Three-Vector Model Predictive Flux Linkage Control for Induction Motors (Postprint)

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Abstract

Model Predictive Flux Control (MPFC) is a novel control method recently proposed that effectively addresses the challenging weighting factor selection issue in traditional Model Predictive Torque Control (MPTC), thereby garnering widespread attention. However, the steady-state performance of MPFC is relatively poor when only a single voltage vector is applied throughout the entire control period. To enhance the steady-state performance of MPFC, some researchers have introduced the concept of two-vector MPFC. While applying three voltage vectors within one control period can further improve the steady-state performance of MPFC, it introduces several issues, including complex vector selection, high computational burden, and elevated switching frequency, which hinder the practical implementation of MPFC. To overcome these challenges, this paper proposes a simple yet practical novel three-vector MPFC. Additionally, to mitigate the impact of inverter nonlinearity on the three-vector MPFC, an improved three-vector MPFC is presented based on the volt-second balance principle. For performance comparison, MPFC based on Space Vector Pulse Width Modulation (MPFC_SVM) is introduced as a reference. The effectiveness of the proposed novel three-vector MPFC is ultimately validated through both simulation and experimental results, with a detailed comparative analysis of the control performance of the three aforementioned methods conducted under identical switching frequencies.

Full Text

Preamble

A Three-Vectors-Based Model Predictive Flux Control of Induction Motor Drives

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Abstract

Model predictive flux control (MPFC) has attracted wide attention as a novel control method that addresses the tedious weighting factor tuning required in conventional model predictive torque control (MPTC). However, when only one voltage vector is applied during each control period, MPFC exhibits high torque and current ripples, resulting in poor steady-state performance. To improve this, researchers have proposed two-vectors-based MPFC schemes. While applying three voltage vectors per control period could further enhance steady-state performance, it introduces significant challenges including complex vector selection, heavy computational burden, and high switching frequency, which hinder practical implementation.

This paper proposes a simple yet highly effective three-vectors-based MPFC that substantially reduces algorithm complexity and switching frequency. To mitigate inverter nonlinearity effects, an improved three-vectors-based MPFC is also developed using volt-second balance principles. For performance comparison, MPFC based on space vector pulse width modulation (MPFC_SVM) is introduced as a benchmark. Simulation and experimental results validate the effectiveness of the proposed novel three-vectors-based MPFC, while providing a detailed comparative analysis of all three methods under identical switching frequencies.

Keywords: Induction motor, model predictive flux control, model predictive torque control, weighting factor

1 Introduction

In high-performance AC motor drives, vector control and direct torque control (DTC) have been widely adopted. Vector control decomposes stator current into d/q-axis components in the synchronous reference frame to independently regulate rotor flux and electromagnetic torque. PI regulators adjust the d/q-axis currents, with space vector pulse width modulation generating inverter switching signals. Despite excellent steady-state performance, vector control suffers from difficulties in PI parameter design, cross-coupling between d/q axes, limited current loop bandwidth, and high switching frequency.

Direct torque control offers fast dynamic response but exhibits poor steady-state performance and variable switching frequency. With the rapid development of digital signal processors, advanced control algorithms like model predictive control (MPC) have become feasible for AC motor drives. First introduced to this field by German scholar Holtz in the 1990s, MPC features fast dynamic response, simple structure, and straightforward handling of nonlinear control variables, garnering significant attention from both academia and industry.

Conventional model predictive torque control (MPTC) requires designing an appropriate weighting factor in its cost function to regulate flux magnitude. However, weighting factor selection is tedious and complex, lacking theoretical foundation and typically requiring extensive simulation and experimental trials. Moreover, traditional MPC demands high sampling frequencies for good steady-state performance. By exploiting the intrinsic relationship between torque and stator flux, MPTC can be transformed into model predictive flux control (MPFC), which uses stator flux vector as the control objective and eliminates weighting factor design.

When only one voltage vector is applied per control period, MPFC exhibits large torque and flux ripples, limiting its application in high-performance drives. To improve steady-state performance, duty cycle optimization concepts have been applied, using multiple voltage vectors per cycle with deadbeat or ripple-minimization methods. Some researchers have proposed multi-vector selection strategies where the first vector continues from the previous cycle' s final vector, reducing switching frequency and computation while improving performance. However, extending to three vectors per cycle significantly increases complexity and switching frequency. For a two-level inverter with seven voltage vectors, three-vector combinations yield $7^3 = 343$ possibilities, making exhaustive search computationally prohibitive for practical implementation.

