A Novel Parameter-free Model Predictive Voltage Control for SPMSM System

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***Abstract*—Addressing the challenge posed by the susceptibility of traditional model predictive voltage control (MPVC) for surface-mounted permanent magnet synchronous motor (SPMSM) system to parameters mismatch, this paper introduces a novel MPVC approach with no motor parameters. Firstly, the traditional MPVC approach is presented briefly. Secondly, within this approach, the related terms of motor parameters are transformed into inductance factor that only contains current and voltage information, then a nonparametric voltage prediction model is constructed. Thirdly, through simple sector judgment, the optimal voltage vector required for effective control is directly deduced from the reference voltage. Lastly, the simulation outcomes clearly demonstrate the efficacy of the suggested approach.**

Keywords—model predictive voltage control (MPVC), inductance factor, nonparametric.

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been extensively utilized owing to China's recent rapid growth in the production of major rare earth permanent magnet materials. It has been widely employed in emerging industries including aerospace and electric cars on account of its straightforward rotor structure, superior efficiency, and reliable performance[1-2]. Currently, model predictive control (MPC) has replaced traditional control strategies for PMSM, because of its ease in limiting variables, intuitive modelling approach, adaptable online optimization approaches, and simple handling of the interaction between numerous inputs and multiple outputs[3]. However, the efficacy of this approach relies on the motor parameter's precision. In instances where motor parameters change on account of unmodeled factors such as temperature rise, calculation of the cost function may introduce errors, subsequently affecting the accuracy of the voltage vector and thereby influencing the the motor's overall control performance[4]. This phenomenon of parameters mismatch leading to the degradation of system control performance has attracted many scholars' attention[5-6].

To counteract the impact of motor parameters mismatch on PMSMs, some scholars have devised strategies involving observers to enhance the system's immunity against interference. Common observers are Luenberger observer[7], rolling time domain estimator[8] and extended state observer [9]. In [10], a approach was taken by introducing a sliding mode term to improve the system's robustness in conjunction with the original Luenberger term. At the same time, to enhance the observer's simplicity, appropriate simplifications were applied to the initial state equation. Employing the differential evolution technique for global optimization of the observer's gain coefficient contributed to minimizing the need for manual tuning, reducing both the unpredictability and arbitrariness inherent in manual setup.

In addition, some scholars revised the MPC based on motor parameters identification[10], which aims to revise the controller model in real-time by identifying the changing parameters online. In [12], a approach is presented for the parameter's real-time estimation in PMSM system. This approach distinctively integrates two distinct segments of recursive least squares algorithms (denoted as fast and slow) with ample real-time data acquired from the motor, enabling the comprehensive estimation of all four mechanical parameters, as opposed to merely a subset of them.

Recently, some scholars have proposed motor parameter--free predictive control approach, which predicts the future stator current based on the measured and calculated current difference. In [13], a approach for model-free predictive current control technique centered on current error identification is delineated. For determining following switching state for inverter at the least cost function, all that is accomplished by employing stator current measurements alongside current differences associated with distinct switching states of the inverter.Implementing this strategy is simple. Reference [14] puts forward a novel MPCC approach which utilizes a motor parameter-free predictive model. This model incorporates a real-time model updating mechanism without inclusion of motor parameters. Precise reference current values are derived through data sampling and storage using the current prediction deviation. As a result, the system's control performance is emancipated from its dependency on the motor parameter accuracy.

To further mitigate the adverse effects of parameters mismatch on system's performance, a novel MPVC approach with no motor parameters is proposed in this paper. This approach builds a motor parameter-free voltage prediction model with only current and voltage data, and the calculation is simple. Then based on fast vector selection, the optimal voltage vector is directly acquired without the need to traverse through predictions of the eight fundamental voltage vectors. The primary contents of this paper are outlined as below: In Section II, the traditional MPVC approach is introduced, Section III presents a concise analysis of the influence stemming from parameter mismatch in traditional MPVC. Then a simple nonparametric voltage prediction model is offered. In Section IV, the validity of the suggested approach is substantiated through the analysis of simulation outcomes. Finally, this paper concludes in Section V.

