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An Improved Finite Control Set Model Predictive Current Control Strategy for Five-Phase PMSMs

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Abstract. In this paper, finite control set model predictive current control strategy for five-phase permanent magnet synchronous motor is analysed. At first, virtual voltage vectors are adopted to avoid including all the 32 voltage vectors of five-phase inverter into the control set. Besides, under different rotor speed, estimated voltage vector is predicted in advance so that a new online updated adaptive control set can be established with proper voltage amplitude and only three vectors. Consequently, current ripples and computational burden can be much reduced. At last, experimental results are presented and indicate the performance improvement of the proposed control strategy.

1. Introduction

Because of the advantages of fault-tolerant capability and small torque ripples, five-phase permanent magnet synchronous motor (PMSM) gains much attention recently, especially in some high performance conditions like vehicle drive [1, 2]. Hence, analysis about control system of five-phase PMSM is necessary.

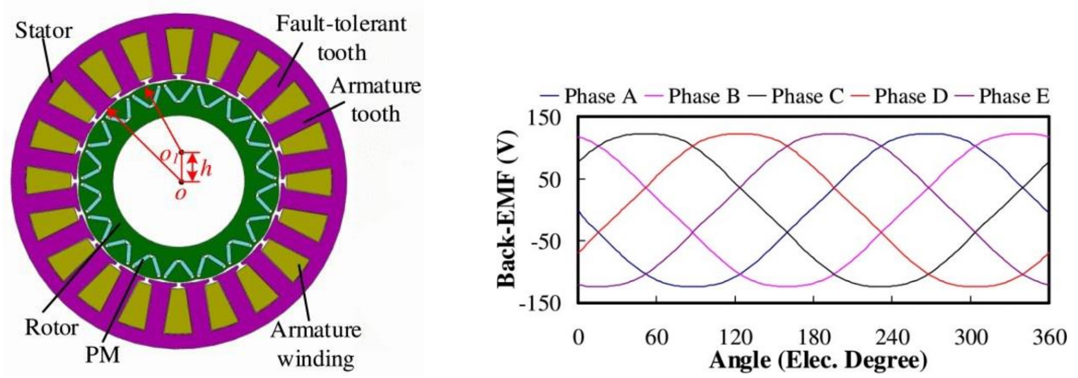
Model predictive control (MPC) is a kind of model-based non-linear control theory which has been used in PMSM control. According to the difference of control set, MPC includes two main categories, continuous control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC) [3]. CCS-MPC calculates the optimal voltage vector with cost function and outputs it by pulse width modulation (PWM). FCS-MPC checks all voltage vectors in a prepared control set with cost function and chooses the optimal one to output directly. Therefore, unlike CCS-MPC, the voltage output is discrete in FCS-MPC and can only be selected from the pre-established control set, which means ripples in current or torque will be larger in FCS-MPC [4]. Worse still, in conventional FCS-MPC, all the voltage vectors in control set should be assessed so that the computational burden is heavy. In five phase motor control system, this issue will be severer as the control set is larger [5]. However, FCS-MPC do not need voltage modulation and in this point calculation burden is lighter than CCS-MPC, so the main task of FCS-MPC research should be to reduce ripples and mitigate computational burden.

In [6], to reduce torque and flux ripples and improve the performance of FCS-MPC, an extended control set of 20 modulated voltage vectors is proposed instead of using only 8 vectors and a pre-selective scheme is designed to reduce the computational burden caused by increased number of voltage vectors. In [7], FCS-MPC with virtual voltage vectors is proposed for five-phase motor control. The third harmonics is restrained and only 11 voltage vectors need to be judged by cost function rather than 21 or even 31. However, constant amplitude of the vectors is not appropriated in all conditions, especially in low speed case.

In this paper, an improved finite control set model predictive current control (FCS-MPCC) algorithm for five-phase PMSM is proposed. A new online updated adaptive control set containing only three voltage vectors is proposed and the amplitude of the vectors are matched to different rotor speed. Experimental results are presented to verify this method.

2. Model of Five-Phase PMSM and Inverter

The structure of the analysed five-phase PMSM is presented in Fig. 1(a) and due to the fractional-slot concentrated-windings design, the fundamental harmonic dominates the back electromotive force (back-EMF) of the motor which is almost sinusoidal with the THD of 1.73%, as shown in Fig. 1(b) [2]. Therefore, the motor can be mathematically modelled by only considering the fundamental harmonic rather than bringing in the extra third harmonic space.



