Predictive direct torque control for permanent-magnet synchronous machines based on duty ratio modulation

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Abstract. In this paper, Two-step model predictive control based on duty ratio modulation of permanent magnet synchronous machine (PMSM) is proposed. There is a large amount of computation in the two-step predictive control. In this paper, a fast vector selection method is proposed to solve the problem of computational complexity. The proposed voltage vector selection method avoids the complete enumeration for testing all feasible voltage vector, and the calculation method of duty are discussed. This control method achieves a constant switching frequency, and the torque fluctuation is smaller, inheriting the advantages of predictive control response speed. To investigate the effectiveness of the proposed method, two-step predictive direct torque control based on duty ratio modulation (TSPTC-DM), comparison of one-step predictive direct torque control based on duty ratio modulation (OSPTC-DM) and finite control set model predictive torque control (FCS-MPTC) is shown.

1. Introduction
PMSM take an important role in different application areas due to their high efficiency, power density, low electrical losses etc. Therefore, it has been widely used in various industries [1]. Examples of their application include various types of automation equipment, automatic processing equipment and robots. Favorable torque characteristics make PMSM particularly suitable for servo applications in which the torque output may be required as smooth as possible.

In automotive electric traction drives, the control of the electric machine is done using Field-Oriented Control (FOC) and direct torque control (DTC). The characteristics of PMSM has strong nonlinear and multi-variable, nonlinear, the traditional PI control, vector control is a linear control method for nonlinear systems and time-varying characteristics can better control. In recent decades, many nonlinear control algorithms have been widely studied for the PMSM system to improve the control performance, such as sliding mode control [2], fuzzy control [3], and adaptive control [4]. These control methods from different aspects to enhance the performance of the system, but also to achieve a better effect.

In a variety of advanced control technologies, Model Predictive Control (MPC) has been widely used in industrial control. The main characteristic of the MPC is that it uses the model of the system to predict the future behavior of the controlled variables over a prediction horizon. Predictive control can effectively handle multi-variable case, system constraints and nonlinearities in a very intuitive way. Thought the large amount of calculation is a big challenge to the predictive control, the development of computing and digital signal processing in the last decade can basically solve the problem [5][6].
As the control algorithm requires a large amount of calculation, the corresponding calculation time is longer, then the computer technology is not yet developed, the method has not been more attention and rapid development. With the rapid development of modern microprocessors, MPC computing problems can be better resolved, in recent decades, many domestic and foreign scholars on the MPC technology in the field of power electronics applications more and more interested in the technology also successfully used in various related fields, such as power converters, high performance motor control[7][8].

Finite-State-Set Model Predictive Control (FCS-MPC) is an important part of the predictive control family, many articles using this method for torque control, named model predictive torque control with a finite control set (FCS-MPTC) [9]. In this method, an optimal voltage vector is chosen as the control quantity in one sampling period. Therefore, this control method has the problem of large torque ripple, the same as the direct torque control. In many literatures, FCS-MPTC is used to combine with a duty ratio modulation. In this way, two voltage vectors, the nonzero vector with the zero vector, are selected in one sampling period, the time of the action of the two voltage vectors is calculated. With this method, the problem of torque ripple is effectively solved.

Figure 1. PMSM powered by two-level inverters

FCS-MPTC based on duty ratio modulation is a one-step predictive control method, the realization is relatively simple, but the one-step prediction does not reflect the advantages of rolling optimization. In many applications, multi-step predictions are often used to improve system performance. With the increase of prediction horizon, the computation will be exponentially increased. A huge burden of computing will bring the system cannot work properly. For this problem, this paper proposes a fast method of vector selection, calculation at each step prediction, effectively reduce the need to verify the reasonable vector, and then reduce the amount of computation.

The remaining paper is organized as follows: The mathematical model for a three-phase two-level grid connected power converter is established section 2. Control design is proposed in section 3. Simulation results based on Matlab/Simulink are included in section 4. Finally, conclusions are addressed in Section 5.

2. Model of PMSM
In this paper, PMSM is driven by a three-phase voltage source inverter as shown in Figure 1. The mathematical model of PMSM in the coordinate system can be expressed by voltage equation, flux linkage equation, torque equation and motion equation.

The basic idea of MPC is to use the system model to predict the expression of the next sampling stage variable. For the prediction method, a commonly used prediction method is the Euler approximation method, which replaces the system differential equation with the forward Euler equation, which is simple and effective and has been widely used. In order to obtain the state value of the next sampling
stage, the prediction model of the motor should be established first. Permanent magnet synchronous motor coordinate system under the flux expression can also be expressed as follows,

\[
\begin{align*}
\frac{d\psi_d}{dt} &= u_d - \frac{R_s}{L_d}\psi_d + \omega_s\psi_q - \frac{R_s}{L_d}\psi_f \\
\frac{d\psi_q}{dt} &= u_q - \frac{R_s}{L_d}\psi_q - \omega_s\psi_d
\end{align*}
\]

where is treated as a constant. Because the sampling period is very small, electrical angular velocity can be seen as a constant, then the use of Euler approximation, \(dq\) coordinate system motor prediction flux and predictive current expression,

\[
\begin{align*}
\psi_d(k + 1) &= T_s u_d + (1 - \frac{R_s}{L_d}T_s)\psi_d + \omega_s\psi_q T_s + \frac{R_s}{L_d}T_s\psi_f \\
\psi_q(k + 1) &= T_s u_q + (1 - \frac{R_s}{L_d}T_s)\psi_q - \omega_s\psi_d
\end{align*}
\]