This paper proposes a novel three-vectors-based MPFC that dramatically reduces algorithm complexity and switching frequency. The first vector continues from the previous cycle' s final vector, the second is a zero vector, and the third is selected from six active vectors. An improved version based on volt-second balance further mitigates inverter nonlinearity effects. Comparative analysis with MPFC_SVM demonstrates the proposed method' s superior steady-state performance and lower switching frequency, with experimental validation confirming its effectiveness.

2 Induction Motor Mathematical Model

Using stator current $\mathbf{i}_s$ and stator flux $_s$ as state variables, the dynamic equations of an induction motor in the stationary reference frame can be expressed as:

$$p\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

where $\mathbf{x} = [\mathbf{i}_s \quad _s]^T$, $p = d/dt$ is the differential operator, $\mathbf{u}_s$ is the stator voltage, and $\mathbf{A}$ and $\mathbf{B}$ are system matrices containing motor parameters.

In practice, the continuous-time model must be discretized to predict state variables at the $(k+1)$ sampling instant. To improve prediction accuracy, a second-order Euler formula is employed:

$$\mathbf{x}_{k+1}^{p} = \mathbf{x}_k + T_{sc}(\mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k)$$

$$\mathbf{x}_{k+1} = \mathbf{x}_{k+1}^{p} + \frac{T_{sc}}{2}(\mathbf{A}\mathbf{x}_{k+1}^{p} + \mathbf{B}\mathbf{u}_k - \mathbf{A}\mathbf{x}_k - \mathbf{B}\mathbf{u}_k)$$

where $\mathbf{x}_{k+1}^{p}$ is the predicted correction variable, T_{sc} is the control period, and $\mathbf{x}_{k+1} = [\mathbf{i}_{s,k+1} \quad {}_{s,k+1}]^T$ represents the predicted next-state variables.

The electromagnetic torque can then be predicted as:

$$T_{e,k+1} = \frac{3}{2} N_p(\ {}_{r,k+1} \otimes \mathbf{i}_{s,k+1})$$

where N_p is the number of pole pairs, $\otimes$ denotes the cross product, and ${}_r$ is the rotor flux.

3 Novel Three-Vectors-Based MPFC

[Figure 1: see original paper] shows the overall control diagram of the proposed three-vectors-based MPFC for induction motor drives, comprising a speed outer loop, stator flux equivalence transformation, cost function, full-order observer, vector selection, and duty cycle optimization. Field-weakening operation is not considered, so the stator flux magnitude reference is set to the rated value.

3.1 State Variable Estimation

Since stator flux and electromagnetic torque cannot be measured directly, accurate estimation of internal state variables is crucial for MPFC performance. A full-order observer provides high observation accuracy across a wide operating range and can be expressed as:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} + \mathbf{G}(\mathbf{i}_s - \hat{\mathbf{i}}_s)$$

where $\hat{\mathbf{x}} = [\hat{\mathbf{i}}_s \ \hat{}_s]^T$ contains observed values and $\mathbf{G}$ is the feedback gain matrix.

The design of $\mathbf{G}$ and adaptive rate coefficients directly affects system stability and robustness. This paper employs pole-shifting-left method to design a constant gain matrix:

$$\mathbf{G} = \begin{bmatrix} -b & 0 \\ 0 & -b\frac{L_r}{L_m} \end{bmatrix}$$

where $b = -40$ has proven robust against motor parameter variations.

3.2 Equivalent Stator Flux Vector Transformation

Traditional MPC controls electromagnetic torque and stator flux magnitude with a cost function:

$$J_1 = |T_e^{ref} - T_{e,k+1}| + k_\Psi |\Psi_s^{ref} - \Psi_{s,k+1}|$$

The weighting factor k_Ψ lacks theoretical design guidelines and is typically determined empirically, limiting practical applicability. By exploiting the internal relationship between torque and flux, the torque and flux magnitude can be equivalently transformed into a stator flux vector, eliminating weighting factor design. The corresponding cost function becomes:

$$J_2 = | {}_s^{ref} - {}_{s,k+1}|$$

With flux magnitude reference set to rated value Ψ_s^{ref}, and using estimated rotor flux from the observer, the reference stator flux vector angle when torque reaches its reference can be derived as:

$$\theta_s^{ref} = \theta_r + \arcsin\left(\frac{2L_r T_e^{ref}}{3N_p L_m \Psi_r \Psi_s^{ref}}\right)$$

The complete reference stator flux vector is then:

$${}_s^{ref} = \Psi_s^{ref} e^{j\theta_s^{ref}}$$

To compensate for one-sample delay in digital implementation, the reference vector for $(k+2)$ instant is calculated using predicted rotor flux ${}_{r,k+2}$ obtained from the current model, assuming constant rotor speed within one control period due to the large mechanical time constant.

