \frac{d}{dt} i_{q1(k+1)} = i_{q2(k)} + \frac{T_s}{L_{q1}} \left(v_{q2} - R_{s2} i_{q2(k)} - \omega L_{d2} i_{d2(k)} - M \frac{d}{dt} i_{q1(k)} - M \omega i_{d(k)} - \sqrt{\frac{3}{2}} \omega \phi_f \right) \end{cases} \tag{8}$$

Ts: the sampling period

2.3.5. Predicted Flus and Torque Estimation

The prediction of stator flux and torque is obtained based on the estimation in relation 5, at each sampling period k; the next-step stator flux is predicted by:

$$\begin{cases} \phi_{s\alpha i(k+1)} = \phi_{s\alpha i(k)} + T_s(v_{\alpha i} - R_{si} i_{\alpha i(k+1)}) \\ \phi_{s\beta i(k+1)} = \phi_{s\beta i(k)} + T_s(v_{\beta i} - R_{si} i_{\beta i(k+1)}) \end{cases} \quad i = 1.2 \tag{9}$$

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

$$T_{e(k+1)} = \frac{3}{2} p \left(\left(\varphi_{\alpha 1(k+1)} I_{\beta 1(k+1)} - \varphi_{\beta 1(k+1)} I_{\alpha 1(k+1)} \right) + \left(\varphi_{\alpha 2(k+1)} I_{\beta 2(k+1)} - \varphi_{\beta 2} I_{\alpha 2(k+1)} \right) \right) \tag{10}$$

2.3.6. 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 [55]:

$$F = \left| T_{eref} - T_{e(k+1)} \right| + k \left| \varphi_{siref} - \varphi_{si(k+1)} \right| \tag{11}$$

K is the weighting factor.

The weighting factor K determines the relative importance of torque and flux errors. A smaller K improves torque response and reduces ripple, while a larger K enhances flux regulation. Since the cost function involves direct evaluation without iteration, the method remains computationally efficient.

Where T_{eref} and φ_{siref} are the reference values of torque and flux respectively, $T_{e(k+1)}$ and $\varphi_{si(k+1)}$ are values of predicted torque and flux respectively.

This function will be calculated to obtain eight Vs 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 is chosen [7].

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

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

3. Results and Discussion

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 Fig. 4, 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 (as in (1) and (2)). Two operating scenarios were tested: (1) load torque variation at constant speed and (2) speed reversal under rated load. The obtained results are presented in Fig. 5 and Fig. 6 and compared with those from a conventional hysteresis-based DTC under identical conditions. Fig. 5 illustrates the dynamic and steady-state responses of torque, stator current, flux, and speed when the load torque varies from 5 N·m to 10 N·m at a constant reference speed of 100 rad/s. The stator current waveforms in Fig. 5 appear smoother and nearly sinusoidal under the PDTC scheme. The stator-flux trajectory also becomes more circular, confirming that the predictive cost-function control ensures constant-magnitude flux and steady torque production. These enhancements translate to higher efficiency and reduced mechanical stress on the rotor shaft and bearings.

