A Comparison between Five-Level Virtual Voltage Vectors Based on MPC-DSVPWM and Field Oriented Control of Two-Level Inverter for PMSM Drive

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ABSTRACT

Model predictive control (MPC) is a popular choice for electric drive applications due to its ease of implementation, and fast dynamics. However, when a two-level inverter is used, it can result in large current ripples due to a limited number of voltage vectors. Therefore, this study proposes a method called the five-level virtual voltage vectors based on MPC with discrete space vector pulse width modulation (FLVV-MPC-SVPWM) to improve steady-state performance of the current control for permanent magnet synchronous motors (PMSMs). The proposed method generates virtual voltage vectors that are equivalent to the ones produced by a 5-level active neutral-point clamped converter (5L-ANPC), resulting in a total of 125 voltage vectors. The proposed FLVV-MPC-SVPWM aims to achieve a steady state performance near to that of the widely-used field-oriented control approach (FOC). The results of FLVV-MPC-SVPWM have near the steady-state performance as FOC, and guarantee a faster dynamic response.

1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) are a popular choice for variable-speed applications due to their ability to maintain a constant magnetic field without the need for an external power source, resulting in high efficiency and reliable operation [1]. Field-oriented control approach (FOC) and direct torque control (DTC) are the commonly used control strategies. FOC provides better steady-state performance but requires more complex tuning and has slow dynamic performance. On the other hand, DTC has a simple control structure, and fast dynamic performance but has a large current/torque ripples and variable switching frequency [2]. Model predictive control (MPC) has emerged as a popular control strategy in recent years, thanks to its ability to incorporate nonlinear dynamics, optimize multivariable systems, and deliver fast and accurate responses in a wide range of applications. Nonetheless, conventional MPC suffers from high current ripples, resulting from variable switching frequencies and a limited number of voltage vectors (VVs) that can undermine system stability and performance [1]. A method combining discrete space vector modulation (DSVM) with MPC has been proposed to synthesize a wide number of virtual VVs which result in improved steady-state performance and achieve a constant switching frequency. To enhance the steady-state performance of current control for PMSMs and achieves comparable performance as FOC in a two-level inverter, this study suggests using the five-level virtual VVs based on MPC with discrete space vector PWM method (FLVV-MPC-DSVPWM). This method generates 125 virtual VVs similar to those produced by a 5L-ANPC. The proposed method generates each virtual VV from switching states that have 0, 1,2,3,4 values which represent voltage level values. Then by computing the v_α and v_β, real and virtual VVs are easily generated. A comparison between FLVV-MPC-SVPWM and FOC in terms of both steady-state and transient-state performance is presented.

2. PROPOSED MPC-DSVPWM FOR PMSM

The study focuses on a PMSM that is powered by a two-level inverter. The voltage equations of the PMSM in the rotor reference frame are presented in equation (1).

$$\begin{aligned} v_d &= R_s I_d + L_d \frac{d}{dt}(I_d) - \omega_e L_q I_q, \\ v_q &= R_s I_q + L_q \frac{d}{dt}(I_q) + \omega_e L_d I_d + \omega_e \phi_f, \end{aligned} \tag{1}$$

The equations involve several parameters, including voltage components along the d- and q-axes denoted by v_d and v_q, respectively. The current components along the d- and q-axes are represented by I_d and I_q, respectively. R_s is the per-phase stator resistance, while L_d and L_q refer to the inductances along the d- and q-axes, respectively. Additionally, the equations take into account the electrical rotor speed, ω_e, and the flux linkage established by the rotor, φ_f. The discrete-time model can be derived through forward Euler discretization. Equation (2) demonstrates an approximation for the derivative of I with respect to time (dI/dt),

$$\frac{d}{dt} = \frac{I_{(k+1)} - I_{(k)}}{T_s}, \tag{2}$$

The sampling interval is represented by T_s. The current prediction of PMSM is calculated in (3).

