Letters

A Switched Ultra-Local Model-Free Predictive Controller for PMSMs

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***Abstract*—Existing model-free predictive control (MFPC) methods are primarily based on mature controller design formulas, with various observers added to these controllers. Currently, there is a lack of modifications to the mechanism of model-free predictive control itself. This letter starts with the original formulation of the ultra-local model and redesigns a model-free predictive control method from the fundamental formula level. First, a term based on an exponential-like function is proposed, modifying the proportion of the controller's error term, called exponential MFPC. Subsequently, a switching control concept is introduced into the controller design, facilitating better integration of the existing method with the new one, ensuring system performance across different error intervals. Ultimately, the effectiveness of the proposed switched ultra-local MFPC is demonstrated by the experimental result of the superiority in the loading aspect with smaller speed overshoot and speed oscillations.**

***Index Terms*—Model-free predictive control (MFPC), switching control system.**

I. Introduction

IN RECENT years, model predictive control (MPC) for permanent magnet synchronous motors (PMSMs) has garnered considerable attention and has shown promising research results [1], [2]. Currently, the predominant method employed in the current loop is model predictive current control [3]. This method is based on the voltage–current model of the PMSM, incorporating motor inductance, resistance, and flux linkage parameters. However, these parameters vary under different operating conditions, posing a persistent challenge to robustness [4], [5].

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To address the issue of parameter robustness, scholars have proposed a model-free predictive approach, directly considering the input–output relationship, autonomously assigning parameters, and adjusting them [6], [7], [8], [9]. The control parameters are assigned based on actual physical relationships [10], improving the interpretability to some extent, although the model-free perspective has been somewhat weakened. Another way of model-free prediction is to use the difference of current. Subtractions in two-phase d, q currents are employed to predict motor voltages [11]. A model-free predictive control method is employed in the two-phase stationary coordinate system, demonstrating satisfactory performance [12]. This method requires both alpha and beta current controls to utilize model-free predictive control. The approach proposed by the authors in [13] and [14] consists of differentiating the stator current, presenting an alternative model-free control strategy. However, the differential method for current amplifies current noise to some extent, potentially affecting control effectiveness.

In addition, signal tracking involves alternating current (ac) variables, which require real-time compensation by an extended state observer [10], introducing a certain level of complexity. Yang et al. [15] applied the Luenberger method, which is grounded in linear observer theory. Both of these theories are based on high-gain parameters, which need prolonged tuning in practical experiments to ensure system stability, and considerable computational resources are required.

The above-mentioned approaches innovate from the perspective of control scenarios or from the viewpoint of observers, without modifying the formulation of the model-free predictive control (MFPC), particularly the ultra-local MFPC methodology. Thus, this letter contributes in the following ways: 1) This letter intends to adopt the MFPC method for current and voltage on the q-axis, analyzing the superiority based on the differentiation of the reference current on the q-axis. 2) This letter proposes a new scheme of MFPC based on an exponential-like error term and removes the disturbance observer term. 3) This letter proposes a method for switched-MFPC that combines MFPC and the new designed exponential-MFPC.

II. Implemented Model-Free Predictive Control

A. Derivation Flow of MFPC

For a single-input single-output nonlinear system, the ultra-local model can be expressed as follows:

$$\dot{I}_q = \alpha U_q + D \tag{1}$$

where $U_q \in \mathbb{R}$ and $\dot{I}_q \in \mathbb{R}$ are the system input voltage and output current derivative, respectively, $\alpha \in \mathbb{R}$ is a nonphysical scaling factor selected by the designer, and $D \in \mathbb{R}$ denotes the unknown part of the system including the unknown structure and disturbances. Since

$$\dot{I}_q = \dot{I}_q^* + K_{I_q} e_{I_q} \tag{2}$$

the following relationship is given:

$$U_q = \left(-\hat{D} + \dot{I}_q^* + K_{I_q} e_{I_q}\right)/\alpha \tag{3}$$

where $\hat{D} \in \mathbb{R}$ is the estimated value of D, $\dot{I}_q^*$ is the derivative of the reference value of q current, $K_{I_q} \in \mathbb{R}$ is the control gain that needs to be tuned, and $e_{I_q} \in \mathbb{R}$ is the current tracking error.