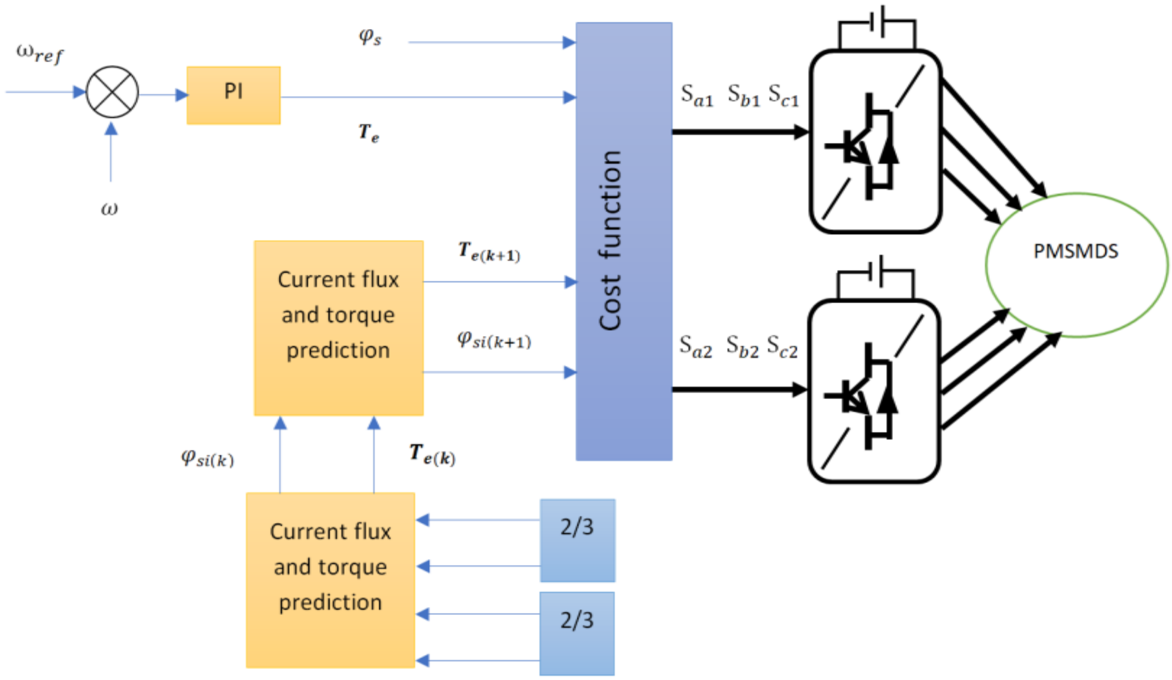

Fig. 4. Diagram of predictive direct torque control of double star permanent magnet synchronous machine (PMSMDS)

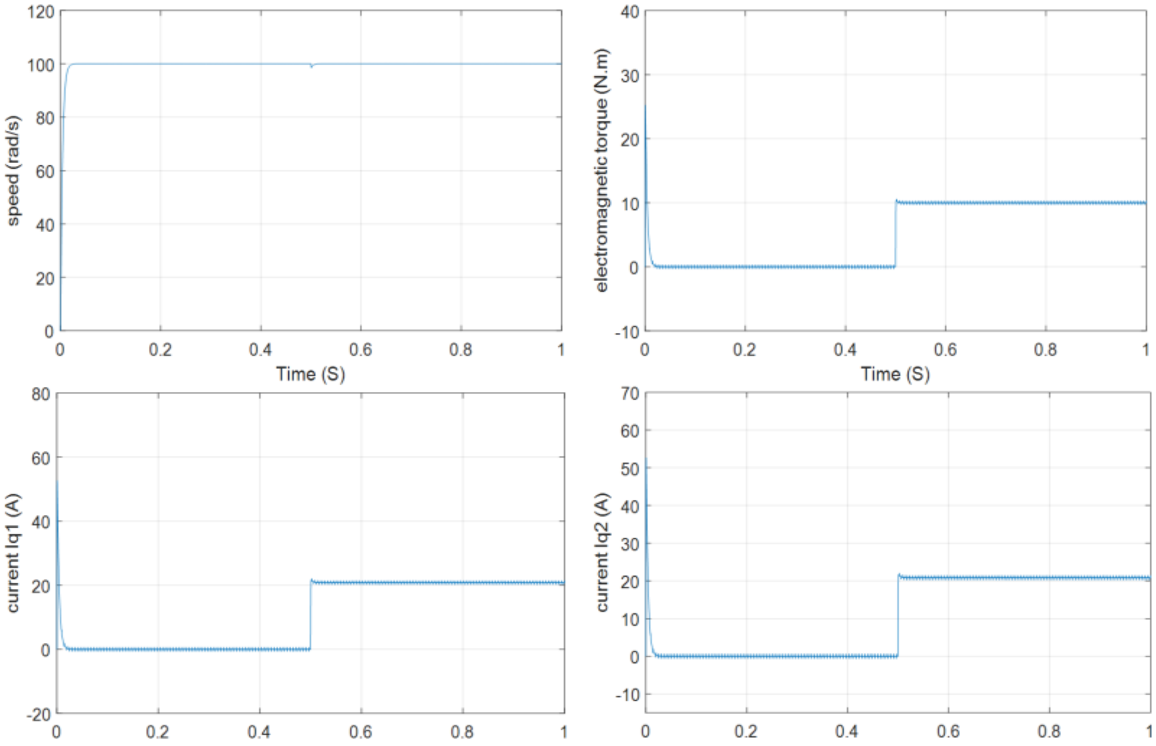

Fig. 5. Dynamic and static characteristics of the predictive DTC of the DSPMSM during load torque variation

Fig. 6 shows the transient response when the motor reverses rotation direction from +100 rad/s to −100 rad/s under a 10 N·m load. The PDTC exhibits excellent dynamic behavior, maintaining stable flux amplitude and smooth torque during reversal. The electromagnetic torque follows the reference quickly with negligible overshoot, and speed reversal completes in approximately 10 ms without instability. In contrast, the conventional DTC suffers from high-frequency torque pulsations and increased flux distortion during reversal, due to its non-predictive switching behavior.

