

Robust Finite-Set Model Predictive Control for High-Performance Permanent Magnet Direct Current Motor Drives

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ABSTRACT

Permanent magnet direct current (PMDC) motor drives must deliver fast and accurate velocity tracking, yet they remain difficult to control because the terminal voltage and armature current can readily exceed the operating limits imposed by the converter and machine, leading to winding damage and converter degradation. Conventional cascade controllers cannot systematically enforce these physical limits during rapid transients without sacrificing tracking bandwidth, and they confront saturation only after the control command has been generated. This study presents a single-loop constrained finite-set model predictive control (FS-MPC) strategy for high-performance PMDC speed regulation and benchmarks it against standard cascade proportional-integral (PI) and anti-windup cascade PI controllers under identical operating conditions. A discrete-time PMDC model derived from the coupled armature-current and rotor-speed dynamics predicts the future trajectories, and at each sampling instant a finite set of admissible terminal-voltage candidates is evaluated through a cost function that jointly weighs speed-tracking error, control effort, and a soft armature-current limit. The proposed controller reaches the reference speed in approximately 0.02 s with negligible overshoot, whereas the anti-windup and standard cascade PI controllers settle in roughly 0.15 s and 0.18–0.20 s, the latter with pronounced overshoot. This transient gain is obtained at the cost of a higher short-duration current and torque excursion alongside a small finite-set steady-state ripple. The findings indicate that embedding voltage limitation and current-limit penalization within a single predictive decision can curtail loop-interaction and windup effects, offering a practical route to faster, constraint-aware speed control for compact industrial PMDC servo drives.

Keywords: Constraint handling, finite-set model predictive control (FS-MPC), PMDC motor drives, transient response

1. INTRODUCTION

Permanent magnet direct current (PMDC) motors are widely used in servo drives, robotics, industrial automation, electric-traction subsystems, and laboratory motion-control platforms because of their direct torque–current relationship, compact structure, and relatively simple drive requirements. Although AC machines and brushless drives dominate many high-power applications, PMDC motors remain an attractive choice wherever precise speed regulation, fast transient response, and straightforward actuation are required. Because the achievable precision and energy efficiency of these drives are governed directly by the quality of their speed control, a rigorous and quantitative assessment of any alternative control strategy is essential before it can be recommended for these applications. Such advanced control design is nonetheless demanding in practice, because PMDC drives operate under converter voltage limits, allowable armature-current limits, friction effects, load disturbances, and safety constraints.

Classical proportional-integral (PI) and cascade PI controllers are still the most common control solutions in industrial motor drives because they are easy to understand, computationally light,

and simple to implement. In a conventional cascade architecture, the outer speed loop generates a current reference, and the inner current loop generates a terminal-voltage command. This structure improves practical commissioning compared with a single PI speed loop, but it also introduces loop-interaction effects and sequential tuning requirements. In addition, when the current or voltage command saturates during rapid acceleration or load disturbances, the speed-loop integrator may continue to accumulate error. This windup effect can produce large overshoots, slow recovery, and increased thermal stress. Anti-windup modifications reduce these problems, but they are corrective mechanisms applied after saturation occurs rather than predictive mechanisms that evaluate constraint effects before the control action is applied.

Model predictive control (MPC) provides a different control philosophy. Instead of generating the control input from instantaneous error alone, MPC predicts the future behavior of the plant and selects the input that minimizes the performance criterion while considering constraints. Finite-set MPC (FS-MPC) is especially suitable for power-electronic motor drives because the controller can directly evaluate a finite number of admissible voltage or switching candidates. This characteristic allows

speed-tracking performance, control effort, and current-limit considerations to be incorporated in one decision process. Recent studies have shown the effectiveness of FS-MPC and related predictive approaches to DC motors, brushless direct current (BLDC) drives, permanent magnet synchronous motor (PMSM) drives, induction motors, and power electronic converters^{1-9,17-23,31-36}.

Despite this progress, the specific PMDC speed-control problem considered in this study remains insufficiently addressed. Many predictive-control studies focus on AC, PMDC, and PMSM drives, or converter systems, where the plant structure and performance objectives differ from those of a PMDC motor. Existing DC motor predictive-control studies have demonstrated the feasibility of FS-MPC and model-predictive speed regulation^{1-3,16,18}, but the literature still lacks a concise PMDC-focused assessment in which a single-loop constrained FS-MPC controller is benchmarked against both standard cascade PI and anti-windup cascade PI controllers under identical plant parameters, voltage limits, current limits, reference speed, and load condition. Moreover, existing comparisons often emphasize faster tracking without explicitly discussing the speed-current-torque trade-off that arises when a predictive controller accelerates the rotor more aggressively.

The research gap addressed in this study is therefore not the general invention of MPC for motor drives, but the focused formulation and assessment of a PMDC-specific, single-loop constrained predictive-control framework. To the best of the authors' knowledge, this is the first study to provide a quantitative FS-MPC assessment for PMDC drives that is benchmarked directly against both standard cascade PI and anti-windup cascade PI controllers under identical plant parameters, voltage limits, current limits, reference speed, and load condition, and that explicitly resolves the speed-current-torque trade-off arising when a predictive controller accelerates the rotor more aggressively. The proposed controller selects the terminal voltage directly from a finite candidate set and evaluates the predicted speed and current trajectories before applying the command. This contrasts with cascade PI control, where the voltage command is produced through two separately tuned feedback loops and saturation is addressed only after the controller output has been generated. By placing speed tracking, voltage limitation, and armature-current-limit penalization within a single finite-set decision process, the proposed approach establishes whether FS-MPC offers a practical transient-performance advantage for PMDC drives and characterizes the trade-offs that accompany that improvement.

The main contributions of this study are as follows:

A discrete-time PMDC drive model is developed from coupled electrical and mechanical dynamics, including armature resistance and inductance, back-EMF, electromagnetic torque, viscous friction, Coulomb friction, load torque, converter voltage limits, and armature-current-limit considerations.

A single-loop FS-MPC speed-control framework is formulated to directly select the terminal voltage, avoiding the nested speed-current tuning interactions inherent in cascade PI structures.

A finite-horizon cost function is implemented by combining the speed-tracking error, voltage-effort penalization, and soft armature-current-limit penalization over the prediction horizon. The proposed controller is compared under identical simulation

conditions with standard cascade PI and anti-windup cascade PI controllers in terms of speed, current, torque, and terminal-voltage responses.