By discretizing the q-axis current using first-order differentiation, $\dot{I}_{q,k}^*$ is described as follows:

$$\dot{I}_{q,k}^* = \left(I_{q,k}^* - I_{q,k-1}^*\right)/T_s. \tag{4}$$

B. Priority of Model-Free Predictive Control Using Current Reference

From (4), the following relationship is derived:

$$\begin{aligned}\dot{I}_{q,k}^* &= K_{P_\omega}\left(e_{\omega_k} - e_{\omega_{k-1}}\right)/T_s + K_{I_\omega}\left(\sum_{k=1}^{N} e_{\omega_k} - \sum_{k=1}^{N} e_{\omega_{k-1}}\right) \\ &= \left(K_{P_\omega}\left(e_{\omega_k} - e_{\omega_{k-1}}\right) + K_{I_\omega} e_{\omega_k} T_s\right)/T_s \end{aligned} \tag{5}$$

where $T_s \in \mathbb{R}$ is the sample time, $K_{P_\omega} \in \mathbb{R}$ and $K_{I_\omega} \in \mathbb{R}$ are the PI control gains for speed loop, and $e_{\omega_k} \in \mathbb{R}$ is the speed tracking error. The term of current reference difference can ultimately be simplified to a form of PD controller using PI control parameters of speed loop as shown in (5). In this letter, $K_{P_\omega} = 0.01$ and $K_{I_\omega} = 0.1$ for PMSM speed control loop. Compared with the following (6) of q current difference

$$\dot{I}_{q,k} = \left(U_{q,k} - R_s I_{q,k} - \omega_{e,k} L_d I_{d,k} - \omega_{e,k}\psi_f\right)/L_q \tag{6}$$

when $I_{q,k}, I_{d,k}, \omega_k$, and $U_{q,k}$ encounter a small variable increment, the coefficients of the formula can be observed to provide a simple assessment of the physical quantity's sensitivity to disturbance. Evidently, as seen from (7), different physical quantities affect $\dot{I}_{q,k}$, and the coefficients of some terms are significantly larger than that in $\dot{I}_{q,k}^*$. In the formula, $\varepsilon_\bullet$ represents the noise associated with the corresponding physical quantity, and the physical parameters within the equation are given in Table II.

$$\begin{aligned}\varepsilon_{\dot{I}_{q,k}^*} &= K_{P_\omega}\left(\varepsilon_{e_{\omega_k}} - \varepsilon_{e_{\omega_{k-1}}}\right)/T_s + K_{I_\omega}\varepsilon_{e_{\omega_k}} \\ \varepsilon_{\dot{I}_{q,k}} &= \varepsilon_{U_{q,k}}/L_q + R_s\varepsilon_{I_{q,k}}/L_q + \varepsilon_{\omega_{e,k}}\varepsilon_{I_{d,k}} - \varepsilon_{\omega_{e,k}}\psi_f/L_q. \end{aligned} \tag{7}$$

Hence, the model-free architecture in this letter using the difference of q current reference value $\dot{I}_{q,k}^*$ is less prone to noise compared to directly using the q current difference $\dot{I}_{q,k}$.

C. Switched-Model-Free Predictive Control (SMFPC) Method

In this section, a SMFPC method is presented. The implementation of the method is straightforward, the first part is the

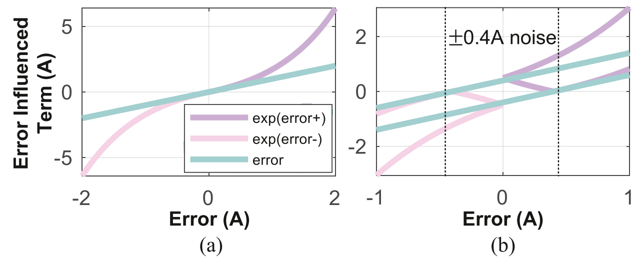

Fig. 1. (a) Influence of error term: error $= (I_{q,k}^* - I_{q,k})$, exp(error+) $= (\exp(|I_{q,k}^* - I_{q,k}|) - 1)$, exp(error-) $= (1 - \exp(|I_{q,k}^* - I_{q,k}|))$ in (8), (9), and (10). (b) Influence of error term with $\varepsilon_{e_{I_{q,k}}} = \pm 0.4$ noise: error $= (I_{q,k}^* - I_{q,k} + \varepsilon_{e_{I_{q,k}}})$, exp(error+) $= (\exp(|I_{q,k}^* - I_{q,k} + \varepsilon_{e_{I_{q,k}}}|) - 1)$, and exp(error-) $= (1 - \exp(|I_{q,k}^* - I_{q,k} + \varepsilon_{e_{I_{q,k}}}|))$.