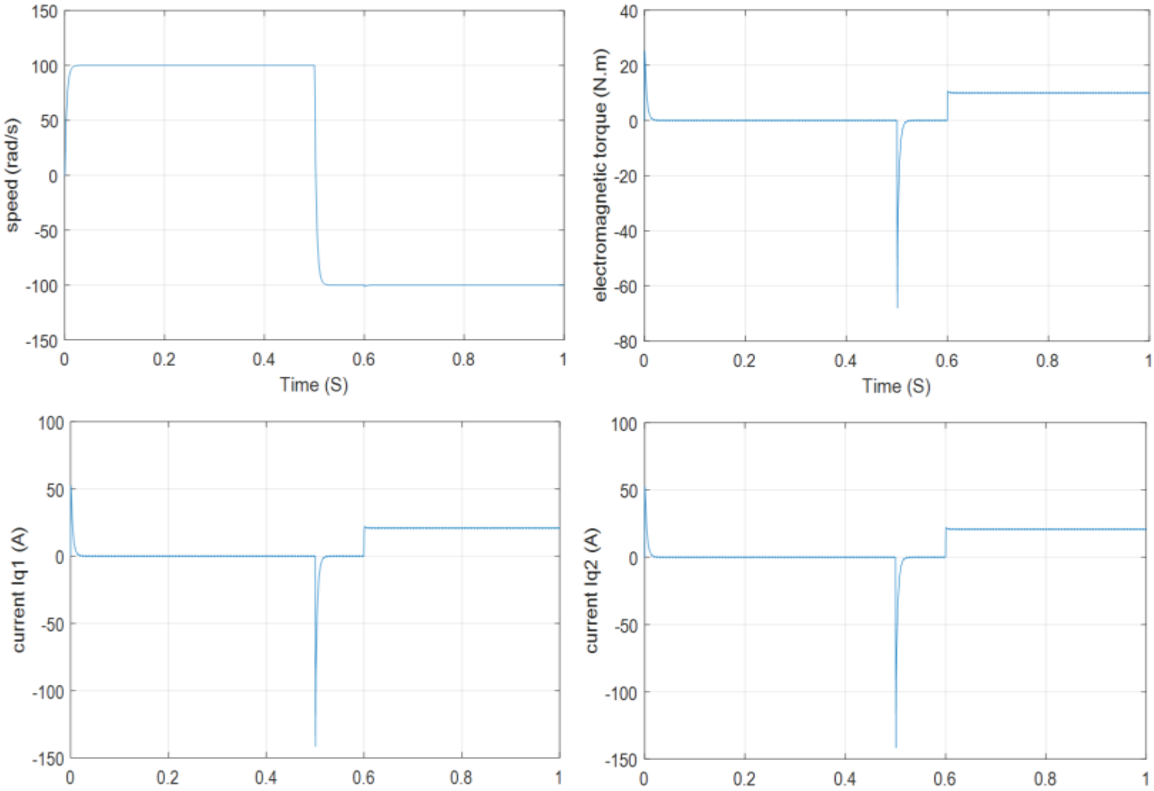

Fig. 6. Dynamic and static characteristics of the predictive DTC of the DSPMSM during when reversing the direction of rotation

The obtained results confirm that PDTC provides significantly smoother torque and lower current distortion while preserving fast transient response. Reduced THD and torque ripple improve inverter efficiency and extend component lifetime. The simulation results validate that integrating predictive evaluation with a PI regulator yields constant switching frequency and stable operation under both load and speed transients. The predictive control minimizes flux and torque errors in a single computation cycle, making it feasible for real-time DSP implementation. Although simulations assume an ideal inverter without dead-time or sensor noise, future hardware-in-the-loop tests will incorporate these non-idealities. Furthermore, since the computational complexity scales linearly with the number of voltage vectors, the method remains scalable for higher-power DSPMSM drives. From a practical standpoint, the reduction in torque ripple and THD directly enhances drive efficiency, reduces acoustic noise, and improves mechanical durability.