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2023 26th International Conference on Electrical Machines and Systems (ICEMS) | 979-8-3503-1758-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICEMS59686.2023.10344915

II. Analysis of Traditional MPVC Approach

Within the dq-axes, the voltage equation for the surface-mounted permanent magnet synchronous motor (SPMSM) is stated as :

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\cdot\left(\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix}\right) + \omega_e\cdot\begin{bmatrix} -L_d & 0 \\ 0 & L_q \end{bmatrix}\cdot\begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} 0 \\ \psi_f \end{bmatrix} \quad (1)$$

where u_{dq} and i_{dq} denote the voltages and currents in the dq-axes, respectively. R , ψ_f and ω_e denote the resistances, rotor flux linkage and motor angular velocity, respectively. L_d and L_q denote inductance in the dq-axes. In SPMSM, $L_d = L_q = L$.

According to (1), the prediction current model of SPMSM at the following moment is acquired as:

$$\begin{bmatrix} i_d^p(k+1) \\ i_q^p(k+1) \end{bmatrix} = \begin{bmatrix} 1-R\cdot T/L & \omega_e(k)\cdot T \\ -\omega_e(k)\cdot T & 1-R\cdot T/L \end{bmatrix}\begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} T/L & 0 \\ 0 & T/L \end{bmatrix}\begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} - \begin{bmatrix} 0 \\ (\omega_e(k)\cdot T\cdot\psi_f)/L \end{bmatrix} \quad (2)$$

where $i_d^p(k+1)$ and $i_q^p(k+1)$ denote the predictive current in the dq-axes at k+1 moment. $i_d(k)$ and $i_q(k)$ denote the sampling current in the dq-axes at k moment. $u_d(k)$ and $u_q(k)$ denote chosen voltage vector in the dq-axes.

Utilizing the principle of current deadbeat control, the reference voltage in traditional MPVC approach can be predicted as below.

$$\begin{bmatrix} u_d^{ref} \\ u_q^{ref} \end{bmatrix} = \begin{bmatrix} \frac{L}{T}-R & \frac{L}{T} & \omega_e(k)\cdot L & 0 \\ \omega_e(k)\cdot L & 0 & \frac{L}{T}-R & \frac{L}{T}-R \end{bmatrix}\begin{bmatrix} i_d(k) \\ i_d^{ref} \\ i_q(k) \\ i_q^{ref} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e(k)\cdot\psi_f \end{bmatrix} \quad (3)$$

where u_d^{ref} and u_q^{ref} denote the dq-axes reference voltage.

By constructing cost function (5), the required voltage vector with the least voltage predicted error is chosen from the set of eight fundamental voltage vectors as the best choice for application in the following control period. Fig. 1 demonstrates the traditional MPVC system control structure.

$$g = \left|u_d^{ref} - u_d^i\right| + \left|u_q^{ref} - u_q^i\right| \quad (4)$$

where u_d^i and u_q^i are one of the eight fundamental voltage vectors in the dq-axes.

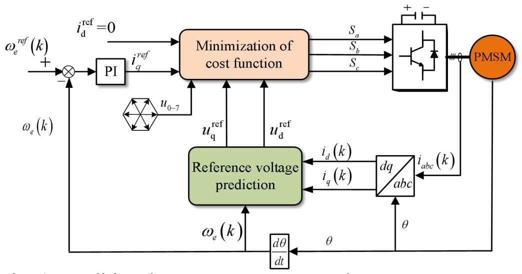


Fig. 1. Traditional MPVC system control structure.

III. Proposed Nonparametric MPVC Approach

As evident from (3), the reference voltage model includes inductance, resistance and flux linkage parameters. In cases where the parameters employed in the prediction model deviate from the true motor parameters, the resulting error in reference voltage due to parameters mismatch can be described as below.

$$\begin{cases} \Delta u_d = u_{d0}^{ref} - u_d^{ref} \\ \quad = \Delta R\cdot i_d(k) + \Delta L\cdot[i^*_d - i_d(k)]/T - \omega_e\cdot\Delta L\cdot i_q(k) \\ \Delta u_q = u_{q0}^{ref} - u_q^{ref} \\ \quad = \Delta R\cdot i_q(k) + \Delta L\cdot[i^*_q - i_q(k)]/T - \omega_e\cdot\Delta L\cdot i_d(k) \\ \quad + \omega_e\cdot\Delta\psi_f \end{cases} \quad (5)$$

where $\begin{cases} \Delta R = R - R_0 \\ \Delta L = L - L_0 \\ \Delta\psi_f = \psi_f - \psi_{f0} \end{cases}$ ΔR , ΔL and $\Delta\psi_f$ denote the parameters error. R , L and ψ_f denote the resistance, inductance, flux-linkage in the model. R_0 , L_0 and ψ_{f0} denote the accurate motor parameters. u_{d0}^{ref} and u_{q0}^{ref} denote the accurate reference voltage.