The performance discussion explicitly interprets the transient-speed improvement together with the corresponding current and torque peaks, finite-set ripple, and practical limitations of the simulation study.

Within the scope of this study, the term robust is used in a restricted engineering sense to indicate improved transient behavior in the presence of actuator limits and current-limit penalization under the investigated simulation condition. Full robustness against parameter uncertainty, unmodeled dynamics, measurement noise, sampling-delay effects, and hardware nonidealities is not claimed and is left for future work.

The remainder of the study is organized as follows. Section 2 presents a focused critical review of related predictive-control, PI-based, and constrained-control studies. Section 3 develops the PMDC motor model and its discrete-time prediction form. Section 4 presents the proposed FS-MPC. Section 5 describes the PI-based benchmark controllers. Section 6 discusses the simulation results and comparative performance. Section 7 concludes the study and outlines limitations and future work.

2. LITERATURE REVIEW

2.1. Predictive Control for DC and Related Motor Drives. FS-MPC for electrical drives has been investigated extensively because it can directly evaluate admissible voltage or switching states and select the candidate that minimizes a prescribed cost function. For DC motor applications, Šlapák et al.¹ demonstrated that finite-control-set predictive speed control can be formulated from a discrete motor model and quadratic tracking objective. Thanh et al.² extended predictive speed control to chopper-fed brushed DC motors with online parameter estimation, emphasizing that prediction accuracy is strongly affected by motor-parameter variations. Sahin³ further considered MPC velocity-control design and software-in-the-loop verification for brushed DC motors, highlighting implementation-related issues before hardware deployment.

These DC motor studies demonstrate the relevance of predictive control for brushed and permanent-magnet DC drives. However, they do not fully address the comparison pursued in this study. This study focuses on a PMDC-specific single-loop FS-MPC formulation in which the terminal voltage is selected directly while speed tracking, voltage effort, and current-limit penalization are evaluated simultaneously. The comparison is also performed against both standard cascade PI and anti-windup cascade PI controllers using the same motor parameters and operating conditions, which is necessary for isolating the effect of the control structure.

Broader predictive-control studies on PMDC, PMSM, induction-motor, and electric-vehicle drives further confirm the usefulness of MPC in high-performance electrical-drive applications^{4-9,17,19-23,37}. These studies show that predictive control can improve dynamic response, reduce ripple, and handle multi-objective control requirements compared with classical control structures. Nevertheless, their results cannot be transferred directly to PMDC drives without a dedicated formulation. The

PMDC motor has a simpler electromechanical structure and a direct relationship between armature current and electromagnetic torque, which makes the speed-current-torque trade-off especially important. Therefore, a PMDC-focused predictive-control assessment remains useful even though MPC has already been widely studied for other motor classes.

2.2. PI, Anti-Windup, and Cascade Control Approaches. PI-based controllers are dominant in practical motor-drive systems because they are simple, transparent, and computationally inexpensive. Anti-windup PI structures, disturbance-observer-based PI controllers, variable desaturation methods, composite PI schemes, and improved tuning strategies have been proposed to reduce overshoot and improve recovery during saturation^{10–15}. These developments are important because saturation is unavoidable in practical drive systems, particularly during startup, rapid reference changes, and load disturbances.

Cascade control architectures provide an additional level of practical improvement by separating speed and current regulation. Recent studies have proposed closed-form cascade-control gain design, fractional-order cascade control, fuzzy cascade control, intelligent tuning, and adaptive cascade PI structures for DC and PMDC motor drives^{24–30}. These methods improve the performance of classical PI structures and can reduce commissioning effort. However, they still rely on nested loops in which the outer speed controller and inner current controller must be tuned sequentially. Furthermore, current and voltage saturation are typically addressed by limiting the generated references or controller outputs, meaning that constraint handling is reactive rather than predictive.

This study is motivated mainly by this distinction. In a cascade PI controller, the controller first generates the desired current or voltage and then applies saturation or anti-windup correction if it exceeds the allowable range. In the proposed FS-MPC strategy, each admissible voltage candidate is evaluated before application using the predicted speed and current trajectories. Thus, current-limit penalization and voltage limitation are integrated into the control decision. This difference provides a clear technical basis for comparing FS-MPC with standard and anti-windup cascade PI controllers rather than treating MPC as only another tuning alternative.

2.3. Constraint Handling and Implementation Issues in MPC. Constraint handling is one of the main reasons for considering MPC in motor drives and power-electronic systems. General MPC design guidelines emphasize the role of input constraints, state constraints, cost-function weights, prediction horizon, computational burden, and feasibility management^{6–8,31}. Studies on constrained nonlinear MPC, robust MPC, converter current constraints, and fixed-switching-frequency FS-MPC further show that predictive control can directly incorporate practical limitations into the decision process^{32–35}. These observations are relevant to PMDC drives because armature overcurrent can increase thermal stress, stress power-electronic devices, and reduce drive reliability.

At the same time, FS-MPC is not free from practical limitations. A basic finite voltage set can introduce steady-state current, torque, and voltage ripple because the applied voltage

changes among discrete candidates. The computational load also increases with the number of candidates and the prediction horizon. In addition, when current limits are implemented through a large penalty rather than by rejecting infeasible candidates, the constraint behaves as a soft constraint and may still permit short transient excursions. These limitations should be stated explicitly to avoid overstating the capability of the method.

For this reason, this study formulates the current limit as a penalized constraint within the finite-set cost function and interprets the results accordingly. The objective is not to claim absolute current protection under all uncertainties, but to evaluate whether adding current-limit penalization to the PMDC FS-MPC decision process improves the transient behavior relative to cascade PI controllers under identical simulation conditions. If strict current protection is required in hardware, the finite-set search should be modified to discard all candidates that violate the allowable current magnitude over the prediction horizon.

2.4. Research Gap in Literature. The reviewed literature shows three main trends. First, predictive control has become an effective framework for electrical drives and power converters, but many studies focus on AC, PMDC, PMSM, induction-motor, or converter applications rather than on a compact PMDC speed-control problem. Second, PI and cascade PI controllers remain practically important, and anti-windup or intelligent tuning methods can improve their behavior; however, these methods generally treat saturation after the controller command has been generated. Third, constraint-aware MPC formulations are well established, but their practical benefit for PMDC motors must be evaluated together with the current and torque transients that accompany fast speed response.

