Model Predictive Current Control for Permanent Magnet Synchronous Motor Drives: A Comprehensive Review

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Abstract: *Model Predictive Current Control (MPCC) has emerged as one of the most promising advanced control techniques for Permanent Magnet Synchronous Motor (PMSM) drives due to its dynamic response, high current tracking accuracy, and capability to handle multivariable systems with system constraints. With the increasing adoption of PMSM drives in electric vehicles, industrial automation, robotics, aerospace, and renewable energy systems, the demand for high-performance current control strategies has significantly increased. This review paper presents a comprehensive analysis of MPCC techniques developed for PMSM drive applications, covering their operating principles, mathematical foundations, control architectures, and implementation methodologies. The paper systematically reviews conventional finite control set MPCC (FCS-MPCC), continuous control set MPCC (CCS-MPCC), multi-vector MPCC, duty-cycle-based MPCC, and recently proposed intelligent and optimization-assisted predictive control strategies. A comparative evaluation is provided based on current ripple, torque ripple, switching frequency, computational complexity, steady-state performance, dynamic response, robustness against parameter variations, and implementation feasibility. Furthermore, recent advancements integrating artificial intelligence, adaptive control, optimization algorithms, and machine learning with predictive current control are discussed to highlight emerging research directions. The review also identifies existing challenges, including computational burden, parameter sensitivity, model mismatch, and real-time implementation issues, while outlining potential future research opportunities for next-generation high-performance PMSM drive systems. This paper serves as a comprehensive reference for researchers and engineers seeking an in-depth understanding of the current state of MPCC techniques and their future development in advanced electric drive applications.*

Keywords: *Model Predictive Current Control (MPCC), Permanent Magnet Synchronous Motor (PMSM), Multi-Vector Predictive Control, Electric Drives, Current Control, Torque Ripple, Switching Frequency.*

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) have become one of the most widely used electrical machines in modern drive systems because of their high efficiency, high power density, compact size, low maintenance requirements, and excellent dynamic performance. Compared with conventional induction motors and brushed DC motors, PMSMs provide superior torque-to-weight ratio, higher efficiency, and improved reliability, making them highly suitable for applications such as electric vehicles (EVs), hybrid electric vehicles (HEVs), industrial automation, robotics, aerospace systems, railway traction, machine tools, and renewable energy conversion systems [1–4]. The increasing demand for energy-efficient transportation and high-performance industrial drives has further accelerated research on advanced control techniques for PMSM-based drive systems [5].

The overall performance of a PMSM drive largely depends on the effectiveness of its current control strategy. Conventional control techniques such as Field-Oriented Control (FOC) and Direct Torque Control (DTC) have been extensively employed because of their mature implementation and satisfactory performance. FOC achieves decoupled control of torque and flux by transforming stator currents into the rotating dq reference frame, thereby enabling independent regulation of the motor torque and magnetic flux [6]. Although FOC provides excellent steady-state accuracy, it requires multiple cascaded control loops, accurate machine parameters, pulse-width modulation (PWM), and careful controller tuning, which increase implementation complexity and limit transient performance [7]. On the other hand, DTC offers a faster dynamic response and simpler control architecture but suffers from significant torque ripple, variable switching frequency, and increased current harmonics, particularly under low-speed operating conditions [8].

To overcome these limitations, Model Predictive Control (MPC) has emerged as a powerful control methodology for electrical drives. MPC utilizes a mathematical model of the system to predict future behavior over a finite prediction horizon and determines the optimal control action by minimizing a predefined cost function [9]. One of the major advantages of MPC is its ability to simultaneously optimize multiple control objectives while directly considering system constraints. Consequently, MPC has gained considerable attention in power electronics and motor drive applications because of its fast transient response, excellent tracking capability, and straightforward inclusion of nonlinear constraints [10, 11].

Among various predictive control approaches, Model Predictive Current Control (MPCC) has become one of the most widely investigated techniques for PMSM drives. In MPCC, future stator currents are predicted for all possible inverter switching states, and the switching vector that minimizes the cost function is selected for implementation during the next sampling interval [12]. This approach eliminates the need for conventional PWM modulation and cascaded PI controllers while providing fast current tracking, improved dynamic response, and enhanced torque control [13]. Owing to these advantages, MPCC has become increasingly attractive for high-performance applications requiring rapid response and precise current regulation.

