FINITE CONTROL SET BASED ON THE VOLTAGE VECTOR REPRESENTATION OF SWITCHING STATE

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Abstract: This paper introduces novel approach in the implementing of finite control set model predictive control for the permanent magnet synchronous motor. This approach is based on the pre-generating of voltage vectors based on the specific switching state of voltage source inverter. The limitation of the pre-generating is based on the resolution of encoder used to measure mechanical angle of rotor. Proposed algorithm is described and tested in PIL simulation using Jetson Nano, for the control algorithm execution, and Simscape model of motor.

Keywords: finite control set, model predictive control, voltage vectors, optimization, general-purpose computing

1 INTRODUCTION

Finite control set (FCS) model predictive control (MPC) of the permanent magnet synchronous motor (PMSM) is based on the calculation of the optimal switching state of voltage source inverter (VSI) [3]. The computation of all possible combinations across the whole prediction horizon has huge computational demands. One of the aims of the research in the field is the acceleration of the computation. One of approaches is the reduction of the control set [2]. The approach described in this paper is based on the [1]. Further acceleration is done by using pre-generated vectors.

The paper is organized as follows. First chapter analyzes the problem of evaluating model with imbued switching states. Following by the second chapter, which introduces the approach of pre-generated voltage vectors. Third chapter describes the usage of introduced idea in algorithmic way. The last chapter discusses the simulation results of the applied algorithm.

2 ANALYSIS

The prediction of the future states of the controlled system is essential part of predictive control. The evaluation of the model is necessary for the correct prediction. During control of fast systems, such as PMSM, it is necessary to perform the evaluation as fast as possible.

The difference equations describing current in dq-frame - $i_d(k+1), i_q(k+1)$ - are

$$\begin{aligned}
i_d(k+1) = {} & \left(1 - T_s\frac{R_s}{L_d}\right) i_d(k) + T_s P_p \frac{L_q}{L_d}\omega_m(k) i_q(k) + \frac{T_s}{L_d}\left(\sqrt{\frac{2}{3}}\cos\vartheta_e(k)\right) u_A(s(k)) + \\
& + \frac{T_s}{L_d}\left(-\frac{1}{\sqrt{6}}\cos\vartheta_e(k) + \frac{1}{2}\sin\vartheta_e(k)\right) u_B(s(k)) \\
& + \frac{T_s}{L_d}\left(-\frac{1}{\sqrt{6}}\cos\vartheta_e(k) - \frac{1}{2}\sin\vartheta_e(k)\right) u_C(s(k))
\end{aligned} \tag{1}$$

$$i_q(k+1) = \left(1 - T_s\frac{R_s}{L_q}\right) i_q(k) - T_s P_p \frac{1}{L_q}\left(L_d i_d(k) - \Psi_{PM}\right)\omega_m(k) + \frac{T_s}{L_q}\left(-\sqrt{\frac{2}{3}}\cos\vartheta_e(k)\right) u_A(s(k)) +$$
$$+ \frac{T_s}{L_d}\left(\frac{1}{\sqrt{6}}\sin\vartheta_e(k) + \frac{1}{2}\cos\vartheta_e(k)\right) u_B(s(k)) + \frac{T_s}{L_d}\left(\frac{1}{\sqrt{6}}\sin\vartheta_e(k) - \frac{1}{2}\sin\vartheta_e(k)\right) u_C(s(k)) \tag{2}$$

where

i_d, i_q are stator current components in dq frame,	L_d, L_q are rotor inductance components,
ω_m is rotor mechanical angular speed,	P_p is number of pole pairs,
ϑ_e is rotor electrical angle,	Ψ_{PM} us permanent magnet flux,
u_A, u_B, u_C are phase voltages,	T_s is sampling period,
R_s is stator winding resistance,	$s(k)$ is switching state of VSI.

The necessity of evaluating of functions sin and cos combined with computation of required multiplications in every step of prediction increases the computational demands of the optimization algorithm. This leads to the prolonging of computational time and makes the solving of optimization problem harder in real-time.

Therefore, requirements of the real-time computation lead to need for simplifications, such as vector representation described in following section.

3 VECTOR REPRESENTATION

The parts of equations (1) and (2) with phase voltages are representation of voltages $u_d(k)$ and $u_q(k)$ given by the information about switching state $s(k)$ and electrical angle $\vartheta_e(k)$.