As indicated from (5), it can be observed that the parameters mismatch will result in the existence of reference voltage error. In such situation, the chosen voltage vector may not align with the best vector necessary for the present control system, thereby affecting control performance of the motor. Reference[14] proves that the disparity of inductance and flux linkage much affect the selection of voltage vectors in traditional MPVC approach, while the variation in the resistance parameter exerts minimal impact on the traditional MPVC approach. The length of this article is limited and will not be repeated here.

To mitigate the influence of motor parameters inaccuracy on the control performance of the traditional MPVC approach, a novel MPVC approach with no motor parameters is put forward. In Fig. 2, the system control structure of the suggested approach is presented. The detailed design is as follows.

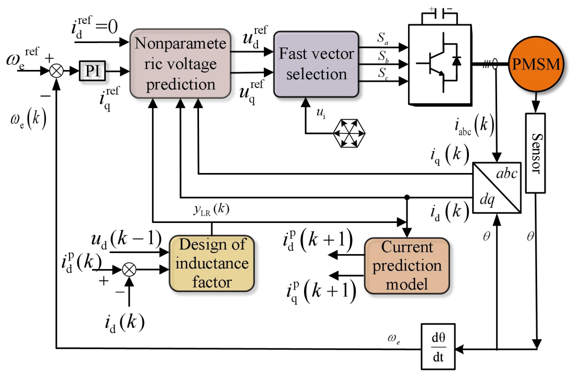


Fig. 2. System control structure of the suggested approach.

A. Construction of Incremental Voltage Prediction Model

To nullify the flux linkage, an incremental formula is put forward. That is to say, by subtracting the voltage prediction model at k-1 moment from the voltage prediction model at k moment is depicted as below.

$$\begin{cases} u_d(k) = u_d(k-1) + (\frac{L}{T} - R)(i_d(k-1) - i_d(k)) \\ \quad -\frac{L}{T}(i_d^p(k+1) - i_d^p(k)) - \omega_e(k) \cdot L \cdot (i_q(k) - i_q(k-1)) \\ u_q(k) = u_q(k-1) + (\frac{L}{T} - R)(i_q(k-1) - i_q(k)) \\ \quad -\frac{L}{T}(i_q^p(k+1) - i_q^p(k)) + \omega_e(k) \cdot L \cdot (i_d(k) - i_d(k-1)) \end{cases} \quad (6)$$

In (6), the value of L/T is much larger than that of R, so it is reasonable to assume that $L/T - R$ is nearly equivalent to L/T, and the resistance is eliminated in the voltage equation. This simplification yields the following expression:

$$\begin{cases} u_d(k) = u_d(k-1) + x_{LR}(k) \cdot (i_d^p(k+1) - i_d(k) - i_d^p(k) + i_d(k-1)) \\ \quad -\omega_e \cdot x_{LR}(k) \cdot T \cdot (i_q(k) - i_q(k-1)) \\ u_q(k) = u_q(k-1) + x_{LR}(k) \cdot (i_q^p(k+1) - i_q(k) - i_q^p(k) + i_q(k-1)) \\ \quad +\omega_e \cdot x_{LR}(k) \cdot T \cdot (i_d(k) - i_d(k-1)) \end{cases} \quad (7)$$

where $x_{LR} = L/T$.

B. Design of Nonparametric Voltage Prediction Model

According to (7), there is only one related term of motor parameters in the incremental voltage prediction model. It is required to translate the motor parameters relevant term into a model that solely consists of current and voltage information. This transformation aims to nullify the repercussions of parameters mismatch and achieve the voltage prediction with no motor parameters.

In order to simplify calculation, this paper focuses on constructing a d-axis current prediction model, and adopts a direct calculation approach to eliminate parameters. In (2), the value of TR/L is significantly below 1, leading to the exclusion of resistance effects. Then predicted current at k moment in the d-axis is presented as below.

$$i_d^p(k) = y_{LR}(k-1) \cdot u_d(k-1) + i_d(k-1) + T\omega_e(k-1) i_q(k-1) \quad (8)$$

where $y_{LR} = T/L = 1/x_{LR}$, denotes the inductance factor with model parameter.