(a) (b)

(a) Structure of the motor (b) back-EMF

Figure. 1. The analysed five-phase PMSM

In the synchronous rotating d-q frame where d-axis is aligned with phase A axis, the relationship between stator voltage v_d, v_q and current i_d, i_q is

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} L_d i_d \\ L_q i_q \end{bmatrix} + \begin{bmatrix} R_s & -\omega_e L_q \\ \omega_e L_d & R_s \end{bmatrix}\begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \lambda_m \end{bmatrix} \tag{1}$$

where R_s is stator phase resistance, L_d and L_q are inductance in d-axis and q-axis respectively, ω_e is rotor electric speed, and λ_{pm} is flux linkage of permanent magnet. To execute predictive control, motor model in discrete time domain is presented

$$\begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \begin{bmatrix} 1-R_s T_s/L_d & T_s\omega_e(k) \\ -T_s\omega_e(k) & 1-R_s T_s/L_q \end{bmatrix}\begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} T_s/L_d & 0 \\ 0 & T_s/L_q \end{bmatrix}\begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} - \begin{bmatrix} 0 \\ T_s\lambda_m\omega_e(k)/L_q \end{bmatrix} \tag{2}$$

where T_s is the control period.

In a two-level five-phase inverter, up to 32 voltage vectors can be obtained in fundamental space and in third harmonic space correspondingly. All the vectors are shown in Fig. 2.

3. Proposed Finite Control Set Model Predictive Current Control

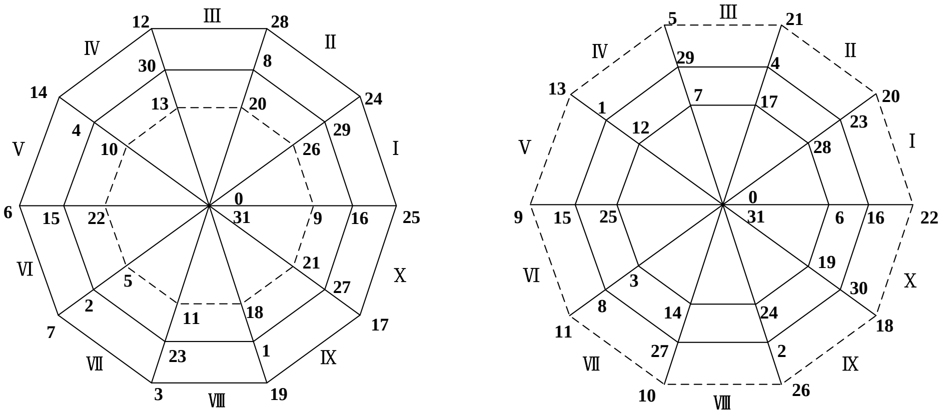
The proposed FCS-MPCC is composed of virtual voltage vectors, current observer, a simplified cost function and the theory of a new online updated adaptive control set.

3.1. Virtual Voltage Vectors

The theory of virtual voltage vectors has been proposed in [7], its main idea is reviewed here. Five-phase PMSM cannot eliminate third order current harmonic in stator windings as its three-phase counterparts do, consequently, specific voltage vector strategy should be designed to avoid third harmonics invasion from the inverter. As shown in Fig. 2, the big vectors locating at the largest decagon in the fundamental space change into small vectors locating at the smallest decagon in the third harmonic space, and the middle vectors in fundamental space correspond to the middle ones in third space. What's more, the big and middle vectors pointing the same direction in fundamental space point opposite when mapped to third harmonic space. Therefore, it has been proved that when the small vectors in fundamental space are excluded and the working time of big vectors T_{big} and middle vectors T_{mid} in fundamental space satisfies

$$T_{big}/T_{mid} = 1.618, \quad (3)$$

third harmonic voltage won't be generated in five-phase inverter and third order current harmonic will therefore be considerably removed. Based on that, the voltage vectors of two-level five-phase inverter can be rearranged with virtual voltage vectors as shown in Fig. 3 and these 11 virtual voltage vectors make up the original control set. The amplitude of the vectors is 0.5527·Udc and every vector contains two switching state.



(a) Fundamental space (b) Third harmonic space

Figure. 2. Voltage vectors provided by two-level five-phase inverter.