By the definition of the 2-level VSI, there exist two possible states on every phase - ON (1) or OFF (0). For three phases this makes total of eight combinations. Every combination can be transformed to the vector of voltage in dq-frame using Park and Clarke transformation

$$\begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} = U_{DC} \begin{bmatrix} \cos(\vartheta_e) & \sin(\vartheta_e) & 0 \\ -\sin(\vartheta_e) & \cos(\vartheta_e) & 0 \end{bmatrix} \begin{bmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} s_A(k) \\ s_B(k) \\ s_C(k) \end{bmatrix}, \tag{3}$$

where U_{DC} is supply voltage and s_A,s_B and s_C are switching states of respective phases.

The transformation shows the combinations $s(k) = [0\ 0\ 0]^T$ and $s(k) = [1\ 1\ 1]^T$ result in same voltage vector $u = [0\ 0]^T$. This makes total of seven possible vectors of voltage. Mentioned vector remains zero for every possible electrical angle ϑ_e. Only six vectors remain dependent on the position of rotor.

These vectors are shown in the figure 1. The vectors are named according to the switching state, e.g. (100) - phase A on, phase B - off and phase C - off. The subscript denotes the rotor angle used for the vector generation.

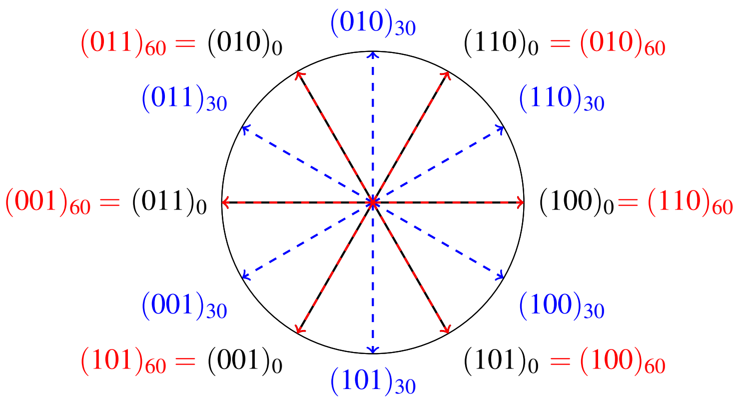


Figure 1: Change of the voltage vector based on the electrical angle ϑ_e

The figure shows the change of the generated vectors for the specific angle ϑ_e. After the angle passes the multiple of 60 degrees, the switching combination generating given vector shifts.

4 ALGORITHM

Drawing on the information mentioned before, the finite control set algorithm can be developed. First of all, the proper finite control set must be defined. Control value of developed algorithm is switching states $s(k)$. Model used in optimization problem uses mapping

$$s(k) \rightarrow \begin{bmatrix} u_d\left(\vartheta_e(k)\right) \\ u_q\left(\vartheta_e(k)\right) \end{bmatrix}. \tag{4}$$

Now, it is necessary to generate the vectors of voltage. Drawing on the information in the figure 1, the values must be pre-calculated for only one switching state.

The pre-generating of vectors comes with one complication. The real count of possible voltage vectors is infinite. To solve this issue, the parameters of practical realization are utilized. Every encoder used for the measurement of the rotor angle has finite resolution. In the developed algorithm, the number of pre-generated vectors is connected with the defined resolution of encoder.

For the resolution r, the $r+1$ voltage vectors are pre-generated. Additional vector is zero vector. If the zero vector is chosen, the switching state $s(k) = [0\,0\,0]^T$ is selected.

The one of essential parts of the control algorithm is prediction. During this phase, all possible combinations of switching states are evaluated. Then the optimal combination is selected and switching state is applied to VSI.

For proper function of algorithm, it is necessary to define the way of finding out the currently used vectors. For the initial position $\vartheta_e = 0$, the position p of n-th used vector in pre-generated vectors is

$$p = \left\lfloor \frac{n \cdot r}{6} \right\rfloor. \tag{5}$$

During movement of rotor, shift l occurs. Its value is based on the difference between actual angular position and the multiple of 60 degrees d

$$l = \frac{d}{60} r. \tag{6}$$

Thus, the position of used n-th vector is

$$p = \left\lfloor \frac{n \cdot r}{6} + \frac{d}{60} r \right\rfloor. \tag{7}$$

The optimization is performed with properly selected voltage vectors. It is necessary to transform the result back to switching state.

The result is the number n of given vector for the $\vartheta_e = 0$. Due to the rotation, it is necessary to perform shifting given by the multiplicity of actual position and 60 degrees m. The order is based on the order of vectors in the figure 1. The exception to this is the zero vector.