4. Conclusion

This study presented an advanced Predictive Direct Torque Control (PDTC) strategy for the Double Star Permanent Magnet Synchronous Machine (DSPMSM), integrating model predictive evaluation with a PI regulator to achieve constant switching frequency and improved dynamic performance. Simulation results demonstrated that, compared with conventional DTC, the proposed approach confirming its effectiveness and efficiency. Theoretically, the work extends predictive control principles to dual-star architectures by explicitly modeling magnetic coupling and embedding a simple PI regulator within the predictive loop, ensuring smooth torque sharing and low computational complexity. Although the results are simulation-based, real-time implementation challenges such as computational load, parameter sensitivity, and inverter non-idealities remain to be addressed. Future work will focus on experimental validation using DSP hardware, adaptive weighting-factor tuning, and comparison with other advanced strategies such as MPC-SVM and intelligent DTC. Overall, the proposed PDTC method offers a promising and practical solution for high-performance multiphase motor drives, combining predictive accuracy with real-time feasibility for industrial applications.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] L. Ge, J. Zhong, J. Huang, N. Jiao, S. Song, R. W. De Doncker, “A Novel Model Predictive Torque Control of Srms With Low Measurement Effort,” *IEEE Transactions on Industrial Electronics*, vol. 70, no. 4, pp. 3561–3570, 2022, https://doi.org/10.1109/TIE.2022.3179564.

[2] W. Ding, J. Li, J. Yuan, “An Improved Model Predictive Torque Control for Switched Reluctance Motors with Candidate Voltage Vectors Optimization,” *IEEE Transactions on Industrial Electronics*, vol. 70, no. 5, pp. 4595–4607, 2022, https://doi.org/10.1109/TIE.2022.3190895.

[3] A. Ouanouki, K. Kouzi, D. Difi, M. Ghibeche, “Predictive Control Strategy for Two Five-Phase Permanent Magnet Synchronous Motors Connected in Series Powered by a Single Inverter,” *International Journal of Robotics and Control Systems*, vol. 5, no. 2, p. e5758, 2025, https://doi.org/10.54021/seesv5n2-022.

[4] Z. Su, X. Sun, G. Lei, M. Yao, “Model-free Predictive Current Control for Dual Three-Phase Pmsm Drives With an Optimal Modulation Pattern,” *IEEE Transactions on Industrial Electronics*, vol. 71, no. 9, pp. 10140-10149, 2024, https://doi.org/10.1109/TIE.2023.3327554.

[5] P. G. Carlet, A. Favato, S. Bolognani, F. Dorfler, “Data-Driven Continuous-Set Predictive Current Control for Synchronous Motor Drives,” *IEEE Transactions on Power Electronics*, vol. 37, no. 6, pp. 6637–6646, 2022, https://doi.org/10.1109/TPEL.2022.3142244.

[6] C. Xue, W. Song, X. Feng, “Finite Control-Set Model Predictive Current Control of Five-Phase Permanent-Magnet Synchronous Machine Based on Virtual Voltage Vectors,” *IET Electric Power Applications*, vol. 11, no. 5, pp. 836-846, 2017, https://doi.org/10.1049/iet-epa.2016.0529.

[7] I. Gonzalez-Prieto, M. J. Duran, J. J. Aciego, C. Martin, F. Barrero, “Model Predictive Control of Six-Phase Induction Motor Drives Using Virtual Voltage Vectors,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 27–37, 2017, https://doi.org/10.1109/TIE.2017.2714126.

[8] X. Zhang, Z. Zhao, Y. Cheng, Y. Wang, “Robust Model Predictive Current Control Based on Inductance and Flux Linkage Extraction Algorithm,” *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 14893-14902, 2020, https://doi.org/10.1109/TVT.2020.3043474.

[9] X. Zhang, Y. Cheng, Z. Zhao, and K. Yan, “Optimized Model Predictive Control with Dead-Time Voltage Vector for Pmsm Drives,” *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 3149-3158, 2021, https://doi.org/10.1109/TPEL.2020.3012985.

