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Eliminating Current Harmonics of Six-Phase Permanent Magnet Synchronous Machine Using Deadbeat Current Control Based on Improved Predictive Model

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Received: 2024-09-14 Revised: 2025-07-13 Accepted: 2025-08-18

Abstract

This paper proposes dead beat current control (DBCC) based on predictive model control for six-phase asymmetric permanent magnet synchronous machine (PMSM). First, the DBCC solution is adopted to obtain the expected reference voltage vector (RVV); Then two groups of virtual vectors, a total of 24 vectors with different values will be defined for it. Due to the reduction of current harmonics, two in-phase virtual vectors that are closer to RVV are subsequently selected as predictor vectors. The next step is to define a cost function consisting of the error between the RVV and the available prediction vectors, Then, the two selected virtual vectors are evaluated and the function that minimizes the cost function is evaluated at the next moment, only two predictor vectors are needed, which greatly reduces the computational burden. Meanwhile, the weighting coefficient of torque prediction control is avoided. Moreover, to achieve easy implementation with standard PWM switching sequence, 18 virtual vectors are replaced by them. Finally, the proposed method has been studied comparatively with other methods. The results and validation of the article have been done using MATLAB software.

Keywords

Elimination of current harmonics; Six-phase permanent magnet synchronous machine; Dead beat current control; Improved predictive model;

1. Introduction

Six-phase permanent magnet synchronous machines are increasingly attractive for high-power and safety-critical applications owing to their high torque density, improved efficiency, and fault-tolerant capability. Because of the additional degrees of freedom introduced by the extra phases, the stator variables of an asymmetrical six-phase machine are mapped, through the vector space decomposition (VSD) transformation, into two orthogonal subspaces: the electromechanical energy-conversion α - β subspace and the non-producing x - y subspace. This structure, while beneficial, poses a serious control challenge: any voltage generated in the x - y subspace, where the load impedance is low, produces large harmonic currents that degrade the phase-current quality.

Model predictive control (MPC) has become a popular solution for multiphase drives because of its fast dynamic response and simple concept. Two main families exist: model predictive torque control (MPTC) and model predictive current control (MPCC). In both, a cost function is evaluated for all admissible voltage vectors of the two-level six-phase voltage source inverter (VSI). As 48 active vectors exist, evaluating all of them is computationally expensive; the common practice evaluates only the 12 largest vectors, which still entails 13 evaluations per sampling period and leaves the harmonic-suppression potential of other active vectors unexploited. Furthermore, MPTC requires a weighting factor to balance the torque and flux error terms, whose tuning is nontrivial; using the current-based cost function alone, in turn, suppresses x - y harmonics only partially. Recent studies confirm this trade-off: virtual-vector-based schemes suppress harmonic currents effectively, but synthesizing more virtual vectors increases the computational burden unless an efficient vector-selection mechanism is introduced [S1], [S2]. Direct DBCC, although computationally light, always generates voltage in the x - y subspace and therefore cannot regulate harmonic currents.

This paper proposes an MPC strategy for an asymmetrical six-phase PMSM that unifies DBCC with virtual-vector synthesis. The main novelties are: (1) two groups of virtual vectors are composed specifically to suppress x - y harmonic currents; (2) the DBCC solution is adopted to compute the RVV, which reduces the candidate set to two or three vectors and thereby the computation time significantly; (3) a new cost function evaluates the error between the RVV and the selected virtual vectors directly, simplifying the predictive model and eliminating the weighting factor; and (4) 18 virtual vectors with non-standard PWM switching sequences are replaced by equivalent virtual vectors with standard sequences, enabling straightforward practical implementation.

2. Methodology

2.1. Machine modeling and predictive model

The stator variables of the asymmetrical six-phase PMSM are transformed into the stationary frame using the VSD matrix $T_{\alpha\beta}$, mapping phase quantities into the α - β and x - y subspaces, followed by the park transformation for the d - q axes. Since energy conversion occurs only in the α - β subspace, the stator voltage equations in both subspaces, together with the self-leakage inductance L_l , yield the machine model. Applying the forward Euler method to these equations gives the discrete predictive model by which the stator currents at the next sampling instant, in both the d - q and x - y subspaces, are predicted. Because only the α - β components contribute to energy conversion, the cost function can be defined either on the d - q current error alone, or augmented with the x - y current components to suppress harmonic currents. The two-level six-phase VSI provides $2^6 = 64$ switching states, which map into 48 active voltage vectors distributed over the two subspaces; each vector is identified by the decimal equivalent of its binary switching state $S_a \dots S_f$.