Principle of the transformation for the case of $n = 1$ and $m = 2$ is shown in the following figure.

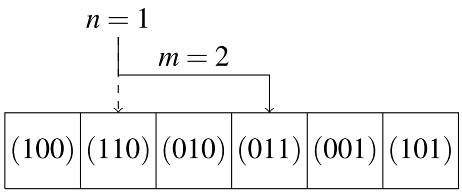


Figure 2: Transformation of vector to switching state

5 RESULTS

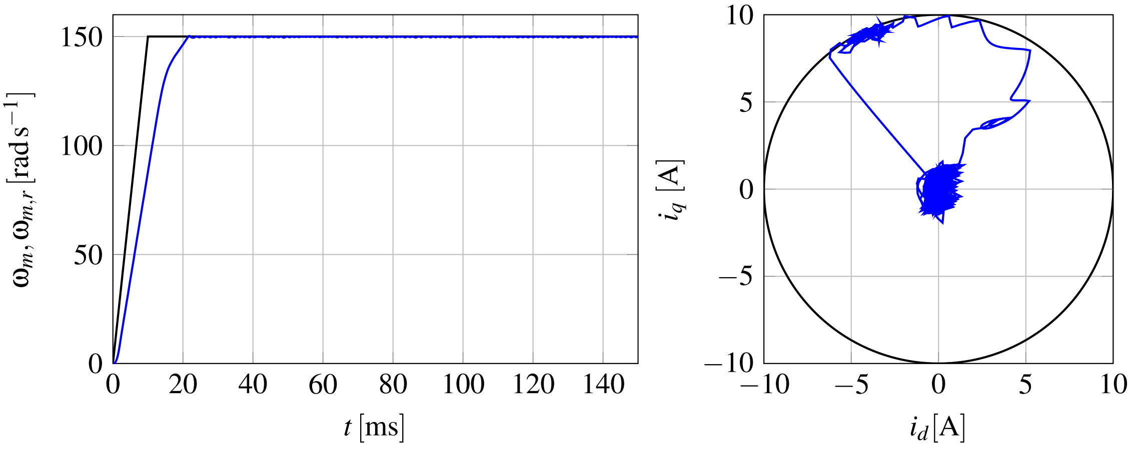
Proposed algorithm was tested in the PIL simulation. Simscape model of PMSM and VSI was used for the simulation of their behavior. For the algorithm execution, Jetson Nano was used. The communication was established via UDP protocol. Table 1 shows the parameters of simulated PMSM.

Table 1: Parameters of PMSM

Parameter	Value
R_s	$0.822\ \Omega$
L_d	$0.016\ \mathrm{H}$
L_q	$0.024\ \mathrm{H}$
Ψ_{PM}	$0.097 \times 10^{-3}\ \mathrm{Wb}$
Pp	5
J	$0.870 \times 10^{-3}\ \mathrm{kg\,m^2}$
ω_r	$150\ \mathrm{rad\,s^{-1}}$
T_R	$7.275\ \mathrm{N\,m}$
I_R	$10\ \mathrm{A}$
U_{DC}	$200\ \mathrm{V}$

The simulation run with the encoder with the resolution $r = 4096$. The experiment tested, whether the algorithm is able to track the reference angular speed. The derivative of the initial ramp was purposely chosen higher than the rated torque of the motor to test, whether is the algorithm able to keep the current within its limit. The Figure 3 a) shows the results of the reference tracking experiment. The results show algorithm was able to ensure the reference tracking. The 3 b) shosw the value of current was kept within the limit of $I_R = 10$ A.

The results are dependent on the chosen period. The sampling period was selected based on the length of execution of algorithm. First part is the time required by the solution of optimization problem. The measurement has show the value around 10 µs, which is 33 % improvement, when compared to the approach in [1]. The time required by the communication and data manipulation did not change. Thus, the sampling period was set to 100 µs.



(a) Angular speed, black - reference, blue - measurement

(b) Current in dq-frame

Figure 3: Results of the tracking reference experiment

6 CONCLUSION

This paper introduced the novel approach in the implementation of finite control set model predictive control. This approach is based on the pre-calculation of possible voltage vectors generated by the switching state of the voltage source inverter. The number of pre-calculated vectors is connected with the resolution of used encoder. The strategy of selecting specific vectors a backward transformation to the switching state is described.

The algorithm based on the introduce method was tested in PIL simulation. The experiment has confirmed the ability of algorithm to ensure the reference tracking and to keep the stator current within its limits.

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