[10] Y. Zhang, S. Li, W. Yi, Y. Yang, K. Cao, B. Luo, “A Robust Model Predictive Current Closed-Loop Control with Parameter Estimation Strategy Based on Immune Chaotic Antipredator PSO for PMSM,” *IEEE Transactions on Power Electronics*, vol. 40, no. 1, pp. 1836–1848, 2025, https://doi.org/10.1109/TPEL.2024.3476118.

[11] Y. Wang, X. Wang, and W. Xie, “Deadbeat Model-Predictive Torque Control with Discrete Space-Vector Modulation for Pmsm Drives of Power Converters and Electrical Drives,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 6930-6939, 2017, https://doi.org/10.1109/TIE.2017.2652338.

[12] M. P. Akter, S. Mekhilef, N. M. L. Tan, H. Akagi, “Modified Model Predictive Control of a Bidirectional AC–DC Converter Based on Lyapunov Function for Energy Storage Systems,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 704-715, 2016, https://doi.org/10.1109/TIE.2015.2478752.

[13] J. Lu, “An Improved Predictive Controller for PMSM based on Dual-Channel Feedback,” *Journal of Physics: Conference Series*, vol. 2785, no. 1, p. 012056, 2024, https://doi.org/10.1088/1742-6596/2785/1/012056.

[14] M. S. Mousavi *et al*., "Predictive Torque Control of Induction Motor Based on a Robust Integral Sliding Mode Observer," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 3, pp. 2339-2350, 2023, https://doi.org/10.1109/TIE.2022.3169831.

[15] X. Sun, Y. Zhu, Y. Cai, M. Yao, Y. Sun, and G. Lei, "Optimized-Sector-Based Model Predictive Torque Control with Sliding Mode Controller for Switched Reluctance Motor," *IEEE Transactions on Energy Conversion*, vol. 39, no. 1, pp. 379-388, 2024, https://doi.org/10.1109/TEC.2023.3301000.

[16] W. Zhang *et al*., "An Improved Model Predictive Torque Control for PMSM Drives Based on Discrete Space Vector Modulation," *IEEE Transactions on Power Electronics*, vol. 38, no. 6, pp. 7535-7545, 2023, https://doi.org/10.1109/TPEL.2023.3257399.

[17] Y. Liu *et al*., "Three-Vector-Based Model Predictive Torque Control for Dual Three-Phase PMSM With Torque and Flux Ripples Reduction," *IEEE Transactions on Power Electronics*, vol. 39, no. 8, pp. 10009-10020, 2024, https://doi.org/10.1109/TPEL.2024.3390791.

[18] X. Li, Z. Xue, L. Zhang, W. Hua, "A Low-Complexity Three-Vector-Based Model Predictive Torque Control for SPMSM," *IEEE Transactions on Power Electronics*, vol. 36, no. 11, pp. 13002-13012, 2021, https://doi.org/10.1109/TPEL.2021.3079147.

[19] G. Fang, J. Ye, D. Xiao, Z. Xia, A. Emadi, "Computational-Efficient Model Predictive Torque Control for Switched Reluctance Machines With Linear-Model-Based Equivalent Transformations," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 6, pp. 5465-5477, 2022, https://doi.org/10.1109/TIE.2021.3091918.

[20] X. Li, Z. Xue, X. Yan, L. Zhang, W. Ma, W. Hua, "Low-Complexity Multivector-Based Model Predictive Torque Control for PMSM With Voltage Preselection," *IEEE Transactions on Power Electronics*, vol. 36, no. 10, pp. 11726-11738, 2021, https://doi.org/10.1109/TPEL.2021.3073137.

[21] J. Bonaldo, J. Riccio, E. Zerdali, M. Rivera, R. Monteiro, P. Wheeler, "Comparative Analysis of Weighting-Factor-Free Predictive Control Strategies for Direct Torque Control in Permanent Magnet Synchronous Machines," *Processes*, vol. 13, no. 8, p. 2614, 2025, https://doi.org/10.3390/pr13082614.

[22] M. Hassan *et al*., "A Look-Up Table-Based Model Predictive Torque Control of Ipmsm Drives with Duty Cycle Optimization," *ISA Transactions*, vol. 138, pp. 670-686, 2023, https://doi.org/10.1016/j.isatra.2023.02.007.

[23] M. Becker, M. Stender, O. Wallscheid, "Nonlinear Efficiency-Optimal Model Predictive Torque Control of Induction Machines," *TechRxiv*, 2023, https://doi.org/10.36227/techrxiv.24664137.v1.