2.2. Reference voltage vector computation by DBCC

In the conventional MPCC, the optimal vector is obtained indirectly through the cost function with current-error constraints, requiring evaluation of 13 vectors. The proposed method instead computes the RVV explicitly: using the Euler discretization of the predictive model (Eq. 11), the d - q currents at the next instant are predicted (Eq. 12), and a two-step predictor compensates the digital computation delay (Eq. 13). Imposing the deadbeat constraint that the predicted current error vanish (Eq. 14) yields the d - q components of the RVV (Eq. 15), which is then used directly in the cost function to evaluate candidate vectors.

2.3. Virtual vector synthesis and harmonic suppression

Two groups of virtual vectors, 24 in total and with different magnitudes, are synthesized for x - y harmonic suppression [S1]. For the vectors of group G1, the duration of the neutral (zero) vectors inserted within each vector is computed to obtain the equivalent virtual vectors of group G2 (Eq. 22). To suppress the harmonic currents, the operating-time ratio of the real vectors of groups L3 and L4 is constrained (Eq. 23); solving the resulting constraints (Eq. 24) gives the durations T'_m and T'_n of the constituent real vectors. In addition, the 18 virtual vectors of sectors S2, S3, and S4 that contain non-standard PWM switching sequences are replaced by 18 equivalent virtual vectors with standard PWM sequences, so that all 24 virtual vectors can be implemented readily. Compared with the conventional MPCC, the number of prediction vectors is reduced considerably (from 13 to 2–3), the predictive model is simplified, the weighting factor is no longer needed, and the harmonic currents are suppressed by construction of the virtual vectors.

3. Discussion and Results

The proposed method was validated in MATLAB/Simulink on an 11 kW asymmetrical six-phase PMSM, with conventional MPCC and direct DBCC implemented as benchmarks. The sampling frequency was set to 10 kHz for all methods, and a step-load dynamic test was performed: starting at 800 rpm, the rated load is suddenly applied. The machine and control parameters are listed in Table 1.

Table 1. Machine and Control System Parameters

Parameter	Value
Rated power	11 kW
Rated speed	1500 rpm
Rated torque	70 N·m
Number of pole pairs	3
Stator resistance	4.5 Ω
d -axis inductance	0.035 H
q -axis inductance	0.055 H
Permanent-magnet flux	0.55 Wb
Machine-load inertia	0.021 kg·m ²

In steady-state operation at 800 rpm with 70 N·m load, the phase-current amplitude reaches 15 A. The current

quality of direct DBCC and conventional MPCC is markedly poorer than that of the proposed method, owing to the large x - y harmonic currents: the direct DBCC cannot regulate the x - y subspace at all, while the conventional MPCC suppresses it only partially. The proposed method yields nearly zero harmonic currents and a sinusoidal phase current.

The measured phase-current THD at 10 kHz sampling is 7.98% for the proposed method, compared with 20.47% for the conventional MPCC and 23.52% for direct DBCC; even at a halved sampling frequency of 5 kHz, the proposed method keeps a lower THD (13.82%) than both benchmarks, thanks to the regulation of the x - y components by the virtual vectors. Spectral analysis shows that the large 5th and 7th harmonics present with the benchmark methods are substantially reduced by the proposed scheme.

The average switching frequency, measured as 3510 Hz for conventional MPCC and 6205 Hz for the proposed MPC at 10 kHz sampling, confirms the better steady-state performance at comparable switching effort; at 5 kHz sampling the proposed method's average switching frequency (3340 Hz) is even lower than that of the conventional MPCC. Under step load change from 35 N·m to 70 N·m at 0.5 s, the torque command is tracked smoothly and rapidly, and the current quality remains consistent with the steady-state results across different loads and speeds (500 rpm and 1000 rpm). Regarding computational effort, the total execution time is 30.8 μ s for direct DBCC, 54.2 μ s for conventional MPCC, and 55.6 μ s for the proposed method, while the number of prediction-vector iterations is reduced from 13 to 3, a significant simplification relative to the conventional MPCC.

4. Conclusions

A novel RVV-based model predictive control with suppressed harmonic currents and reduced computational burden has been proposed for an asymmetrical six-phase PMSM. The main contributions are: (1) two groups of virtual vectors are composed with the objective of reducing harmonic currents; (2) the DBCC solution is adopted to compute the RVV and select the appropriate candidate voltage vectors, considerably reducing the computation time; (3) a new cost function is defined to evaluate directly the error between the RVV and the selected virtual vectors, which simplifies the predictive model significantly and removes the need for a weighting factor; and (4) 18 virtual vectors with non-standard PWM switching sequences are replaced by equivalent virtual vectors with standard PWM sequences, so that all virtual vectors can be implemented in practice. The proposed MPC provides phase currents of much better quality than direct DBCC and conventional MPCC, and the simulation results confirm the validity of the proposed approach.

5. References

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