Several variants of MPCC have been developed to improve control performance. Finite Control Set Model Predictive Current Control (FCS-MPCC) directly evaluates the discrete switching states of the voltage source inverter and selects the optimal voltage vector at each sampling instant [14]. Although FCS-MPCC offers excellent dynamic performance, it generally suffers from variable switching frequency and relatively high current ripple. To address these limitations, Continuous Control Set Model Predictive Current Control (CCS-MPCC) incorporates modulation techniques to generate continuous voltage references, thereby reducing harmonic distortion and maintaining a constant switching frequency [15]. More recently, Multi-Vector MPCC has attracted significant attention by applying multiple voltage vectors within a single sampling period, resulting in lower current ripple, reduced torque ripple, improved steady-state accuracy, and enhanced overall efficiency [16, 17].

In addition to these developments, researchers have proposed several enhanced predictive control strategies involving duty-cycle optimization, adaptive weighting factor selection, deadbeat predictive control, robust predictive control, and artificial intelligence-assisted predictive algorithms [18–21]. Machine learning techniques, fuzzy logic, neural networks, particle swarm optimization (PSO), grey wolf optimization (GWO), and reinforcement learning have also been integrated with predictive control frameworks to improve parameter estimation, computational efficiency, robustness, and adaptability under varying operating conditions [22–24]. These intelligent approaches have significantly expanded the applicability of MPCC in modern electric drive systems.

Despite the remarkable progress achieved in recent years, several practical challenges remain. The computational complexity associated with evaluating multiple candidate voltage vectors during each sampling interval requires high-speed digital processors and efficient optimization algorithms [25]. Moreover, the performance of MPCC is highly sensitive to machine parameter variations, model uncertainties, inverter nonlinearities, and measurement noise [26]. The appropriate design of cost functions, optimal weighting factor selection, and balancing dynamic response with switching losses continue to be active research topics [27].

Considering the rapid advancements in predictive control technologies, a comprehensive review is necessary to summarize recent developments and identify future research opportunities. This review paper presents an extensive survey of Model Predictive Current Control techniques for PMSM drives. The paper discusses the operating principles, mathematical modeling, classification, and implementation of various MPCC strategies, including FCS-MPCC, CCS-MPCC, Multi-Vector MPCC, duty-cycle-based predictive control, robust predictive control, and intelligent optimization-assisted predictive methods. Furthermore, a comparative analysis of these techniques is presented based on current ripple, torque ripple, switching frequency, computational complexity, robustness, and implementation feasibility. Finally, current research challenges and future directions are highlighted to provide researchers and practicing engineers with a comprehensive understanding of emerging trends in predictive current control for next-generation PMSM drive systems.