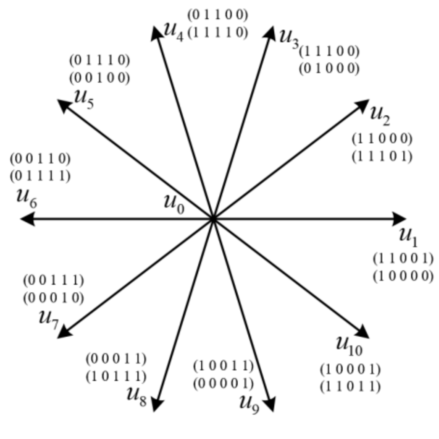


Figure. 3. Virtual voltage vectors

3.2. Current Observer

In a real control system, sampling and calculating will occupy some time thus the derived control signal based on present control period system state can be used to drive the inverter only in next control period. This delay will cause vibration or even instability. To compensate the delay, stator current in next control period $\hat{i}_d(k+1)$ and $\hat{i}_q(k+1)$ should be predicted and predictive control signal can be generated based on predicted current.

Considering i_q here, in discrete time domain,

$$u_q(k) = R_s i_q(k) + L_q \cdot \left(i_q(k+1) - i_q(k)\right)/T_s + \omega_e(k)\left(L_d i_d(k) + \lambda_m\right), \tag{4}$$

and the d-axis current observer can be derived from (4), as

$$\hat{i}_q(k+1) = u_q(k)T_s/L_q + \left(1 - R_s T_s/L_q\right)i_q(k) - \omega_e(k)T_s\left(L_d i_d(k) + \lambda_m\right)/L_q . \tag{5}$$

The d-axis current observer can be construct in the same way.

3.3. Cost Function

As the third order voltage harmonic is no longer introduced by inverter when adopting virtual voltage vectors and back-EMF of the five-phase PMSM is almost sinusoidal, there is no need to include third order current harmonic items in the cost function as the conventional FCS-MPCC strategy does. Therefore, the cost function in the proposed FCS-MPCC is defined as

$$J = \left|i_{dref}(k+2) - i_d(k+2)\right| \cdot \gamma + \left|i_{qref}(k+2) - i_q(k+2)\right| \tag{6}$$

where, γ is a controllable coefficient, $i_{dref}(k+2)$ and $i_{qref}(k+2)$ are the current reference in k+2 control period. $i_d(k+2)$ and $i_q(k+2)$ are the estimated currents which are calculated by the virtual voltage vectors in control set using

$$\begin{bmatrix} i_d(k+2) \\ i_q(k+2) \end{bmatrix} = \begin{bmatrix} 1 - \frac{R_s T_s}{L_d} & T_s\omega_e(k+1) \\ -T_s\omega_e(k+1) & 1 - \frac{R_s T_s}{L_q} \end{bmatrix} \begin{bmatrix} \hat{i}_d(k+1) \\ \hat{i}_q(k+1) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_d} & 0 \\ 0 & \frac{T_s}{L_q} \end{bmatrix} \begin{bmatrix} u_{dset} \\ u_{qset} \end{bmatrix} - \begin{bmatrix} 0 \\ \frac{T_s \lambda_m \omega_e(k+1)}{L_q} \end{bmatrix} \tag{7}$$

where, u_{dset} and u_{qset} are the voltage vectors in control set. As the control period T_s is short enough, rotor speed can be treated as constant in two contiguous period, i.e., $\omega_e(k+1) = \omega_e(k)$.

3.4. Online Updated Adaptive Control Set

In the original virtual voltage vector control set, the amplitude of each voltage vector is stable, equal to the maximum voltage that the DC bus can support, resulting in that none of the vectors in the control set is actually suitable in some cases especially when rotor speed is small, i.e., back-EMF is small. To solve this problem, an online updated adaptive control set is proposed to adjust the amplitude of the virtual voltage vectors in control set and to reduce the computational burden of FCS-MPCC.

First, as voltage vectors will work in next control period, the rotor direction in next control period is calculated

$$\theta_e(k+1) = \theta_e(k) + \omega_e(k) \cdot T_s \tag{8}$$

where, $\theta_e(k)$ and $\theta_e(k+1)$ are the rotor direction at current control period and next period respectively.

Second, estimated voltage vector u_{dest} and u_{qest} in next control period is estimated by

$$\begin{bmatrix} u_{dest}(k+1) \\ u_{qest}(k+1) \end{bmatrix} = \begin{bmatrix} R_s - L_d/T_s & -\omega_e(k)L_q \\ \omega_e(k)L_d & R_s - L_q/T_s \end{bmatrix} \begin{bmatrix} \hat{i}_d(k+1) \\ \hat{i}_q(k+1) \end{bmatrix} + \begin{bmatrix} L_d/T_s & 0 \\ 0 & L_q/T_s \end{bmatrix} \begin{bmatrix} i_{dref}(k+2) \\ i_{qref}(k+2) \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e(k)\lambda_{pm} \end{bmatrix} \tag{9}$$

and can be transferred to stator α-β frame by

$$\begin{bmatrix} u_{\alpha est}(k+1) \\ u_{\beta est}(k+1) \end{bmatrix} = \begin{bmatrix} \cos\left(\theta_e(k+1)\right) & -\sin\left(\theta_e(k+1)\right) \\ \sin\left(\theta_e(k+1)\right) & \cos\left(\theta_e(k+1)\right) \end{bmatrix} \begin{bmatrix} u_{dest}(k+1) \\ u_{qest}(k+1) \end{bmatrix} \tag{10}$$