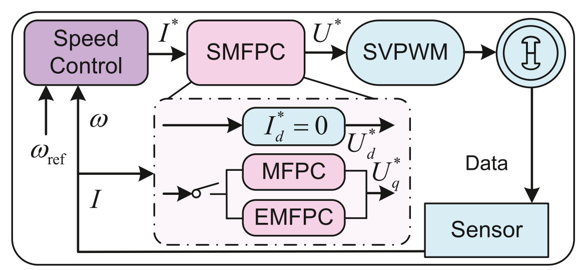

Fig. 2. Structure of SMFPC.

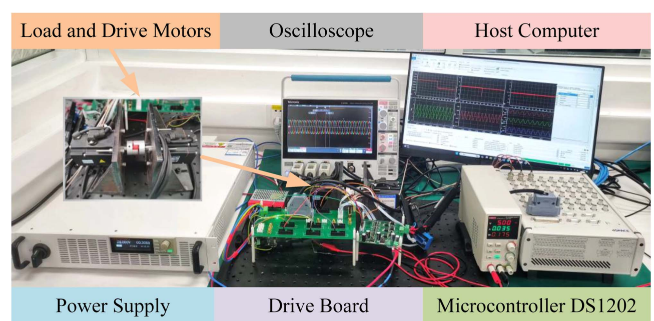

Fig. 3. Experimental setup of a 200-W surface-mounted PMSM testbench.

ultra-local MFPC controller referred to [6] and [10] with the integral part and without the disturbance term, as shown in the following with discretized form:

$$\begin{aligned} U_{q,k} &= \left(\dot{I}_{q,k}^* + K_a\left(I_{q,k}^* - I_{q,k}\right) + K_b\sum_{k=1}^{N}\left(I_{q,k}^* - I_{q,k}\right)\right)/\alpha \\ |e_{I_{q,k}}| &< e_{I_{q,\text{thres}}} \end{aligned} \tag{8}$$

where $K_a, K_b \in \mathbb{R}$ are the corresponding coefficients for proportional term and integral term, e_{I_q} is the current tracking error, and $e_{I_{q,\text{thres}}}$ is the switching threshold regarding the current error. Another switched part is exponential-MFPC (EMFPC) with an addition of exponential term to amplify the influence of error

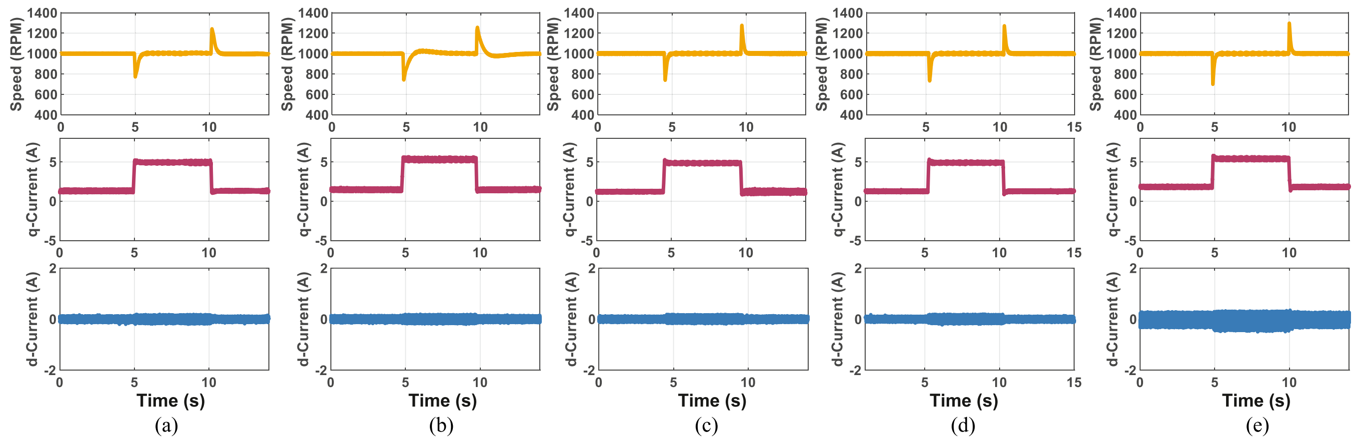

Fig. 4. Spontaneous loading and unloading experiment with 0.3 N · m load. (a) SMFPC with parameter set 1. (b) MFPC with parameter set 2. (c) SMFPC with parameter set 3. (d) MFPC with parameter set 4. (e) PI gain scheduling. (Parameter sets are given in Table I.).