Accordingly, the gap addressed in this study is the lack of a concise PMDC-focused study that formulates speed regulation as a single-loop finite-set voltage-selection problem, includes armature-current-limit penalization in the predictive decision process, and benchmarks the resulting controller against standard cascade PI and anti-windup cascade PI controllers under the same plant and load conditions. This positioning distinguishes this study from broad MPC surveys, AC-drive predictive-control studies, and PI-tuning studies that do not directly evaluate the same constrained PMDC speed-control problem.

3. PROPOSED PMDC MOTOR MODEL

3.1. PMDC Motor Mathematical Model. The PMDC motor is a cornerstone of modern servo drive applications that combine the mechanical simplicity of brushed commutation with the magnetic efficiency of rare-earth permanent magnets. The state-space representation is derived directly from the coupled electromechanical dynamics, ensuring that every equation corresponds precisely to the Simulink plant model, labeled “Plant of PM DC motor 750 W”.

3.1.1. Electrical subsystem dynamics. Applying Kirchhoff’s voltage law to the armature circuit yields the fundamental electrical equation governing the PMDC motor. The terminal voltage V_t must overcome three distinct voltage drops: the resistive drop across the armature winding $R_a i_a$, ω is the motor velocity, the inductive voltage $L_a(di_a/dt)$, and the back-EMF e_b ,

induced by the rotating armature in the permanent magnet field:

$$V_t = R_a i_a + L_a \frac{di_a}{dt} + K_e \omega. \quad (1)$$

By rearranging Equation (1) to isolate the current derivative, the state equation governing the electrical subsystem is obtained. This expression, as implemented in the upper portion of the Simulink plant model, defines the dynamic behavior of the armature current relative to the input terminal voltage and the back-EMF:

$$\frac{di_a}{dt} = \frac{1}{L_a} [V_t - R_a i_a - K_e \omega]. \quad (2)$$

The Simulink block diagram realizes Equation (2) through a summing junction that accepts the positive terminal voltage input (port V_{t_ref}), subtracts the resistive drop via the gain block " R_a ", and subtracts the back-EMF computed by multiplying the angular velocity through the gain block " K_e ". This difference propagates through a gain of " $1/L_a$ " and integrates via a $1/s$ transfer function block to produce the armature current i_a .

3.1.2. Mechanical subsystem dynamics. Newton's second law for rotational systems establishes the relationship between the electromagnetic torque produced by a motor and the resulting angular acceleration. The torque balance equation consists of four distinct components: the electromagnetic torque $T_e = K_t i_a$, viscous friction torque $B\omega$, Coulomb friction torque T_f , and load torque T_L :

$$J \frac{d\omega}{dt} = K_t i_a - B\omega - T_f - T_L. \quad (3)$$

Isolating the angular acceleration yields the mechanical state equation:

$$\frac{d\omega}{dt} = \frac{1}{J} [K_t i_a - B\omega - T_f - T_L]. \quad (4)$$

The lower section of the Simulink plant model implements Equation (4) precisely. A summing junction receives the electromagnetic torque (armature current multiplied by " K_t "), subtracts the viscous friction via " B " multiplied by the feedback angular velocity, subtracts the constant Coulomb friction " T_f ", and subtracts the load torque (set to 25% of rated torque via " $T_{rated} \times 0.25$ "). The resulting net torque passes through " $1/J$ " gain and integrates to produce ω (output port ω_{m_act}).

3.1.3. Motor parameters. Table 1 presents the complete parameter set used for the system modeling and controller design. These values characterize an 750-W industrial-grade PMDC motor, designed for high-performance servo applications that require precise speed regulation and robust torque response under variable load conditions.

3.2. Discrete-Time Model for Predictive Control. The FS-MPC algorithm requires discrete-time state predictions over a finite horizon. Equations (2) and (4) are discretized using the forward Euler approximation method with a sampling period of

Table 1. PMDC Motor Parameters

Parameter	Symbol	Value
Armature Resistance	R_a	0.324 Ω
Armature Inductance	L_a	0.5 mH
Back-EMF Constant	K_e	0.127324 V · s/rad
Torque Constant	K_t	0.127324 N · m/A
Rotor Inertia	J	2.2×10^{-4} kg · m ²
Viscous Friction Coefficient	B	6.0×10^{-4} N · m · s/rad
Coulomb Friction Torque	T_f	0.03 N · m
Brush Voltage Drop	V_{brush}	2.0 V
Rated Voltage	V_{rated}	48 V
Rated Current	I_{rated}	18.5 A
Rated Speed	n_{rated}	3000 rpm
Rated Power	P_{rated}	750 W

$T_s = 0.0005$ s. This specific sampling rate is selected to capture the fast electrical dynamics of the motor while maintaining computational tractability for real-time implementation on embedded platforms.

For the armature current prediction, discretizing Equation (2) yields:

$$i_a(k+1) = i_a(k) + \frac{T_s}{L_a} [V(k) - \text{sign}(i_a) V_{brush} - R_a i_a(k) - K_e \omega(k)]. \quad (5)$$

The mechanical dynamics similarly predict:

$$\omega(k+1) = \omega(k) + \frac{T_s}{J} [K_t i_a(k) - B\omega(k) - \text{sign}(\omega) T_L]. \quad (6)$$

These discretized governing equations constitute the core of the predictive model, which is implemented as a dedicated processing unit within the simulation environment. To ensure high-fidelity bidirectional operation, the $\text{sign}(\cdot)$ function is used to rigorously account for the direction-dependent characteristics of the brush voltage drop and nonlinear friction torque.

4. PROPOSED FS-MPC METHODOLOGY

The proposed FS-MPC strategy represents a paradigm shift from classical feedback control. Rather than reacting to errors through proportional and integral actions, the predictive controller anticipates future system behavior and selects control actions that minimize a performance cost function over a finite prediction horizon. This algorithm is implemented within a specialized computational block that executes at each sampling instant to determine the optimal terminal voltage based on the discrete-time model of the motor. The theoretical description is closely aligned with the computational model developed for the simulation environment to ensure a high-fidelity representation of the plant and control dynamics.