Then, the amplitude of the estimated vector is

$$u_{est}(k+1) = \sqrt{u_{\alpha est}(k+1)^2 + u_{\beta est}(k+1)^2} . \tag{11}$$

And the position of the estimated vector θ_{est} is

$$\theta_{est}(k+1) = \arctan\left(u_{\beta est}(k+1)/u_{\alpha est}(k+1)\right) \tag{12}$$

Third, according to the estimated vector, define that K is adaptive factor

$$K = u_{est}(k+1) / (0.5527 \cdot U_{dc}) \tag{13}$$

The online updated adaptive control set can be established by including only three voltage vectors, u_{s0}, u_{s1} and u_{s2}, as shown in Fig. 4. The amplitude of u_{s1} and u_{s2} is $K{\cdot}0.5527{\cdot}U_{dc}$.

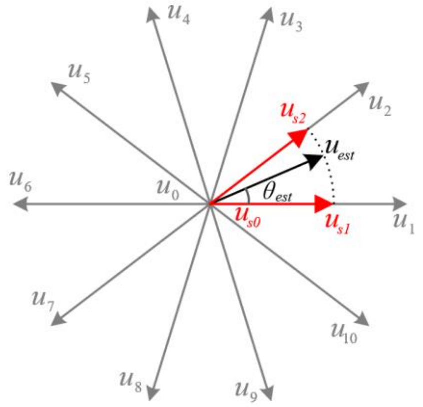


Figure. 4. Online updated adaptive control set when u_{est} is located at region I.

4. Experimental Verification

To verify the feasibility of the proposed FCS-MPCC strategy, experiments are implemented based on a 2 kW prototype. In all experiments, DC bus voltage is set to 120 V, i_q is restricted to about 3.5 A by load, i_d reference is 0. The comparison between sampled phase-a current, i_d and i_q is presented in Fig. 5. At 300 r/min, as shown in Fig. 5 (a) (c), the current oscillation is obvious in conventional FCS-MPCC system, on the other hand, current ripple is much reduced in the proposed FCS-MPCC system. It can be inferred that the voltage vectors with full DC bus voltage magnitude are not suitable for FCS-MPCC under low speed condition and the proposed online updated adaptive control set successfully chooses more appropriate voltage magnitude. When rotor speed is increased to 600 r/min, the conventional FCS-MPCC performs better than before since the rotor speed is increased and back-EMF is larger now and the mismatch between full DC bus voltage magnitude and back-EMF is mitigated. Besides, the proposed algorism still works under optimal condition. The THD of phase-a current at 600 r/min is presented in Fig. 6. Compared with the conventional FCS-MPCC, the proposed method reduces current ripples THD significantly from 16.91% to 9.47%.

Besides, it should be emphasized that since the manufacture error, third order harmonic still exists in back-EMF, third order harmonic contributes to most proportion of current ripple in the proposed FCS-MPCC system.