Ideally, the actual sampling current at k moment in the d-axis can be reformulated as below.

$$i_d(k) = y_{LR0} \cdot u_d(k-1) + i_d(k-1) + T\omega_e(k-1) i_q(k-1) \quad (9)$$

where $y_{LR0} = T/L_0 = 1/x_{LR0}$, denotes the inductance factor with accurate motor parameter.

The predicted difference in d-axis current determined by deducting (9) from (8), leading to the following expression:

$$\begin{aligned} \Delta i_d(k) &= i_d^p(k) - i_d(k) \\ &= \left[y_{LR}(k-1) - y_{LR0} \right] \cdot u_d(k-1) \end{aligned} \quad (10)$$

By simplifying (10), the inductance factor model can be obtained. Theoretically, the inductance factor can be accurately predicted with no motor parameters, that is to say, the value of inductance factor y_{LR} at k moment should align with the actual value y_{LR0}. Therefore, the inductance factor model is denoted as:

$$\begin{aligned} y_{LR}(k) &= y_{LR0} \\ &= y_{LR}(k-1) - \frac{\Delta i_d(k)}{u_d(k-1)} \end{aligned} \quad (11)$$

To mitigate harmonic interferon, y_{LR} undergoes processing through a low-pass filter as outlined below.

$$y_{LR}(k) = (1-\lambda) \cdot y_{LR}(k-1) + \lambda \cdot y_{LR}(k) \quad (12)$$

where $y_{LR}(k)$ is the output value of the filtering at k moment, $y_{LR}(k-1)$ is the output value of the filtering at k-1 moment. λ denotes the filter coefficient. It is experimentally verified that the value of λ is 0.01.

Substituting the obtained inductance factor into (7), the nonparametric voltage prediction model is derived as below.

$$\begin{cases} u_d^{ref}(k) = u_d(k-1) + (i_d^p(k+1) - i_d(k) - i_d^p(k) + i_d(k-1)) / y_{LR}(k) \\ \quad -\omega_e \cdot T \cdot (i_q(k) - i_q(k-1)) / y_{LR}(k) \\ u_q^{ref}(k) = u_q(k-1) + (i_q^p(k+1) - i_q(k) - i_q^p(k) + i_q(k-1)) / y_{LR}(k) \\ \quad +\omega_e \cdot T \cdot (i_d(k) - i_d(k-1)) / y_{LR}(k) \end{cases} \quad (13)$$

So far, the construction of the nonparametric voltage prediction model as the core of this paper has been completed. It fundamentally solves the problem that MPVC performance depends on motor parameters.

C. Fast Vector Selection

In addition, to streamline the computation, an enhanced approach has been adopted for selecting the optimal voltage vector.

The reference voltage equation within the static coordinate system (αβ-axes) is derived through inverse Park transformation, as depicted follows.

$$\begin{cases} u_\alpha^{ref}(k) = u_d^{ref}(k) \cdot \cos\theta - u_q^{ref}(k) \cdot \sin\theta \\ u_\beta^{ref}(k) = u_d^{ref}(k) \cdot sin\theta + u_q^{ref}(k) \cdot \cos\theta \end{cases} \quad (14)$$

Fig. 3 shows approach for to select the best voltage vector. Within the space voltage vector diagram, it is conceivable to predict the angle of the reference voltage vector as:

$$\theta_u(k) = \arctan \frac{u_\beta^{ref}(k)}{u_\alpha^{ref}(k)} \quad (15)$$

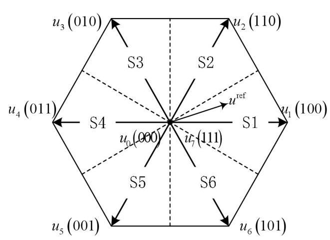


Fig. 3. Illustration of best voltage vector selection.

Equation (15) determines the sector in which the reference voltage is located. TABLE I illustrates that basis for selecting non-zero voltage vector.