3.3 Vector Selection

To improve steady-state performance, this paper adopts a three-vector strategy per control period. The vector sequence is critical for computational efficiency. Analysis reveals that placing the zero vector in the middle position minimizes computation: the first vector continues from the previous cycle' s optimal vector ($\mathbf{u}_{old}$), the second is a zero vector ($\mathbf{u}_0$), and the third is selected from six active vectors ($\mathbf{u}_j$). This arrangement ensures only six predictions are needed per cycle, as shown in [Figure 2: see original paper].

3.4 Vector Duty Cycle Optimization

With the vector sequence $\mathbf{u}_{old} : \mathbf{u}_0 : \mathbf{u}_j$, the flux vector dynamics are:

$${}_{s,k+2} = {}_{s,k+1} + t_1\mathbf{u}_{old} + t_2\mathbf{u}_j - R_s\mathbf{i}_{s,k+1}T_{sc}$$

where t_1 and t_2 are the durations of $\mathbf{u}_{old}$ and $\mathbf{u}_j$, respectively, and $t_0 = T_{sc} - t_1 - t_2$ is the zero-vector time.

The flux tracking error is minimized by solving:

$$\frac{\partial}{\partial t_1}|{}_{s}^{ref} - {}_{s,k+2}|^2 = 0$$

$$\frac{\partial}{\partial t_2}|{}_{s}^{ref} - {}_{s,k+2}|^2 = 0$$

yielding the optimal duty cycles for the two active vectors.

4 Simulation and Experimental Results

4.1 Simulation Results

The proposed method, termed MPFC_3VV, is compared with MPFC_SVM and an improved three-vector MPFC (MPFC_3V) that uses SVM-based volt-second balance to mitigate inverter nonlinearity. Simulations are conducted on a 2.2 kW induction motor platform with parameters listed in [TABLE].

[TABLE]

Simulation sampling rates are set to 10 kHz for MPFC_3VV, 5 kHz for MPFC_SVM, and 10 kHz for MPFC_3V. [Figure 3: see original paper] shows starting responses from standstill to 1500 r/min, demonstrating smooth acceleration with rapid recovery after load application at 0.35 s. [Figure 4: see original paper] confirms stable speed reversal operation.

[Figure 5: see original paper] compares average switching frequencies: MPFC_3VV and MPFC_3V operate at approximately 3.8 kHz and 7.2 kHz, respectively, under rated load. For fair comparison, sampling frequencies are adjusted to 13 kHz (MPFC_3VV) and 7 kHz (MPFC_3V) to achieve a uniform 5 kHz switching frequency matching MPFC_SVM.

[Figure 6: see original paper] and [Figure 7: see original paper] compare torque and flux ripples at identical switching frequencies, showing MPFC_3VV achieves significantly lower ripples than MPFC_3V, while MPFC_SVM exhibits the highest torque ripple. [Figure 8: see original paper] compares current THD, revealing MPFC_3VV produces lower harmonic content than MPFC_3V and comparable to MPFC_SVM.

4.2 Experimental Results

Experimental validation is performed on a two-level induction motor drive platform ([Figure 9: see original paper]) using a TMS320F28335 DSP. Motor parameters and sampling frequencies match the simulation. A magnetic powder brake provides loading.

[Figure 10: see original paper] shows MPFC_3VV starting from standstill to 1500 r/min, exhibiting smooth acceleration with minimal current after DC pre-excitation. [Figure 11: see original paper] demonstrates steady-state operation at rated speed with rated load, confirming excellent steady-state performance, load capacity, and sinusoidal current waveforms.

5 Conclusion

This paper presents a comprehensive study of three-vectors-based model predictive flux control. The proposed MPFC_3VV offers reduced computational burden, simple vector selection, and low switching frequency while eliminating the weighting factor tuning required in conventional MPTC and addressing the complexity issues of traditional three-vector methods. An improved MPFC_3V variant mitigates inverter nonlinearity through volt-second balance principles. Comparative analysis with MPFC_SVM demonstrates that MPFC_3VV achieves superior steady-state performance with lower torque and flux ripples and reduced current THD at identical switching frequencies. Experimental validation confirms the effectiveness of the proposed MPFC_3VV, expanding its industrial applicability. The novel three-vectors-based MPFC meets the performance requirements of high-performance AC motor drives in both steady-state and dynamic operation.

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