[24] C. Zhang, H. Wang, X. Yuan, X. Wu, "Optimized Fuzzy Model Predictive Torque Control With a Dynamic Flux Weighting Factor for Nine-Phase Open-End Winding PMSMs," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 13, no. 2, pp. 2385-2396, 2025, https://doi.org/10.1109/JESTPE.2025.3551758.

[25] D. Lv, W. Ding, Y. Wang, K. Wang, S. Chen, J. Cai, "Finite Control Set Model Predictive Torque Control of Switched Reluctance Motor Based on Three-Phase Four-Leg Inverter," *IEEE Transactions on Industrial Electronics*, vol. 72, no. 10, pp. 9931-9941, 2025, https://doi.org/10.1109/TIE.2025.3553184.

[26] Y. Zhang, P. Yang, K. Cao, Y. Gao, G. Tang, Q. Chen, "Improved Model Predictive Torque Control Strategy Incorporating Decoupled Sliding Mode Disturbance Observer for PMSM," *Progress in Electromagnetics Research C*, vol. 153, pp. 105-117, 2025, https://doi.org/10.2528/PIERC25011502.

[27] S. Li, L. Ma, J. Hou, Y. Ma, R. Lai, "Three-Vector-Based Smart Model Predictive Torque Control of Surface-Mounted Permanent Magnet Synchronous Motor Drives for Robotic System Based on Genetic Algorithm," *Actuators*, vol. 14, no. 3, p. 149, 2025, https://doi.org/10.3390/act14030149.

[28] Y. Guo, F. Jiang, S. Wang, S. Cheng, Z. Hu, "Variable Control Period Model Predictive Current Control with Current Hysteresis for Permanent Magnet Synchronous Motor Drives," *Actuators*, vol. 14, no. 11, p. 517, 2025, https://doi.org/10.3390/act14110517.

[29] M. Z. Rafique, R. Atif, S. Yang, M. Usman, M. Ihsan, M. Usman, "Model Predictive Torque Control with Flying Capacitor Voltage Balancing of 4L-NNPC Inverter Based PMSM Drive," *2025 7th Asia Energy and Electrical Engineering Symposium (AEEES)*, pp. 139-144, 2025, https://doi.org/10.1109/AEEES64634.2025.11019602.

[30] M. Ahmed Ghodbane *et al*., "Enhancing Wind Turbine Efficiency: An Experimental Investigation of a Sensorless Three-Vector Finite Set Predictive Torque Control Approach for PMSG-Based Systems," *IEEE Access*, vol. 13, pp. 118468-118489, 2025, https://doi.org/10.1109/ACCESS.2025.3581837.

[31] I. D. Martin, F. Tinazzi, M. Zigliotto, N. Monzen, and C. M. Hackl, “Continuous Control Set Model Predictive Torque Control of Electrically Excited Synchronous Motors,” *2025 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)*, pp. 1-6, 2025, https://doi.org/10.1109/WEMDCD61816.2025.11014159.

[32] S. Qiao, J. Huang, Y. Xu, K. Song, “Direct Model Predictive Torque Control for Permanent Magnet Synchronous Motor with Voltage Vector Parallel Optimisation Algorithm,” *IET Electric Power Applications*, vol. 19, no. 1, 2025, https://doi.org/10.1109/WEMDCD61816.2025.11014159.

[33] Y. Xu, Z. Li, Q. Gao, S. Kang, B. Zhang, “Dual Torque Duty Cycle Model Predictive Torque Control of Pmsm Based on Extended Voltage Vector,” *Journal of Power Electronics*, vol. 25, no. 11, pp. 2029-2040, 2025, https://doi.org/10.1007/s43236-025-01031-3.

[34] D. Zhang, W. Wang, X. Lin, “An Improved Zero-Sequence Current Suppression Method for Open-Winding PMSM Based on Cost Free Function Model Predictive Torque Control,” *2025 7th Asia Energy and Electrical Engineering Symposium (AEEES)*, pp. 383-388, 2025, https://doi.org/10.1109/AEEES64634.2025.11019291.

[35] D. Difi, “High Efficiency and Quick Response of Torque Control for a Multi-Phase Machine Using Discrete/Continuous Approach: Application to Five-phase Permanent Magnet Synchronous Machine,” *Przegląd Elektrotechniczny*, vol. 1, no. 4, pp. 130-135, 2021, https://doi.org/10.15199/48.2021.04.23.