TABLE I. EVALUATION OF NON-ZERO VOLTAGE SECTOR

Sector	θ_u	u_i
S1	$-30^\circ \sim 30^\circ$	u_1
S2	$30^\circ \sim 90^\circ$	u_2
S3	$90^\circ \sim 150^\circ$	u_3
S4	$150^\circ \sim 210^\circ$	u_4
S5	$210^\circ \sim 270^\circ$	u_5
S6	$270^\circ \sim 330^\circ$	u_6

When the reference voltage vector meets the conditions of (16), the zero vector emerges as the best voltage vector.

$$(u_{i\alpha}(k)-u_\alpha^{ref})^2+(u_{i\beta}(k)-u_\beta^{ref})^2>(u_\alpha^{ref})^2+(u_\beta^{ref})^2 \quad (16)$$

where $u_{i\alpha}$ and $u_{i\beta}$ denote the voltage in the αβ-axes.

IV. SIMULATION VERIFICATION

On the basis of the above theoretical analysis and prediction model, simulations were executed in Matlab/Simulink to substantiate the proficiency of the suggested approach. Both the traditional MPVC approach and the suggested approach are subjected to these simulations for comprehensive assessment. TABLE II presents the specific simulation parameters of the SPMSM.

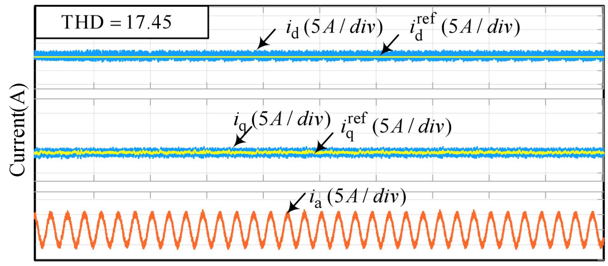
TABLE II. PARAMETER OF SPMSM

Parameter	***Symbol***	***Value***
DC Voltage	U_{dc}(V)	310
Number of pole pairs	p	2
Stator resistance	R(Ω)	3.18
Stator inductance	L(H)	0.0085
Rotor flux linkage	ψ_f(Wb)	0.24
Inertia	J (kg.m^2)	0.0008
Rate speed	n_N(rpm)	2000
Rated load torque	T_n (N•m)	5
Frequency	kHz	10

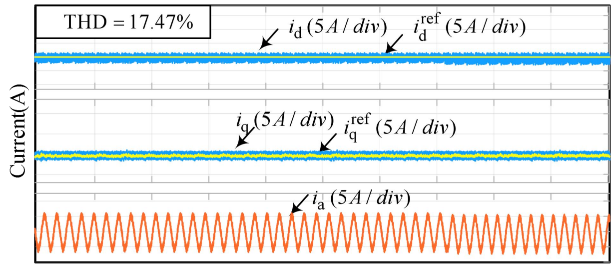
A. Steady Performance Verification

As illustrated in Fig. 4, a comparison is made among the steady-state control performance of the suggested approach, the traditional MPVC approach with precise parameters and the traditional MPVC approach with parameters mismatch ($2L$, $2R$ and $2\psi_f$). The specific test conditions for the steady state are as follows: motor speed set at 1000rpm and load torque maintained at 5N•m.

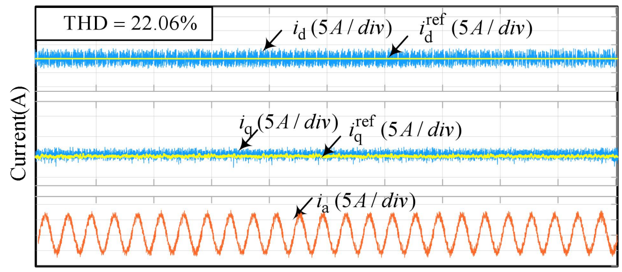
It is evident that the suggested approach produces comparable total harmonic distortion (THD) values to the traditional MPVC approach under accurate parameter condition. But when the parameters are mismatched, the traditional MPVC approach exhibits an increase in THD, amplified phase current ripple, and a static discrepancy of 0.5A in the q-axis current.



(a) Suggested approach



(b)Traditional MPVC with accurate parameters



(c) Traditional MPVC with inaccurate parameters

Fig. 4. The comparison of steady-state performance under different approach.

Furthermore, Fig. 5 illustrates a comparison of THD of three approaches under the conditions of constant torque and different rotating speeds. It can be seen that when the model parameters are mismatched ($2L$, $2R$ and $2\psi_f$), the THD of the traditional MPVC is increased, which means that the capability of the suggested approach to effectively counterbalance the impact of parameters mismatch.