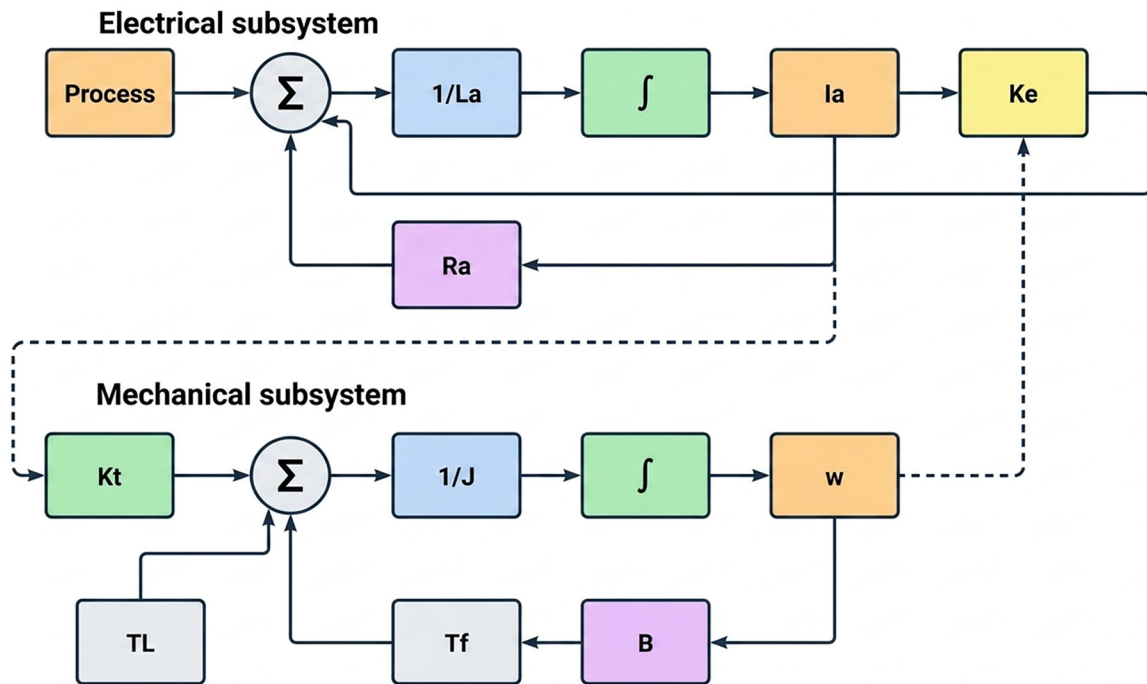


Figure 1. Proposed PMDC plant model illustrating the electrical and mechanical subsystem dynamics

4.1. Proposed Control Architecture. The proposed FS-MPC system, shown in Figure 1, employs a single-loop architecture that fundamentally differs from conventional cascade structures. The controller block receives three inputs: the measured armature current i_a (feedback from plant port i_{a_act}), the

measured angular velocity ω (feedback from port ω_{m_act}), and the reference speed $\omega_{ref} = 150$ rad/s. The single output V_t directly drives the plant through the terminal voltage reference port.

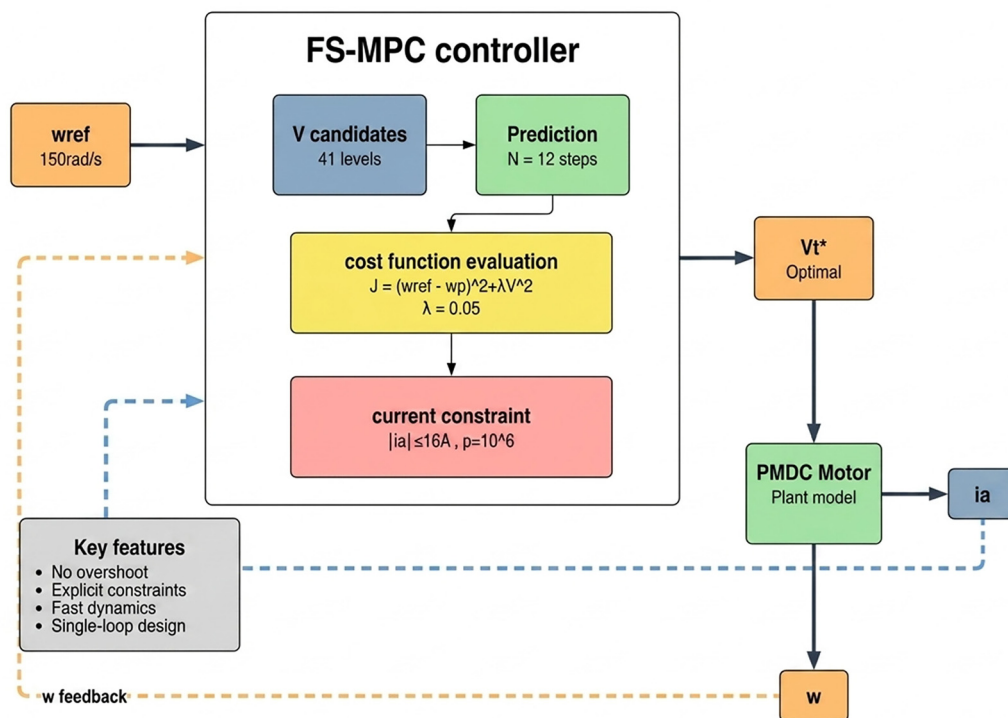


Figure 2. Proposed FS-MPC architecture featuring the single-loop predictive framework, including voltage vector selection, cost function minimization, and explicit current constraint enforcement

This architectural simplicity eliminates the loop-interaction problems inherent in cascade designs. The FS-MPC algorithm jointly optimizes speed tracking and current regulation within a unified cost function, rather than delegating current control to a separate inner loop.

4.2. Proposed Algorithm Implementation. The MATLAB function code, shown in Figure 2, was used to implement the following algorithmic steps at each sampling instant:

Step 1 - Voltage Candidate Generation: The algorithm generates a discrete set of 41 candidate voltages spanning $V_{\min} = -48$ V to $V_{\max} = +48$ V using the MATLAB command $V_candidates = \text{linspace}(V_{\min}, V_{\max}, 41)$. This finite-control set defines the decision space that FS-MPC exhaustively searches.

Step 2 - Multi-Step Prediction: For each candidate voltage V_k , the algorithm predicts future states over $N = 12$ steps. The prediction uses Equations (5) and (6) iteratively, starting from the current measured states:

$$\text{Current prediction: } i_{a,p} = i_{a,p} + T_s \cdot \frac{di_a}{dt} \quad (7)$$

$$\text{Speed prediction: } \omega_p = \omega_p + T_s \cdot \frac{d\omega}{dt} \quad (8)$$

Step 3 - Cost Function Evaluation: The algorithm evaluates a multi-objective cost function combining speed tracking error and control effort:

$$J_{\text{base}} = (\omega_{\text{ref}} - \omega_p)^2 + \lambda V^2 \quad (9)$$

where $\lambda = 0.05$ represents the control effort weighting factor. This term penalizes excessive voltage commands, promoting energy-efficient operation and reducing electromagnetic interference from rapid voltage transitions.