$$\begin{cases} I^z_{\alpha(k+1)} = I_{\alpha(k)} + \dfrac{T_s}{L_d}\left(-R_s I_{\alpha(k)} + L_q \omega_e I_{\beta(k)} + v_{\alpha(k)}\right) \\ I^z_{\beta(k+1)} = I_{\beta(k)} - \dfrac{T_s}{L_q}\left(R_s I_{\beta(k)} + L_d \omega_e I_{\alpha(k)} + L_q \omega_e \phi_f - v_{\beta(k)}\right) \end{cases}, \tag{3}$$

The currents in the stationary reference frame are denoted by $I_{\alpha(k+1)}$ and $I_{\beta(k+1)}$, where $k+1$ represents the next sampling instance. To assess all the VVs generated, the cost function (g^z) measures the error between the predicted and reference currents as in (4),

$$g^z = \left|I^*_{\alpha(k+1)} - I^z_{\alpha(k+1)}\right| + \left|I^*_{\beta(k+1)} - I^z_{\beta(k+1)}\right|. \tag{4}$$

The DSVPWM technique enables the placement of $v_{\alpha(k)}$ and $v_{\beta(k)}$ at any position within the control region of the inverter. Fig 1 shows the space vector diagram of the 125 real and virtual VVs that applied for the two-level inverter, all virtual and real VVs are represented by circular markers. The VVs are evenly distributed across the control region and divided into multiple hexagons. Specifically, the control region is divided into 125 VVs, which corresponds to the voltage vector of a 5-level active neutral-point clamped converter (5L-ANPC). In the 5L-ANPC configuration, the upper and lower DC link voltages are maintained around $V_{DC}/2$, while the flying capacitor voltage is regulated to be around $V_{DC}/4$. This results in the generation of five levels in the output voltage, namely "V_{DC}/2", "V_{DC}/4", "0", "V_{DC}/4", and "V_{DC} d/2". These five levels correspond to 8 switching states, meaning that a 3P-5L-ANPC configuration produces 125 voltage vectors and 512 switching states. Fig 1 displays all the VVs, with "0", "1", "2", "3", and "4" being used to denote the five voltage levels. The proposed method generates each virtual VVs from switching states that have values of 0, 1, 2, 3, or 4. By computing the v_α and v_β values according to equation 5, all real and virtual voltage vectors are generated [4], [5]. For example, V_1 is generated by substituting S_A=1, S_B= 0, and S_C= 0, resulting in

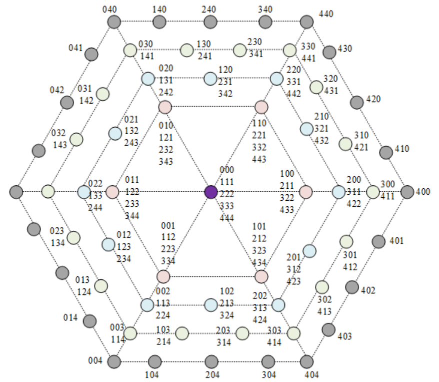


Fig.1 Space vector diagram of virtual 5L-ANPC

Table 1 PMSM parameters

Parameter	Unit	Value
Rated power	kW	5
Rated current	A	17.23
Rated torque	Nm	27.3
Rated speed	r/min	1750
Stator resistance	Ω	0.158
d−axis inductance	H	0.00729
q−axis inductance	H	0.00725
Moment of inertia	$kg\cdot m^2$	0.00666
Permanent magnet flux	Wb	0.264
Number of poles	−	8

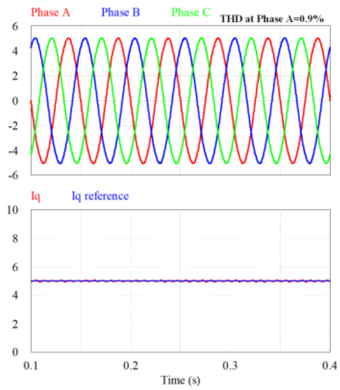
$v_\alpha = 2/3 V_{DC}$ and $v_\beta = 0$, which equals V_1. This approach simplifies the generation of VVs and can enhance the performance of current control in PMSMs

$$v_\alpha = \frac{V_{DC}}{12}(2S_A - S_B - S_C), \quad v_\beta = \frac{V_{DC}}{4\sqrt{3}}(S_B - S_C). \tag{5}$$