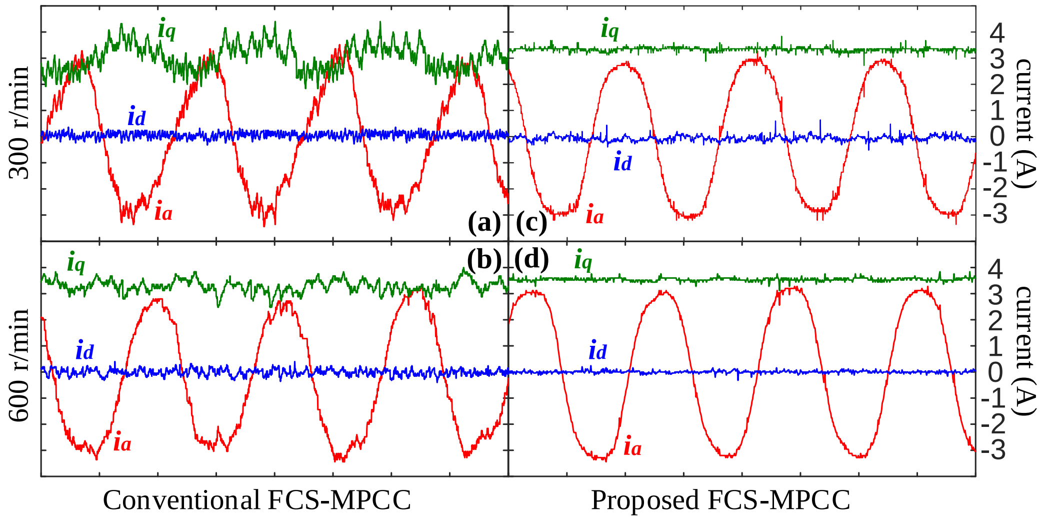


Figure. 5. Experimental results comparison between conventional and proposed FCS-MPCC.

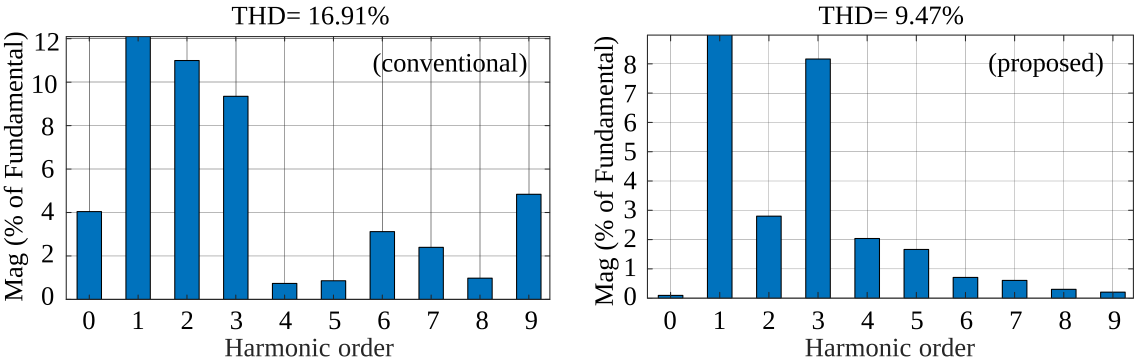


Figure. 6. THD comparison between conventional and proposed FCS-MPCC at 600 r/min.

5. Conclusion

An improved FCS-MPCC strategy for five-phase PMSM has been presented in this paper. Virtual voltage vectors, current observer and a new online updated adaptive control set are included in this method. The optimization of the proposed control system is that optimal voltage vectors with appropriate magnitude is selected according to rotor speed and current ripple can hence be much reduced. Finally, the experimental results confirm the performance improvement of the proposed algorithm.

Acknowledgments

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References

[1] L. Parsa and H. A. Toliyat, "*Five-phase permanent-magnet motor drives*," IEEE Trans. Ind. Appl., vol. 41, no. 1, pp. 30-37, Jan./Feb. 2005.

[2] L. Zhang, Y. Fan, R. D. Lorenz, A. Nied and M. Cheng, "*Design and comparison of three-phase and five-phase FTFSCW-IPM motor open-end winding drive systems for electric vehicles applications*," IEEE Trans. on Veh. Technol., vol. 67, no. 1, pp. 385-396, Jan. 2018.

[3] A. A. Ahmed, B. K. Koh and Y. I. Lee, "*A comparison of finite control set and continuous control set model predictive control schemes for speed control of induction motors*, " IEEE Trans. on Ind. Informat., vol. 14, no. 4, pp. 1334-1346, April 2018.

[4] C. Xia, Y. Wang and T. Shi, "*Implementation of finite-state model predictive control for commutation torque ripple minimization of permanent-magnet brushless DC motor*," IEEE Trans. Ind. Electron., vol. 60, no. 3, pp. 896-905, March 2013.

[5] C. S. Lim, E. Levi, M. Jones, N. A. Rahim and W. P. Hew, "*FCS-MPC based current control of a five-phase induction motor and its comparison with PI-PWM control*," IEEE Trans. Ind. Electron., vol. 61, no. 1, pp. 149-163, Jan. 2014.

[6] T. Wang, C. Liu, G. Lei, Y. Guo and J. Zhu, "*Model predictive direct torque control of permanent magnet synchronous motors with extended set of voltage space vectors*," IET Electric Power Applications, vol. 11, no. 8, pp. 1376-1382, 9 2017.

[7] C. Xue, W. Song and X. Feng, "*Finite control-set model predictive current control of five-phase permanent-magnet synchronous machine based on virtual voltage vectors*," IET Elect. Power Appl., vol. 11, no. 5, pp. 836-846, May 2017.