Step 4 - Current Constraint Enforcement: A critical feature that distinguishes FS-MPC from classical PI control is the explicit handling of current constraints. The algorithm enforces a maximum armature current limit, $i_{a,\max} = 16$ A, through a quadratic penalty term:

$$J_{\text{penalty}} = \rho \cdot (|i_{a,p}| - i_{a,\max})^2 \quad \text{if } |i_{a,p}| > i_{a,\max} \quad (10)$$

The penalty weight $\rho = 10^6$ ensures that current violations incur prohibitively high costs, effectively enforcing a soft constraint that approaches hard-constraint behavior. The total cost becomes:

$$J_{\text{total}} = J_{\text{base}} + J_{\text{penalty}} \quad (11)$$

Step 5 - Optimal Voltage Selection: The algorithm selects the candidate voltage that minimizes J_{total} and applies it directly to the plant. This selection process repeats at each sampling instant in a receding-horizon fashion.

5. TRADITIONAL PMDC MOTOR STRATEGIES

This section describes in detail the implementation of the conventional control strategies. Each theoretical description is strictly aligned with the computational models developed for the

Table 2. FS-MPC Controller Parameters

Parameter	Symbol	Value
Sampling Period	T_s	0.5 ms
Prediction Horizon	N	12 steps
Control Effort Weight	λ	0.05
Current Penalty Weight	ρ	106
Maximum Current Limit	$i_{a,\max}$	16 A
Minimum Voltage	$V_{\min}$	-48 V
Maximum Voltage	$V_{\max}$	+48 V
Voltage Candidates	—	41 levels

simulation environment to ensure a high-fidelity representation of the plant and control dynamics.

5.1. Anti-Windup Cascade PI Controller. The anti-windup cascade PI controller improves upon the standard cascade structure by incorporating an integrator saturation mitigation mechanism. This implementation uses a back-calculation anti-windup scheme designed to prevent integral accumulation during periods of controller output saturation, as shown in Figure 3. By feeding back the difference between the saturated and unsaturated control signals, the integrator is reset dynamically, thereby ensuring a faster recovery and reduced overshoot when the system returns to the linear operating range.

5.1.1. Cascade control structure. The cascade architecture comprises two nested control loops:

Outer Speed Loop: The speed reference $\omega_{\text{ref}} = 150$ rad/s is applied to the anti-windup PI controller block (labeled “Anti-windup PI controller”), which compares it with the measured speed ω (fed back from port $\omega_{\text{m_act}}$). The outer loop then generates a current reference $i_{a,\text{ref}}$ that commands the inner loop.

(Standard Cascade PI, Control Architecture — mirrored wording) The outer speed PI controller processes the speed error and generates a current reference; a saturation block limits this reference before it is passed to the inner current loop.

Inner Current Loop: The current reference passes through a summing junction that computes the error $e_i = i_{a,\text{ref}} - i_a$. A standard proportional-integral-derivative (PID) block (labeled “current i_a , PID Controller, A”) processes this error, followed by a saturation block that limits the terminal voltage command to ± 48 V.

5.1.2. Anti-windup mechanism. The anti-windup subsystem, shown in Figure 3, implements a back-calculation scheme that computes the discrepancy between the unsaturated and saturated controller outputs.

The PI controller with anti-windup operates according to:

$$u_{\text{unsat}} = K_p e + K_i \int e \, dt \quad (12)$$

$$u_{\text{sat}} = \text{sat}(u_{\text{unsat}}, i_{a,\min}, i_{a,\max}) \quad (13)$$

$$e_{\text{aw}} = K_{\text{aw}}(u_{\text{sat}} - u_{\text{unsat}}) \quad (14)$$

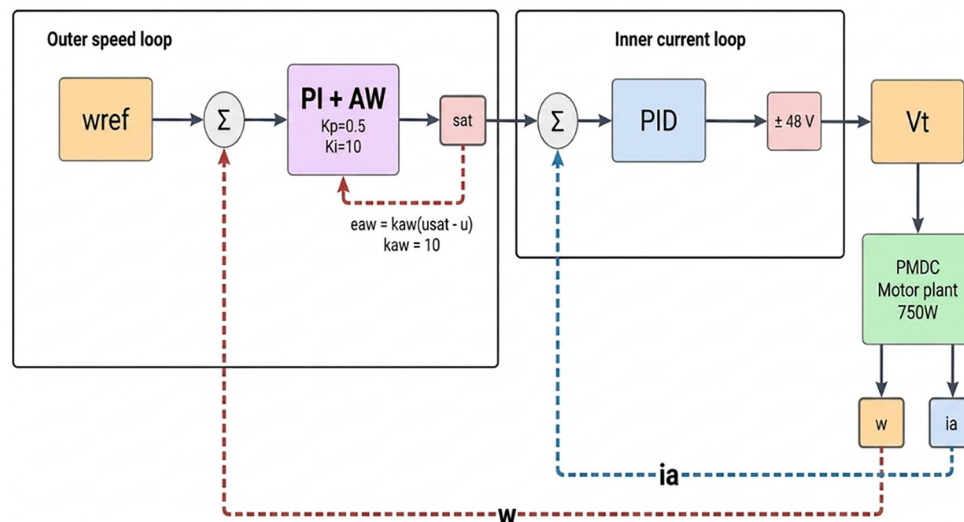


Figure 3. Anti-windup cascade PI control structure, showing dual-loop regulation with outer speed control, inner current control, and back-calculation to mitigate integrator saturation effects

where $K_{aw} = 10$ represents the anti-windup tracking gain. The back-calculation error e_{aw} modifies the integrator input, effectively reducing integral action when saturation occurs. This mechanism is visible in the Simulink diagram as the feedback path from the saturation block output to the summing junction that feeds the integrator (1/s block).

The controller gains extracted from the Simulink model are $K_p = 0.5$ and $K_i = 10$ for the outer speed loop, with the saturation block limiting the output current reference to a specified range (visible as the "ref ia" saturation block in the diagram).

5.2. Standard Cascade PI Controller. The standard cascade PI controller serves as the baseline reference, representing conventional industrial practice. The Simulink implementation, shown in Figure 4, demonstrates a classic two-loop structure without any anti-windup provisions.