term, as illustrated in the following:

$$U_{q,k} = \Bigg(\dot{I}^*_{q,k} + K_1\left(\exp\left(\left|I^*_{q,k} - I_{q,k}\right|\right) - 1\right) + K_2 \sum_{k=1}^{N}\left(I^*_{q,k} - I_{q,k}\right)\Bigg)/\alpha, \text{if } I^*_{q,k} > I_{q,k},\ |e_{I_{q,k}}| > e_{I_{q,\text{thres}}} \tag{9}$$

$$U_{q,k} = \Bigg(\dot{I}^*_{q,k} + K_1\left(1 - \exp\left(\left|I^*_{q,k} - I_{q,k}\right|\right)\right) + K_2 \sum_{k=1}^{N}\left(I^*_{q,k} - I_{q,k}\right)\Bigg)/\alpha, \text{if } I^*_{q,k} < I_{q,k},\ |e_{I_{q,k}}| > e_{I_{q,\text{thres}}}. \tag{10}$$

The graphical representation of the above two formulas and its noise sensitivity are shown in Fig. 1(a) and (b). Here, the switching threshold is suggested to be $e_{I_{q,\text{thres}}} > (I_{q,\text{max,st}} - I_{q,\text{min,st}})$, where $I_{q,\text{max,st}} \in \mathbb{R}$ and $I_{q,\text{min,st}} \in \mathbb{R}$ are the maximum and minimum values in the steady-state process, which can also be regarded as the vibration or noise range. In this letter, $e_{I_{q,\text{thres}}}$ is selected to be 1 A, whose theoretical selection strategy should also be a research direction in the future.

D. Algorithm Implementation

Fig. 2 illustrates the control block diagram of the proposed switching control strategy-based ultra-local model-free predictive control. It can be observed that this method incorporates current loop control. The current loop's I_d control currently maintains I_d^* equal to 0 control method. The modification introduced in this study pertains only to the q-axis current controller, which is replaced with the proposed method. In the proposed strategy, two switching local controllers, MFPC and EMFPC, constitute the SMFPC control strategies, which then feed into the space vector pulsewidth modulation (SVPWM) block.

TABLE I
SUGGESTED CONTROL PARAMETER SETS OF MODEL-FREE PREDICTIVE CONTROL

Parameters	K_a	K_b	K_1	K_2	α	e_{I_q}
Set 1	R_s/L_q	R_sT_s/L_q	R_s/L_q	R_sT_s/L_q	$1/L_q$	1A
Set 2	R_s/L_q	R_sT_s/L_q	R_s/L_q	R_sT_s/L_q	$1/L_q$	-
Set 3	50	$10T_s$	50	$10T_s$	$1/R$	1A
Set 4	300	T_s	300	T_s	$1/R$	-

1 and 3 are for SMFPC, 2 and 4 are for comparison groups of MFPC.

TABLE II
PARAMETERS OF THE PMSM

Parameter	Unit	Value
q Inductance L_q	H	0.00024
d Inductance L_d	H	0.00024
Resistance R_s	Ohm	0.12
Inertia J	kgm^2	0.00008
PM Flux Linkage ψ_f	Wb	0.008
Sample Time T_s	s	0.0001

Since model-free algorithms typically exhibit parameter robustness, the parameters are often nonphysical values that researchers adjust themselves. However, to facilitate future research and enhance the reproducibility of this work, we provide four sets of suggested parameters. These suggested parameters are given in Table I, while the corresponding PMSM parameters are given in Table II.

III. EXPERIMENTAL RESULTS

A. Experimental Setup

The dSPACE DS1202 is utilized to control a 200-W PMSM in the research, as shown in Fig. 3. The parameters of the PMSM are given in Table II. The control frequencies for both speed and current loop are set at 10 kHz.

B. Experimentation

1) Spontaneous Load: The first set of experiments involves comparing the proposed SMFPC, MFPC within q current control loop [6], [10] with the modification form (8), and PI controller