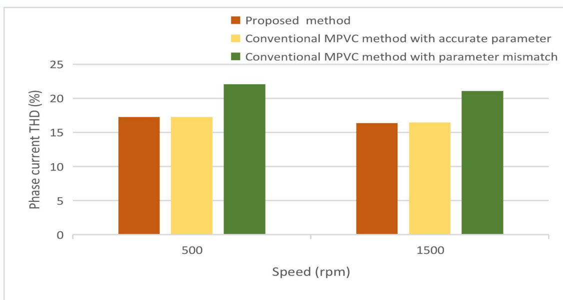
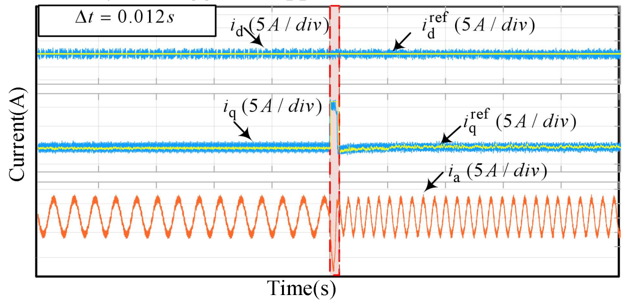


Fig. 5. The comparison of phase current THD among suggested approach, traditional MPVC approach with accurate parameters and traditional MPVC approach with parameter mismatch under different speed.

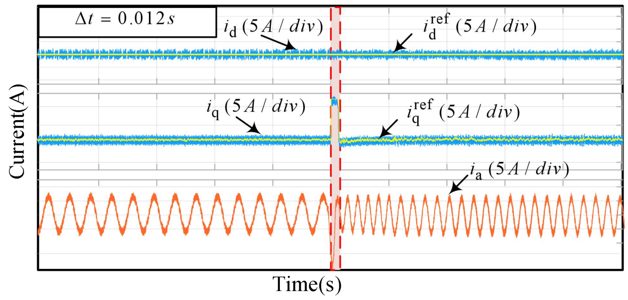
Based on the conducted tests, it is evident that variations in model parameters can indeed negatively affect the control effectiveness of traditional MPVC approach. Conversely, the suggested approach demonstrates remarkable capabilities to counteract the effects of parameters mismatch, and it excels with regard to steady-state performance. These simulation results strongly support the efficacy of the suggested approach.

B. Dynamic respond Verification

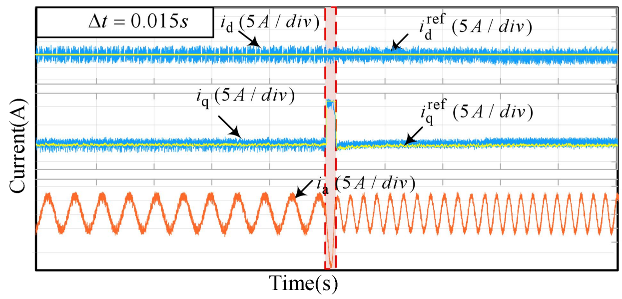
During the dynamic response tests, the testing conditions were selected to include a constant load torque of 5N·m and a sudden change in motor speed from 1000rpm to 2000rpm. Fig. 6 presents comparisons of the dynamic performance of three approaches. It can be seen that under accurate parameters conditions, the suggested approach exhibits a comparable dynamic response time to traditional MPVC approach. However, when the parameters do not match, the corresponding time of traditional MPVC approach increases. This observation presents the effective dynamic performance achieved by the suggested approach.



(a) Suggested approach



(b)Traditional MPVC with accurate parameters



(c) Traditional MPVC with inaccurate parameters

Fig. 6. The comparison of dynamic performance under different approaches.

V. Conclusion

To fundamentally address the control performance issue inherent in traditional MPVC which is dependent upon the precision of model parameters, this papers proposes a novel MPVC approach with no motor parameters. This approach establishes a voltage prediction model without any motor parameters. With only the utilization of current and voltage data, determining the desired optimal voltage vector is a straightforward and accurate process. Simulation outcomes clearly demonstrate that the suggested approach fundamentally addresses the issue that in traditional MPVC approach the system control performance for SPMSM is influenced by the precision of motor parameters.

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