[36] Z. Zhong, J. You, S. Zhou, “Torque Ripple Reduction of DTC Based on an Analytical Model of PMSM,” *World Electric Vehicle Journal*, vol. 11, no. 1, p. 28, 2020, https://doi.org/10.3390/wevj11010028.

[37] M.-F. Hsieh, Y.-C. Weng, “A Low Torque Ripple Direct Torque Control Method for Interior Permanent Magnet Motor,” *Applied Sciences*, vol. 10, no. 5, p. 1723, 2020, https://doi.org/10.3390/app10051723.

[38] Y. Moati, K. Kouzi, A. Iqbal, “Adaptive Optimized Dtc-Svm using Metaheuristic Bat Algorithm for Dsim Fed by Imc Based on Robust Synergetic Speed Controller,” *International Transactions on Electrical Energy Systems*, vol. 31, no. 1, pp. 1-25, 2021, https://doi.org/10.1002/2050-7038.12697.

[39] Y. Cho, Y. Bak, K.B. Lee, “Torque-Ripple Reduction and Fast Torque Response Strategy for Predictive Torque Control of Induction Motors,” *IEEE Transactions on Power Electronics*, vol. 33, no. 3, pp. 2458-2470, 2018, https://doi.org/10.1109/TPEL.2017.2699187.

[40] T. Geyer, G. Papafotiou, M. Morari, “Model Predictive Direct Torque Control-Part I: Concept, Algorithm, and Analysis,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 1894-1905, 2009, https://doi.org/10.1109/TIE.2008.2007030.

[41] H. Guermit, K. Kouzi, S. A. Bessedik, “Novel Design of an Optimized Synergetic Control for Dual Stator Induction Motor,” *COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 38, no. 6, pp. 1828-1845, 2019, https://doi.org/10.1108/COMPEL-01-2019-0042.

[42] T. Zwerger, P. Mercorelli, “Inner Loop Model Predictive Control and Outer Loop Pi Reference Governor for Pmsms with Input and State Saturation for Torque Control,” *Mathematics and Computers in Simulation*, vol. 228, pp. 178-201, 2025, https://doi.org/10.1016/j.matcom.2024.08.006.

[43] Y. Moati, K. Kouzi, “An Efficient of Direct Torque Control of Indirect Three Level Matrix Converter Fed Dual Stator Induction Motor Based on Synergetic Controller,” *Journal Européen des Systèmes Automatisés*, vol. 53, no. 5, pp. 617-627, 2020, https://doi.org/10.18280/jesa.530504.

[44] N. Layadi, A. Djerioui, S. Zeghlache, H. Mekki, A. Houari, J. Gong, F. Berrabah, “Fault-Tolerant Control Based on Sliding Mode Controller for Double-Star Induction Machine,” *Arabian Journal for Science and Engineering*, vol. 45, no. 3, pp. 1615-1627, 2020, https://doi.org/10.1007/s13369-019-04120-1.

[45] E. Amirouche, K. Iffouzar, A. Houari, K. Ghedamsi, D. Aouzellag, “Behavior Analysis of Dual-Star Permanent Magnet Synchronous Generator with Inter-Turn Short Fault,” *International Journal of*

Modelling and Simulation, vol. 45, no. 5, pp. 1701-1710, 2024, https://doi.org/10.1080/02286203.2023.2299898.

[46] T. Han, H. Wang, H. Cheng, Q. Shi, Y. Cao, Y. Liu, “Nonlinear Disturbance Observer-Based Robust Controller for Nonlinear Coupled System of Projectile-DSPMSM Subjected to Aerodynamic Loading and Nonlinearities,” *2023 IEEE International Conference on Unmanned Systems (ICUS)*, pp. 1413-1420, 2023, https://doi.org/10.1109/ICUS58632.2023.10318375.

[47] R. Zhu, C. Di, X. Bao, J. Liu, “Influence of the Slots Number Combinations among the Inner and Outer Stator on Torque Ripple in Dual-Stator Permanent Magnet Synchronous Motors,” *2021 24th International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1137-1141, 2021, https://doi.org/10.23919/ICEMS52562.2021.9634503.