5.2.1. Control architecture. The standard cascade structure mirrors the anti-windup version but omits the back-calculation feedback path. The outer speed PI controller processes the speed error and generates a current reference. A saturation block limits this reference before it enters the inner current loop. The PI speed controller subsystem, shown in Figure 4, implements the standard parallel form.

$$i_{a,ref} = K_p(\omega_{ref} - \omega) + K_i \int (\omega_{ref} - \omega) dt. \quad (15)$$

Table 3. Anti-Windup Cascade PI Controller Parameters

Parameter	Symbol	Value
Proportional Gain (Speed)	K_p	0.5
Integral Gain (Speed)	K_i	10
Anti-Windup Gain	K_{aw}	10
Current Reference Limits	i_{a-lim}	± 16 A
Voltage Output Limits	V_{t-lim}	± 48 V

The Simulink diagram shows the parallel PI structure with gain blocks " K_p Gain" = 0.5 and " K_i Gain" = 10 feeding into a summing junction. The integrator (1/s block) directly receives the speed error without any feedback modification from the saturation block—the defining characteristic that distinguishes this controller from the anti-windup variant.

5.2.2. Integrator windup problem. The absence of anti-windup mechanisms in this controller creates a fundamental vulnerability: when the current reference saturates during startup or load transients, the integrator continues accumulating error. This accumulated integral action must discharge before the controller can respond appropriately to error reversal, manifesting as excessive overshoot in the speed response.

Consider the startup scenario: the speed error is initially $\omega_{ref} = 150$ rad/s. The large error causes rapid integral accumulation, driving the current reference to saturation. Even as the motor accelerates and the error decreases, the integral term remains inflated. When the actual speed approaches or momentarily exceeds the reference, the excess integral action prolongs the high current command, resulting in overshoot that can exceed 30% of the reference value—a behavior clearly visible in the simulation results.

6. RESULTS AND DISCUSSION

This section presents the principal findings of the study and discusses the results in depth with respect to the research objectives.

6.1. Comparative Analysis Framework. To ensure a rigorous comparison, all three controllers operated under identical conditions:

- Reference Speed: $\omega_{ref} = 150$ rad/s (step input at $t = 0$)
- Load Condition: $T_L = 0.25 \times T_{rated} \approx 0.597$ N · m (constant load)
- Voltage Limits: -48 V $\leq V_t \leq +48$ V (DC bus constraint)

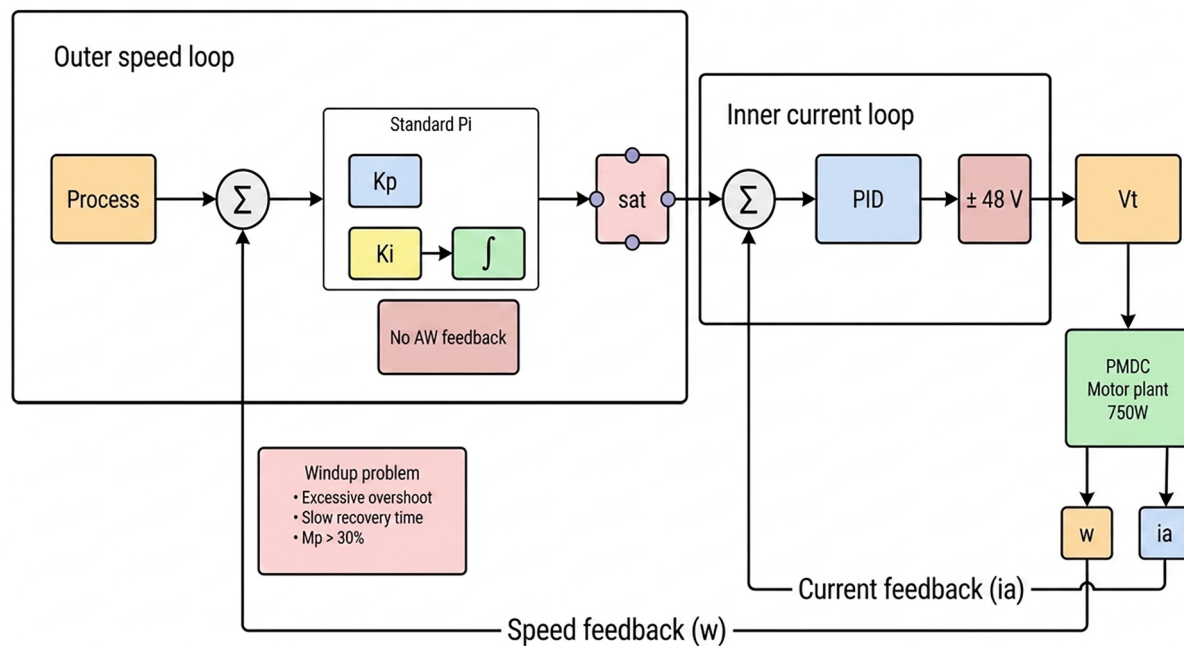


Figure 4. Standard cascade PI control structure, showing dual-loop regulation without anti-windup, leading to integrator saturation and degraded transient performance

- Current Constraint: $i_{a,max} = 16$ A (thermal/demagnetization protection)
- The following evaluation metrics were applied:
- Rise Time (t_r): Time to reach 90% of steady-state speed from initial response.
- Overshoot (M_p): Percentage by which peak speed exceeds reference speed.
- Settling Time (t_s): Time to enter and remain within $\pm 2\%$ error band around the steady state.
- Steady-State Error (e_{ss}): Final deviation from reference speed.
- Current Constraint Satisfaction: Peak armature current relative to 16 A limit.

These metrics, combined with qualitative assessment of control signal behavior and robustness to parameter variations, provide a comprehensive framework for evaluating the relative merits of each control strategy.

6.2. Simulation Discussion. The dynamic performance of the proposed control strategy was evaluated through simulation of a PMDC motor drive system using the parameters listed in Table 1. The implementation details and parameter tuning of the proposed FS-MPC, conventional anti-windup PI, and classical PI controllers are provided in Tables 2 to 4, respectively. All

Table 4. Standard Cascade PI Controller Parameters

Parameter	Symbol	Value
Proportional Gain (Speed)	K_p	0.5
Integral Gain (Speed)	K_i	10
Current Reference Limits	$i_{a,lim}$	± 16 A
Voltage Output Limits	$V_{t,lim}$	± 48 V
Anti-Windup	—	None

controllers were tested under identical operating conditions to ensure a fair and consistent comparison. Meanwhile, Figures 5 to 8 present the comparative responses of angular speed, armature current, electromagnetic torque, and terminal voltage. The proposed FS-MPC strategy demonstrated superior transient performance, achieving faster rise time and improved tracking capability compared to the other methods.