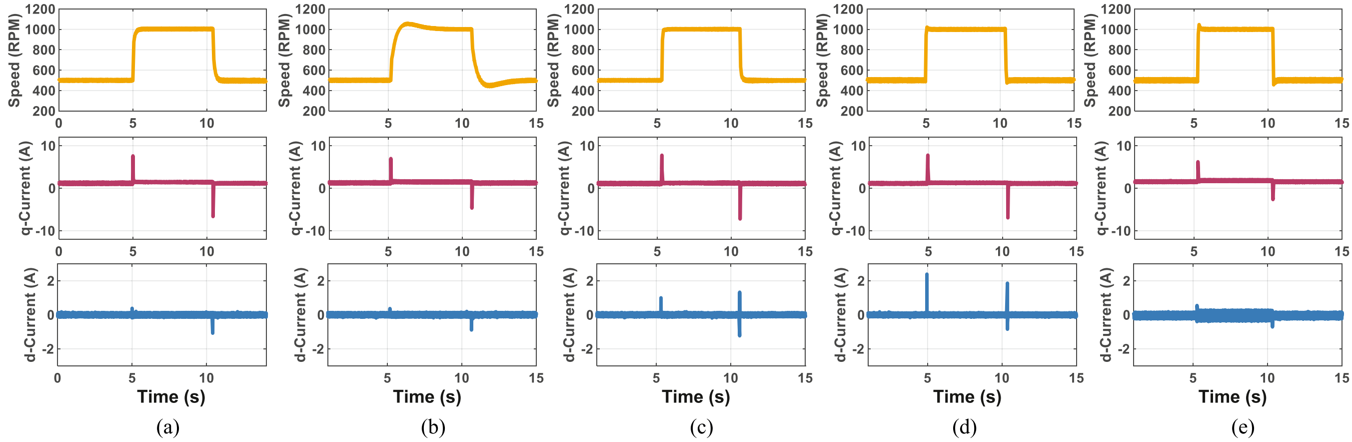

Fig. 5. Acceleration and deceleration with constant 0.3 N · m load. (a) SMFPC with parameter set 1. (b) MFPC with parameter set 2. (c) SMFPC with parameter set 3. (d) MFPC with parameter set 4. (e) PI gain scheduling. (Parameter sets are shown in Table I.).

TABLE III
PERFORMANCE COMPARISON

Performance	SMFPC1	MFPC2	SMFPC3	MFPC4	PIGS
Loading Overshoot (r/min)	228	259	260	270	299
Unloading Overshoot (r/min)	243	257	275	270	295
Loading Recovery Time (s)	0.50	0.73	0.39	0.39	0.39
Unloading Recovery Time (s)	0.55	0.69	0.39	0.39	0.38
Loading Speed Oscillation (r/min)	5.17	5.51	5.74	6.01	5.50
Loading q Current Oscillation (A)	0.07	0.107	0.074	0.075	0.08
Loading d Current Oscillation (A)	0.057	0.07	0.067	0.070	0.167
Rise Time Acc. (s)	0.17	0.41	0.05	0.045	0.035
Rise Time Dcc. (s)	0.25	0.43	0.09	0.07	0.035
Speed Overshoot Acc. (r/min)	0	57	0	21	42
Speed Overshoot Dcc. (r/min)	0	63	0	28	55

1, 2, 3, 4 are parameter sets as shown in Table I. PIGS: PI-gainscheduling.

in $I_d^* = 0$ control, a simplified PI-gain scheduling of [16] with changed proportional gain and integral gain (0.6 and 300 within $e_{I_{q,\text{thres}}}$; 1 and 600 outside $e_{I_{q,\text{thres}}}$) under a sudden increase of the 0.3 N · m load and a sudden decrease of 0.3 N · m load at a speed of 1000 r/min, as depicted in Fig. 4.

2) Acceleration and Deceleration: The second set of experiments investigates the acceleration (Acc.) and deceleration (Dcc.) performance when the PMSM operates without external loads. The motor undergoes acceleration from 500 to 1000 r/min and subsequent deceleration to 500 r/min, as depicted in Fig. 5.

C. Performance Comparison

This letter compares the performance of three methods with different parameter sets across various metrics. This includes overshoot and the corresponding recovery time for sudden load increases and decreases. In addition, the static performance of the motor under load, represented by speed and current standard variance, which directly reflects the oscillation of the operating equipment during practical operation, is considered. In the acceleration (Acc.) and deceleration (Dcc.) phases, the rise time and its corresponding overshoot is monitored. The summarized results are presented in Table III.

IV. CONCLUSION

A. Conclusion

This letter fundamentally alters the formula of ultra-local MFPC by introducing an exponential term. The objective is to increase the weight of the error term throughout the ultra-local MFPC, making the controller more sensitive to errors. In addition, a switching control strategy is incorporated to prevent the motor from adjusting too quickly under the influence of the exponential term, thus avoiding unnecessary reverse overshoot. It is evident that the proposed method exhibits favorable performance in acceleration, deceleration, and loading process.

B. Outlook

Future research can still focus on designing the corresponding observers for the proposed method to achieve a more robust performance. The switching strategy of SMFPC needs to be studied in more detail to achieve smooth transitions between EMFPC and MFPC. In this study, algorithm modifications were specifically provided for the current controller on the q axis to validate the effectiveness of the algorithm. Subsequent research can further extend this controller to the d-axis current.

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