[48] E. Amirouche, K. Iffouzar, A. Houari, K. Ghedamsi, D. Aouzellag, “New Diagnostic and Severity Estimation Method for Inter-Turn Short Fault for Dual Star Permanent Magnet Synchronous Generator,” *Arabian Journal for Science and Engineering*, vol. 47, no. 3, pp. 3573-3581, 2022, https://doi.org/10.1007/s13369-021-06445-2.

[49] M. S. Ahmad, D. Ishak, T. T. Leong, M. R. Mohamed, “Optimization of Double Stator Pmsm with Different Slot Number in Inner and Outer Stators using Genetic Algorithm,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 2, p. 726, 2021, http://doi.org/10.11591/ijpeds.v12.i2.pp726-735.

[50] Y. Guo, F. Jiang, S. Wang, S. Cheng, Z. Hu, “Variable Control Period Model Predictive Current Control with Current Hysteresis for Permanent Magnet Synchronous Motor Drives,” *Actuators*, vol. 14, no. 11, p. 517, 2025, https://doi.org/10.3390/act14110517.

[51] A. Ouanouki, K. Kouzi, D. Difi, M. Ghibeche, M. Sellah, “Field Oriented Control of a Seven-Phase Series Connected Three PMSM Using Fuzzy Logic,” *Algerian Journal of Signals and Systems*, vol. 9, no. 4, pp. 236-242, 2024, https://doi.org/10.51485/ajss.v9i4.245.

[52] I. Benmiloud, K. Kouzi, A. Ameur, “Sensorless Vector Control of Dual Star Induction Motor Associated with Fuzzy Mutual–Mras Estimator in Electric Vehicle,” *Romanian Journal of Information Technology and Automatic Control*, vol. 33, no. 2, pp. 135-146, 2023, https://doi.org/10.33436/v33i2y202310.

[53] D. Hadiouche, H. Razik, A. Rezoug, “On the Modelingand Design of Dual-Stator Windings to Minimize Circulating Harmonic Currents for VSI Fed AC Machines,” *IEEE Transactions on industry applications*, vol. 40, no. 2, pp. 506-515, 2004, https://doi.org/10.1109/TIA.2004.824511.

[54] H. Khouidmi, A. Massoum, “Predictive Control Based Speed, Torque and Flux Prediction of a Double Stator Induction Motor,” *Majlesi Journal of Electrical Engineering*, vol. 13, no. 1, pp. 65-77, 2019, https://mjee.isfahan.iau.ir/article_696339_d2c1284bc43241705222beb905493473.pdf.

[55] F. Wang, S. Li, X. Mei, W. Xie, J. Rodríguez and R. M. Kennel, "Model-Based Predictive Direct Control Strategies for Electrical Drives: An Experimental Evaluation of PTC and PCC Methods," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 3, pp. 671-681, 2015, https://doi.org/10.1109/TII.2015.2423154.

[56] H. Mesloub, M.T. Benchouia, A. Goléa, N. Goléa, M.E.H. Benbouzid, “Predictive DTC Schemes with Pi Regulator and Particle Swarm Optimization for Pmsm Drive: Comparative Simulation and Experimental Study,” *The International Journal of Advanced Manufacturing Technology*, vol. 86, no. 9, pp. 3123-3134, 2016, https://doi.org/10.1007/s00170-016-8406-x.

[57] W. Tao, H. Zhou, C. Ye, C. Chen, “A Novel Finite-Control-Set Model Predictive Torque Control for Five-Phase PMSM with Improved Harmonic Current Suppression,” *IEEE Access*, vol. 13, pp. 18677-18686, 2025, https://doi.org/10.1109/ACCESS.2025.3532624.

[58] Y. Zhou, Z. Yan, Q. Duan, L. Wang, X. Wu, “Direct Torque Control Strategy of Five-Phase PMSM with Load Capacity Enhancement,” *IET Power Electronics*, vol. 12, no. 3, pp. 598-606, 2019, https://doi.org/10.1049/iet-pel.2018.5203.

[59] D. Difi, K. Halbaoui, D. Boukhetala, “Hybrid Control of Five-Phase Permanent Magnet Synchronous Machine using Space Vector Modulation,” *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 27, no. 2, pp. 921-938, 2019, https://doi.org/10.3906/elk-1805-193.

[60] K. Zhang, M. Fan, Y. Yang, L. He, X. Li, “Load Angle Limitation for PMSMs with Sequential Model Predictive Direct Torque Control,” *2019 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, pp. 1-6, 2019, https://doi.org/10.1109/PRECEDE.2019.8753191.