Figure 2. Torque slope under different voltage vectors and position of stator flux

\[\text{Start} \quad \text{Measure the system variables at } T(k) \quad \text{End}\]

\[i = 1 \quad \text{Determine the stator flux sector} \quad \text{measured } \theta_{i1}, \theta_{i2}, \text{ duty cycle } \tau_{i(1)} \quad i = m + i \]

\[i = 1 \quad \text{measured } \theta_{i1}, \theta_{i2}, \text{ duty cycle } \tau_{i(1)} \quad \text{Calculate the cost function } g(.) \quad j = j + 1 \]

\[i = 1 \quad \text{measured } \theta_{i1}, \theta_{i2}, \text{ duty cycle } \tau_{i(1)} \quad \text{Minimize the cost function } g(.) \quad i = i + 1 \]

\[v = \nu_{up} \quad T = T_{up} \quad \text{End}\]
The torque prediction expression can be obtained from equation (2) and equation (3) as follows:

\[ T_e = 1.5(p_y(k + 1)i_q(k + 1) - y_d(k + 1)i_d(k + 1)) \]  

Equation (2),(3) and (4) is called the prediction model of PMSM, and the output value of the \( T(k+1) \) can be predicted by the \( T(k) \) time measurement value and the motor parameter.

3. Control Design

This paper mainly studies a two-step predictive direct torque control method based on duty cycle. The basic principle of voltage vector selection is that in each sector, either the voltage vector that increases the torque is selected, and the switching vector that reduces the torque is also selected. So that the error of the torque can be used to accurately calculate the time of each voltage vector action.

According to the torque change rate to draw the torque in different sectors (angle) and different voltage vector changes. Figure 2 illustrates the torque change rate under different sectors (angle) and different voltage vector changes.

| sector | 1                     | 2                     | 3                     |
|--------|-----------------------|-----------------------|-----------------------|
| First step | \( v_1, v_2, v_3 \) | \( v_2, v_3, v_4 \) | \( v_3, v_4, v_5 \) |
| Second step | \( v_1, v_2, v_3, v_4 \) | \( v_2, v_3, v_4, v_5 \) | \( v_3, v_4, v_5, v_6 \) |

| sector | 4                     | 5                     | 6                     |
|--------|-----------------------|-----------------------|-----------------------|
| First step | \( v_1, v_2, v_3 \) | \( v_2, v_3, v_4 \) | \( v_3, v_4, v_5 \) |
| Second step | \( v_1, v_2, v_3, v_4 \) | \( v_2, v_3, v_4, v_5 \) | \( v_3, v_4, v_5, v_6 \) |
Figure 4. Results of variable speed under proposed control

As can be seen from Figure 2, the torque is reduced by the zero vector, so we only need to select a vector that increases torque. When the stator flux is located at the first sector, the nonzero vector that can increase the torque in $T(k + 1)$ period is $v_1, v_2, v_3$, then the vector $v_1, v_2, v_3, v_4$ is selected in the first step prediction.

Considering that the flux sector may change during the $T(k + 2)$ period, voltage vector should be verified in the second step prediction when the speed is positive, voltage vector should be verified in the second step prediction when the speed is negative. When the stator flux is located at the second sector, the nonzero vector that can increase the torque in $T(k + 1)$ period is, then the vector is selected in the first step prediction. Considering that the flux sector may change during the $T(k + 2)$ period, voltage vector should be verified in the second step prediction when the speed is positive, voltage vector should be verified in the second step prediction when the speed is negative. Take the positive speed as an example, the voltage vectors which need to be verified in the first and two steps of different sectors are given, as shown in table I. the control flow chart is shown in Figure 3.

4. Simulation Results

In this Section, the simulation results are carried out to validate the effectiveness of the proposed control method. The simulation circuit of the Two-level inverter-driven PMSM system is the same as in Figure 1.
The load torque is 1N.m remain unchanged. In time, the speed increased from 0 to 1500 r/ min and maintained to \( t = 0.15 \) s; in time, the speed from 1500r/min constant to 0 r/min. The simulation results are as follows: speed, torque, flux amplitude, a-phase current waveforms from top to bottom.

As can be seen from Figure 4, the system can quickly follow the given acceleration and deceleration can be good; from the torque waveform diagram, the motor can quickly provide the required acceleration and deceleration of the positive and negative torque, and maintained at constant speed Load torque, torque ripple is less than the torque ripple of direct torque control. The flux reference value is obtained by MTPA according to the torque reference output from the speed loop. As can be seen from the Figure 5, when the load torque changes abruptly, the system torque output can respond quickly. The straight axis changes with the cross-axis current, which coincides with the theory that the current change causes the torque change, and the overshoot satisfies design range.

In the case of torque mutation show in Figure 6, the torque fluctuation based on FCS-MPDT comes as the largest, and the difference between the one-step prediction and the two-step prediction is little difference. On the left and right, the two-step prediction is slightly smaller, the response time of the
predictive direct torque is about 4 ms, the torque response time based on duty cycle modulation is 1 ms, and the response time is 1 ms, and the torque response time is 1 ms. The predictive control method has very fast torque response and is consistent with the predictive control response.

5. Conclusion
This paper mainly studies the predictive control method based on duty cycle modulation, for the problem of large computation in two-step prediction, we propose a fast vector selection method in this paper. Through the analysis of different sectors and torque change rate, a fast vector selection method is proposed, which greatly reduces the computational complexity of the system. This paper mainly studies the predictive control method based on duty cycle modulation, for the problem of large computation in two-step prediction, we propose a fast vector selection method in this paper. Through the analysis of different sectors and torque change rate, a fast vector selection method is proposed, which greatly reduces the computational complexity of the system.

6. References
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