II. LITERATURE REVIEW

- The development of Model Predictive Current Control (MPCC) for Permanent Magnet Synchronous Motor (PMSM) drives has evolved significantly over the past three decades. Research has progressed from conventional current control methods to sophisticated predictive control techniques capable of providing superior dynamic performance, reduced torque ripple, and improved current regulation. The following review summarizes the major contributions reported in the literature.
- Holtz [1] presented one of the earliest studies on AC machine dynamic modeling using complex signal flow graphs. The work established a theoretical foundation for advanced motor control techniques by accurately representing machine dynamics in the synchronous reference frame. This modeling approach later became an essential basis for predictive control algorithms.
- Kazmierkowski and Malesani [2] conducted a comprehensive survey of current control techniques for voltage-source PWM converters. Their work compared hysteresis control, PI control, deadbeat control, and predictive control, highlighting the advantages of predictive approaches in achieving rapid current tracking and improved dynamic response.
- Kennel and Linder [3] introduced predictive control concepts for inverter-fed electrical drives. Their study demonstrated that predictive algorithms could directly determine optimal inverter switching states while minimizing current tracking errors, thereby eliminating the need for multiple cascaded control loops.
- Rodriguez *et al.* [4] proposed one of the first Finite Control Set Model Predictive Current Control (FCS-MPCC) strategies for voltage source inverters. The controller predicted future current values for each possible switching state and selected the optimal voltage vector through a cost function minimization process. The proposed approach significantly improved transient response and current regulation compared to conventional PWM-based methods.
- Kouro *et al.* [5] provided a detailed introduction to Model Predictive Control (MPC) for power electronic converters. The authors demonstrated that MPC offers a flexible framework capable of simultaneously optimizing multiple control objectives while incorporating system constraints. Their work accelerated the adoption of predictive control in electrical drive applications.
- Rodriguez and Cortes [6] published one of the most influential books on predictive control for power converters and electrical drives. The book systematically explained predictive control principles, mathematical modeling, cost function design, prediction algorithms, and implementation methods, making it a standard reference for researchers in the field.
- Cortes *et al.* [7] investigated delay compensation techniques in predictive current control systems. The authors proposed methods to compensate computational delays that arise during real-time implementation, thereby improving prediction accuracy and enhancing overall control performance.
- Rodriguez *et al.* [8] presented a comprehensive review of Finite Control Set Model Predictive Control in power electronics. Their study discussed prediction models, optimization strategies, cost function formulation, computational complexity, and practical implementation challenges while identifying future research opportunities.
- Vazquez *et al.* [9] reviewed the application of Model Predictive Control in power electronics and electrical drives. The paper summarized various MPC algorithms and compared their performance in terms of dynamic response, robustness, computational requirements, and industrial applicability.
- Geyer and Quevedo [10] proposed a multistep Finite Control Set MPC strategy that extended the prediction horizon beyond one sampling interval. Their method significantly reduced current distortion and improved steady-state performance while maintaining fast transient characteristics.
- Xie *et al.* [11] developed a deadbeat-based Finite Control Set Model Predictive Torque Control strategy for PMSM drives. By combining deadbeat prediction with predictive optimization, the proposed controller achieved faster torque response, reduced torque ripple, and improved current tracking accuracy.
- Kouro *et al.* [12] further discussed the evolution of Model Predictive Control in power electronics by highlighting recent developments in computational techniques, optimization algorithms, and practical industrial applications. The study emphasized the growing importance of predictive control in modern electric drive systems.
- Geyer [13] presented advanced predictive control methodologies for high-power converters and industrial drives. The book addressed optimization algorithms, long prediction horizons, computational complexity reduction, and practical implementation aspects for industrial applications.

- Zhang and Yang [14] proposed a two-vector predictive torque control strategy that eliminated weighting factors in the cost function. The controller utilized two voltage vectors during each sampling period, resulting in lower torque ripple, reduced current harmonics, and improved steady-state performance.
- Vazquez *et al.* [15] reviewed recent advances in predictive control for power converters and motor drives. The authors highlighted developments in continuous control set MPC, long-horizon optimization, delay compensation, and computational efficiency while discussing future research trends.
- Wang *et al.* [16] proposed a robust Finite Control Set Predictive Torque Control method incorporating disturbance compensation. Experimental results demonstrated enhanced robustness against parameter variations and external disturbances while maintaining excellent dynamic response.
- Ahmed *et al.* [17] compared Finite Control Set and Continuous Control Set Model Predictive Control strategies for electrical drives. Their comparative analysis indicated that CCS-MPC provided lower harmonic distortion and constant switching frequency, whereas FCS-MPC offered faster dynamic response with simpler implementation.
- Wang *et al.* [18] developed an enhanced predictive speed control strategy using a high-gain state observer. The proposed controller eliminated conventional PI regulators and achieved rapid speed tracking with improved robustness under varying operating conditions.
- Wallscheid *et al.* [19] introduced a data-driven recursive least squares algorithm for predictive current control of PMSM drives. The proposed adaptive parameter estimation method significantly improved prediction accuracy under parameter uncertainties and varying operating conditions.
- Li *et al.* [20] proposed an improved Model Predictive Current Control strategy using a current update mechanism for Surface Permanent Magnet Synchronous Motor (SPMSM) drives. Their approach effectively reduced prediction errors and enhanced current tracking performance during transient conditions.
- Tian *et al.* [21] investigated deadbeat predictive control for AC drive systems and demonstrated that optimal voltage vector selection significantly improved dynamic performance while reducing computational delay.
- Wang *et al.* [22] presented an FPGA-based Continuous Control Set Model Predictive Current Control implementation for PMSM drives. Their hardware implementation achieved real-time execution with reduced computational burden and excellent current regulation performance.
- Wang *et al.* [23] proposed a passivity-based Model Predictive Control strategy for inverter-fed motor drives. The controller improved system stability and robustness while maintaining low current distortion under different operating conditions.
- Rodriguez, Cortes, and Geyer [24] reviewed recent advances in predictive control for power electronics and motor drives. The authors discussed emerging research directions including artificial intelligence-assisted predictive control, adaptive optimization, and real-time implementation on advanced embedded processors.
- Brosch *et al.* [25] proposed a model-free predictive current control algorithm using recursive least squares estimation. The controller eliminated dependency on accurate machine parameters while maintaining high current tracking accuracy and improved robustness against parameter uncertainties.
- Peng and Yao [26] presented a comprehensive overview of predictive control technologies for PMSM systems. Their review discussed conventional MPC, FCS-MPC, CCS-MPC, deadbeat predictive control, multi-vector predictive control, and intelligent predictive algorithms while identifying future research opportunities.
- Liu *et al.* [27] proposed an improved deadbeat predictive current control method incorporating enhanced robustness against parameter variations and external disturbances. Simulation and experimental results demonstrated improved dynamic response, reduced steady-state current error, and superior robustness compared to conventional predictive control techniques.