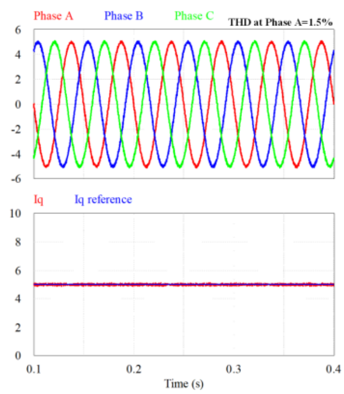
After calculating $v\alpha$ and $v\beta$ according to equation (5), they are transformed to v_A, v_B, and v_C and applied to the two-level inverter. As the two-level inverter does not require capacitor balancing through the optimal vector, the virtual VVs for capacitor balancing is eliminated. For example, only one voltage vector is used from the VV located in the same position. DSVPWM is preferred over DSVM in this study due to its superior performance and lower complexity.

3. RESULT

Simulation results were obtained through the use of the PSIM tool. The simulation results demonstrated the effectiveness of the FLVV-MPC-SVPWM method. The proposed approach was compared against the FOC, using simulation parameters listed in Table I. The



(a)



(b)

Fig.2 Simulation results of I_q and phase A during steady-state at 5A and 300 r/min (a) FOC, and (b) FLVV-MPC-SVPWM

comparison between FOC and FLVV-MPC-SVPWM was conducted under steady-states, with a fixed switching frequency (f_{sw}) of 10 kHz as shown in Fig 2. While FOC had a better THD in I_A phase current compared to the proposed method, FLVV-MPC-SVPWM had a constant f_{sw} and used large number of virtual VVs resulting in lower current ripples and a THD of 1.5%, compared to 0.9% for FOC. Despite FOC's slight advantage in THD, the proposed method had excellent dynamic performance, achieving a faster response time of 1 ms compared to 3.7 ms for FOC in a step change from 2 to 5 A as shown in Fig 3. This fast response with no noticeable oscillations is crucial for many industrial applications, making FLVV-MPC-SVPWM a more desirable option in such scenarios.

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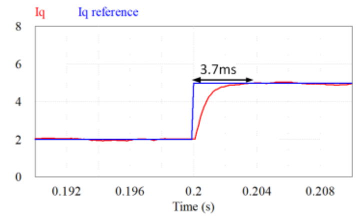
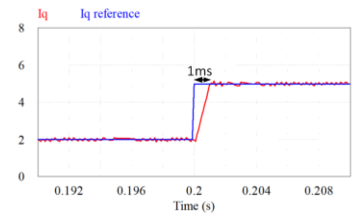
4. CONCLUSION



(a)



(b)

Fig.3 Simulation results of I_q during transient-stat with I_q' change from 2 to 5 at 300 r/min (a) FOC, and (b) FLVV-MPC-SVPWM

This study proposed a creative current control method for a two-level inverter of PMSM. The proposed method generates virtual VVs that are equivalent to the ones produced by a 5-level active neutral-point clamped converter (5L-ANPC). The results show a good steady-state performance comparable to FOC with a faster dynamic response. In addition, the proposed generation of the virtual VVs method could be combined in the future with machine learning methods, which can result in low computation time.

REFERENCE

[1] H.A.G. Al-kaf, S.S. Hakami and K.-B. Lee, "Hybrid Current Controller for Permanent-Magnet Synchronous Motors Using Robust Switching Techniques," *IEEE Trans. Power Electron.*, vol. 38, no. 3, pp. 3711–3724, 2022, Mar.

[2] D. Casadei, F. Profumo, G. Serra, and A. Tani, "FOC and DTC: two viable schemes for induction motors torque control," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 779–787, Sep. 2002.

[3] Y. Yang, J. Pan, H. Wen, X. Zhang, M. Norambuena, L. Xu, and J. Rodriguez, "Computationally efficient model predictive control with fixed switching frequency of five-level anpc converters," *IEEE Trans. Ind. Electron.*, 2021, Dec.

[4] H.A.G. Al-kaf, S.S. Hakami and K.-B. Lee, "Low Complexity MPC-DSVPWM for Current Control of PMSM Using Neural Network Approach," *IEEE Access*, vol. 10, pp. 132596-132607, 2022, Dec.