Figure 5 compares the terminal voltage responses of the three controllers. The proposed FS-MPC reaches the required voltage region very quickly, within about 0.02 s, and then operates around 20–21 V with a small steady-state ripple of nearly ± 1 V. This ripple is expected because the controller selects the voltage

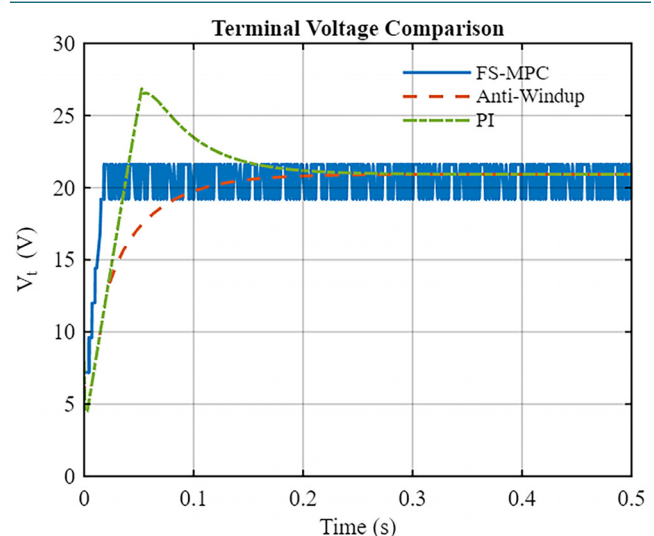


Figure 5. Terminal voltage responses for FS-MPC, anti-windup, and PI controllers under identical operating conditions

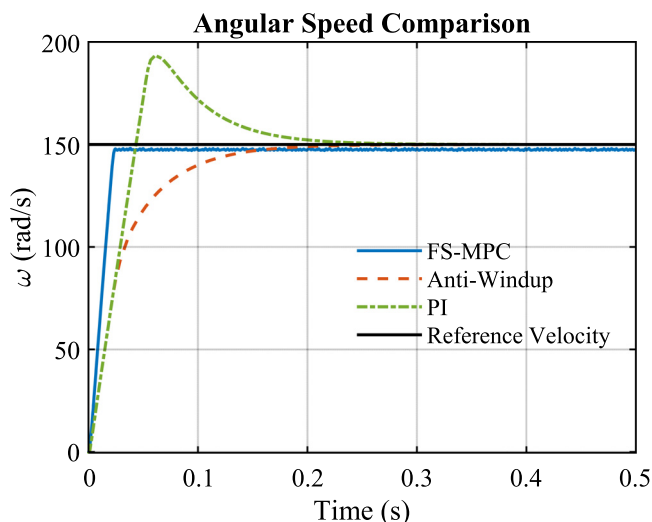


Figure 6. Comparison of angular speed responses for FS-MPC, anti-windup, and PI controllers, highlighting differences in rise time, overshoot, and settling behavior

from a finite set of candidates. The anti-windup cascade PI controller gives a smoother voltage response, but it approaches the steady-state value more slowly, taking approximately 0.15–0.20 s. The standard cascade PI controller shows the largest transient overshoot, with the voltage rising to approximately 26–27 V near 0.05 s before settling close to 21 V. This behavior is mainly related to the integrator windup effect during the startup period. Overall, the figure shows that FS-MPC provides the fastest voltage response, while the anti-windup controller gives the smoothest response. The standard PI controller is the least favorable during the transient period because of its noticeable voltage overshoot.

Figure 6 compares the angular speed responses of the three controllers with the reference velocity of 150 rad/s. The proposed FS-MPC reaches the reference speed very quickly, within approximately 0.02 s, with almost no overshoot. After the transient period, the speed remains close to the reference value with only a very small ripple. The anti-windup cascade PI controller gives a smooth response, but it is slower than FS-MPC and approaches the reference speed after approximately 0.15 s. The standard cascade PI controller shows the largest transient overshoot, where the speed rises to nearly 190 rad/s at approximately 0.05–0.06 s before gradually returning to the reference. This overshoot is mainly due to the windup effect in the speed-loop integrator during startup. Overall, FS-MPC provides the fastest and most accurate speed tracking. The anti-windup controller improves the response compared with the standard PI controller, but it remains slower. The standard PI controller gives the weakest transient performance because of its high overshoot and longer settling time.

Figure 7 shows the armature-current responses of the three controllers. The FS-MPC produces the fastest current response, with a short initial peak of approximately 17–18 A during the first 0.02 s. This brief peak slightly exceeds the 16-A current-limit threshold; the excursion is a direct and expected consequence of formulating the current limit as a soft penalty within the cost function (Section 4) rather than as a hard constraint. The penalty strongly discourages, but does not categorically forbid, momentary violations during the most aggressive phase of acceleration.

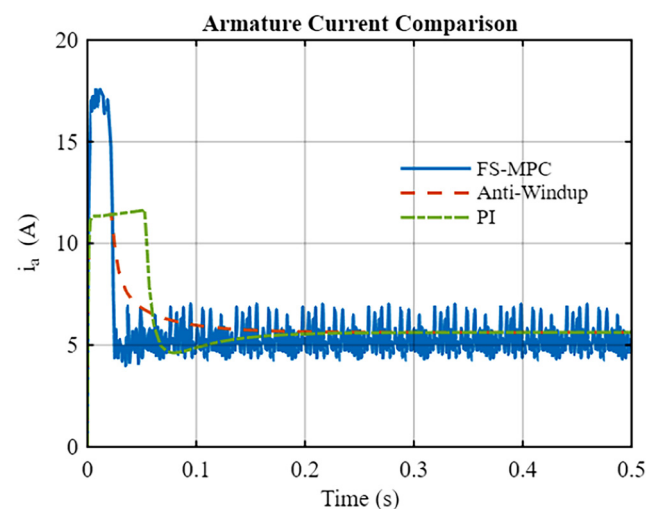


Figure 7. Comparison of armature current responses for FS-MPC, anti-windup, and PI controllers, highlighting differences in transient peak, settling time, and steady-state behavior

Where strict adherence to the 16-A bound is mandatory, the finite-set search can be modified to reject every candidate whose predicted current exceeds the limit over the horizon, as discussed in Section 7. After this transient, the current falls quickly and settles at approximately 5–6 A in less than 0.05 s, with a small steady-state ripple attributable to the finite-set voltage selection. The anti-windup cascade PI controller yields a smoother current response, with a peak of approximately 10–11 A, but takes longer to approach the steady-state level. The standard PI controller maintains approximately 11–12 A for a longer interval before decaying toward steady state, consistent with the windup effect observed in the speed and voltage responses. Overall, FS-MPC delivers a faster current transient that drives quicker convergence to the reference speed, at the cost of a higher short-duration peak and a visible steady-state ripple; the PI-based controllers produce smoother current waveforms but slower transients.