III. CONTROL BLOCK DIAGRAM

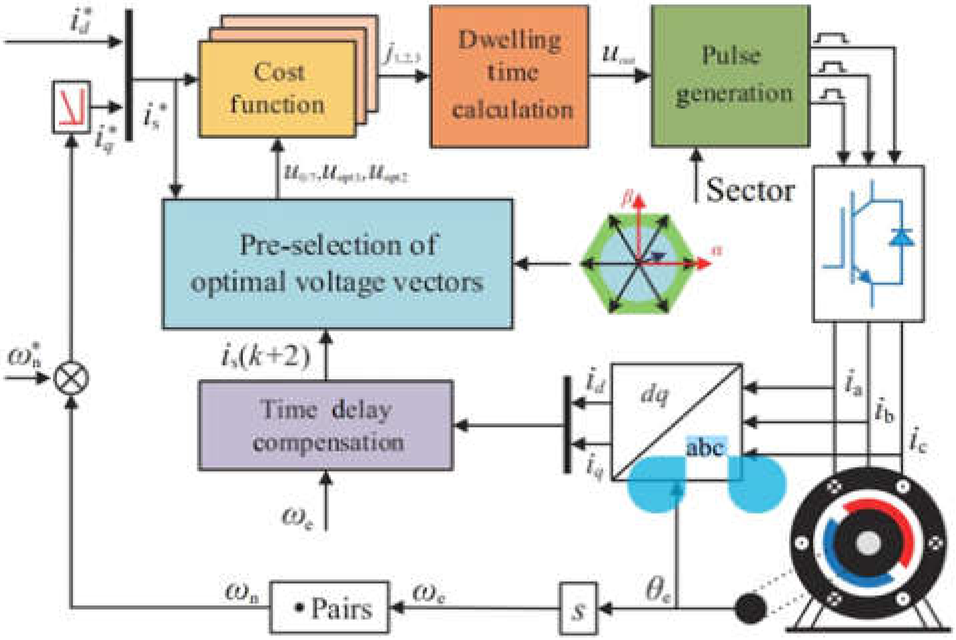

Fig. 1. Control Block Diagram of the proposed MVPCC scheme for PMSM Drive

IV. EXPLAINATION

Illustrates the overall control architecture of the proposed Multi-Vector Model Predictive Current Control (MVPCC) scheme for a Permanent Magnet Synchronous Motor (PMSM) drive. The reference direct-axis current id and quadrature-axis current iq are combined to form the reference current vector is. The measured three-phase stator currents ia,ib,ic are transformed into the synchronous dq reference frame using the Park transformation to obtain the actual current components ic.

The rotor electrical position and electrical angular speed are obtained from the rotor position sensor. A time-delay compensation block predicts the future stator current , thereby reducing the effect of computational and sampling delays. Based on the predicted current and the identified voltage sector, the pre-selection of optimal voltage vectors limits the number of candidate switching vectors, reducing computational complexity.

The selected voltage vectors are evaluated using a cost function, which determines the optimal vector combination by minimizing the current tracking error. The dwelling time calculation block computes the optimal application duration of each selected voltage vector. These calculated switching times are then used by the pulse generation block to generate the inverter gating signals according to the corresponding voltage sector.

Finally, the voltage source inverter applies the switching pulses to the PMSM, ensuring accurate current tracking, reduced torque ripple, lower current harmonics, and improved dynamic performance compared with conventional predictive current control methods.

V. MATHEMATICAL MODELLING OF TRANSFORMER-BASED GRID-CONNECTED INVERTER

The dynamic behavior of a permanent magnet synchronous motor (pmsm) is commonly represented in the rotating d-q reference frame using park's transformation. This transformation converts the three-phase stator variables into two orthogonal components, simplifying the analysis and control of the motor. The mathematical model of the pmsm is expressed by the following voltage equations:

$$V_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega_e L_q I_q \qquad (1)$$

$$V_q = R_s I_q + L_q \frac{dI_q}{dt} + \omega_e L_d I_d + \omega_e \lambda_f \qquad (2)$$

Where V_d and V_q are the d-axis and q-axis stator voltages, I_d and I_q are the corresponding stator currents, R_s is the stator resistance, L_d and L_q are the d-axis and q-axis inductances, ω_e is the electrical angular speed, and λ_f is the permanent magnet flux linkage.

The electromagnetic torque developed by the pmsm is given by

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_f I_q + \left(L_d - L_q\right) I_d I_q\right] \qquad (3)$$

Where T_e is the electromagnetic torque and P is the number of motor poles.

The mechanical dynamics of the pmsm are represented as

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \qquad (4)$$

Where J is the rotor moment of inertia, ω_m is the mechanical angular speed, T_L is the load torque, and B is the viscous friction coefficient.

For digital implementation of model predictive current control (mpcc), the continuous-time current equations are discretized using the forward euler approximation. The predicted d-axis and q-axis currents at the next sampling instant are expressed as

$$I_d(k+1) = I_d(k) + \frac{T_s}{L_d}\left[V_d(k) - R_s I_d(k) + \omega_e L_q I_q(k)\right] \qquad (5)$$

$$I_q(k+1) = I_q(k) + \frac{T_s}{L_q}\left[V_q(k) - R_s I_q(k) - \omega_e L_d I_d(k) - \omega_e \lambda_f\right] \qquad (6)$$

Where T_s is the sampling period.

The predictive controller evaluates these current predictions for all possible inverter voltage vectors and selects the switching state that minimizes the predefined cost function. A commonly used cost function is

$$g = |I_d^* - I_d(k+1)| + |I_q^* - I_q(k+1)| \qquad (7)$$

Where I_d^* and I_q^* are the reference d-axis and q-axis currents, respectively. The voltage vector producing the minimum value of the cost function is applied to the inverter during the next sampling interval, thereby ensuring fast current tracking and improved dynamic performance.

VI. CONCLUSION

This review presented a comprehensive overview of MPCC techniques for PMSM drives, covering the fundamental operating principles, mathematical modeling, and major predictive control strategies, including Finite Control Set MPCC (FCS-MPCC), Continuous Control Set MPCC (CCS-MPCC), Multi-Vector MPCC, deadbeat predictive control, and intelligent optimization-assisted predictive control methods. A comparative analysis highlighted the advantages and limitations of each approach in terms of dynamic response, steady-state performance, computational complexity, switching frequency, and robustness.

The literature indicates that recent research has focused on reducing current ripple, minimizing torque ripple, improving parameter robustness, lowering computational burden, and integrating artificial intelligence, adaptive algorithms, and optimization techniques into predictive control frameworks. These developments have significantly enhanced the applicability of MPCC in electric vehicles, industrial automation, robotics, and renewable energy systems.

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