Figure 8 illustrates the electromagnetic torque responses of the three controllers. The FS-MPC controller gives the fastest

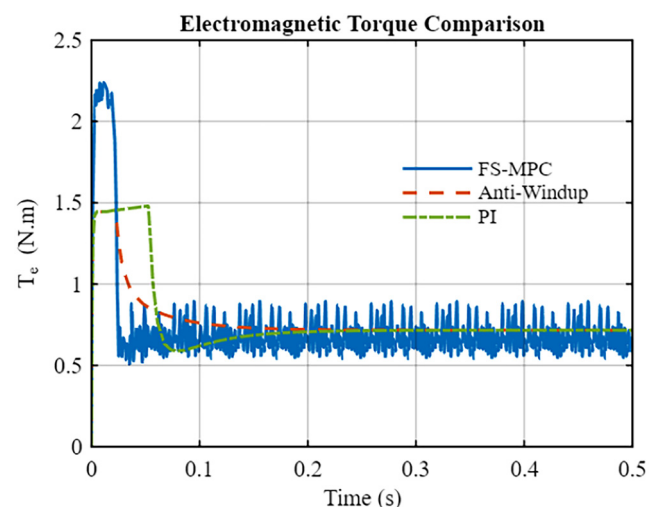


Figure 8. Comparison of electromagnetic torque responses for FS-MPC, anti-windup, and PI controllers, highlighting differences in transient peak, settling time, and steady-state behavior

Table 5. Summary of the main performance indicators extracted from Figures 5 to 8

Performance indicator	FS-MPC	Anti-windup cascade PI	Standard cascade PI
Voltage convergence time	About 0.02 s	0.15–0.20 s	0.18–0.20 s
Voltage peak/ripple	21–22 V, with ± 1 V ripple	About 21 V, smooth	26–27 V overshoot
Speed settling time	About 0.02 s	About 0.15 s	0.18–0.20 s
Speed overshoot	Negligible	Negligible	About 27%
Peak armature current	17–18 A	10–11 A	11–12 A
Current settling time	Less than 0.05 s	0.08–0.10 s	0.10–0.12 s
Peak electromagnetic torque	2.2–2.3 N · m	1.4–1.5 N · m	1.4–1.5 N · m
Torque settling time	Less than 0.05 s	0.08–0.10 s	0.10–0.12 s
Main observation	Fastest response, but with ripple and higher transient current/torque	Smooth response, but slower	Highest overshoot and slowest transient response

torque reaction, with a short peak of approximately 2.2–2.3 N · m during the first 0.01–0.02 s. This high initial torque helps the motor accelerate quickly toward the reference speed. After this transient period, the torque drops rapidly and settles at around 0.65–0.7 N · m, with a small ripple due to finite-set voltage selection. The anti-windup cascade PI controller gives a smoother torque response, but it reaches the steady-state torque more slowly. Its peak torque is approximately 1.4–1.5 N · m, followed by a gradual decrease toward the final value. The standard PI controller also reaches a similar peak torque but maintains it for a longer time before settling. This behavior is consistent with the overshoot observed in the speed response. Overall, FS-MPC provides a faster torque response, which explains its faster speed tracking. However, this improvement comes with a higher short-duration torque peak and visible steady-state ripple. The PI-based controllers produce smoother torque profiles, but their transient responses are slower. Finally, for a comprehensive quantitative summary of the responses illustrated in Figures 5 to 8, the primary transient and steady-state performance metrics of the three controllers are consolidated in Table 5. These values are derived directly from the simulation data to ensure a rigorous comparison.

7. CONCLUSIONS

This study investigates a single-loop finite-set model predictive control strategy for PMDC motor velocity regulation and compares it with standard cascade PI and anti-windup cascade PI controllers under identical simulation conditions. The proposed FS-MPC selects the terminal voltage directly from a finite candidate set using a discrete-time PMDC model and a cost function that penalizes speed-tracking error, voltage effort, and predicted armature-current-limit violation. In contrast to cascade PI control, the proposed approach does not require an outer speed PI loop to generate a current reference and a separately tuned inner current loop to generate the voltage command. Instead, speed regulation and current-limit penalization are considered within the same finite-set decision process.

Under the investigated operating condition of a 150-rad/s reference speed and a 25% rated load, the proposed controller reduces the speed settling time to approximately 0.02 s,

compared with approximately 0.15 s for the anti-windup cascade PI controller and approximately 0.18–0.20 s for the standard cascade PI controller. The standard cascade PI controller also exhibited approximately 27% speed overshoot, whereas the proposed FS-MPC achieved nearly overshoot-free tracking. These results indicate that predictive voltage selection can substantially improve transient speed response and reduce the loop-interaction and windup effects associated with classical cascade PI control.

The results also reveal important trade-offs. The faster FS-MPC response is accompanied by a higher short-duration current and torque transient, which explains the rapid rotor acceleration. In addition, finite-set steady-state ripple appears in the terminal-voltage, armature-current, and electromagnetic-torque responses. The reported current behavior should also be interpreted carefully because the current limit is implemented as a soft penalty in the cost function. Therefore, the controller strongly discourages current-limit violation but does not provide the same guarantee as a hard constraint unless voltage candidates that violate the allowable current magnitude are explicitly rejected.

The main limitation of this study is that the validation is simulation-based and restricted to one reference speed and one load-torque condition. Consequently, the conclusions should be interpreted within the scope of the investigated operating condition rather than as a complete robustness demonstration. Future work should extend the validation through experimental implementation or hardware-in-the-loop testing, evaluate robustness under parameter uncertainty in armature resistance, armature inductance, inertia, friction, and torque constant, and include multiple speed-reference commands, speed reversals, load-torque disturbances, and current-limit stress tests. Further development should also consider hard-constrained FS-MPC and fixed-switching-frequency or modulated FS-MPC formulations to reduce steady-state ripple and improve practical suitability for embedded industrial PMDC drives.

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