Model Predictive Control and Position Sensorless Control Algorithm for Induction Motor

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Abstract. In view of the traditional finite set model predictive control of induction motor, the enumeration method is used to select only one optimal voltage vector in one control cycle, which causes the deviation of stator current in the tracking control process, and a duty cycle model predictive current control algorithm is proposed. In this algorithm, duty cycle control is introduced on the basis of traditional model prediction algorithm. In a control period, an optimal non-zero vector and a zero vector act together, and the action time of the two is calculated. Based on the duty cycle model predictive control algorithm, the model reference adaptive speed estimation algorithm is introduced to improve the robustness of the model. Finally, the dynamic and static characteristics of vector control and two model predictive control algorithms are analyzed through simulation comparison, and the feasibility of the proposed speed estimation algorithm is verified on the basis of the duty ratio model predictive algorithm, and the robustness of the two estimation methods is compared. The superiority of the prediction algorithm of duty cycle model and the improved speed estimation algorithm is proved.

1. Introduction

Induction motors are widely used in production and life due to their advantages such as simple structure and low manufacturing cost. After years of development, the manufacturing technology is relatively mature. In the field of high-performance AC motor control, vector control and direct torque control have been proven to have the advantages of high reliability and robustness, but some shortcomings [1-6] have gradually emerged in the research and application of these two algorithms. For example, it is difficult to design the PI parameters of vector control, there are cross-coupling terms in the d-q axis, the current inner loop bandwidth is limited, and the switching frequency is high, the steady-state performance of direct torque control is poor, and the switching frequency is not fixed, etc.

Model Predictive Control (MPC) is an advanced control algorithm that has the advantages of fast dynamic response, simple structure and easy handling of nonlinear control variables, etc. Due to the increasing requirements for the dynamic response characteristics of induction motors in industrial applications, it is necessary to introduce predictive current control methods into the induction motor vector control system. At present, some scholars have proposed to improve the dynamic response of the system by using the double closed-loop system of the speed prediction controller and the current prediction controller cascade [7]. This method has been fully studied in the permanent magnet motor control system. Research, many scholars at home and abroad have carried out the research on torque and flux-linkage predictive control, and achieved good control performance. For example, reference [8]...
uses the traditional model predictive torque control (MPTC) algorithm to control induction motor, but the weight function needs to be designed in the objective function to reasonably adjust the two control objectives of torque and flux linkage. The process is relatively cumbersome and lacks theoretical support. Reference [9] converts torque and stator flux linkage amplitude into stator flux linkage vector through the internal relationship between motor flux linkage and torque, thus avoiding the weight coefficient design in MPTC. This control method is called model prediction flux control (MPFC). The traditional model predictive control adopts single vector control, which causes the control target to fluctuate greatly. In order to solve this problem, some scholars have proposed many improvement schemes such as duty cycle control, double vector and triple vector, and proved their superiority [10-12]. However, among many model predictive control of induction motors, there are few studies on model predictive current control (MPCC).

In addition, at present the position sensorless control of induction motors is mainly realized by the observer method. The main observers are Model Reference Adaptive System (MRAS), Sliding Mode Observer (SMO), Extended Kalman filter method (EKF). In addition, there are speed estimation methods such as high-frequency signal injection method. A single observer generally faces problems such as strong parameter dependence and large chattering of the estimation results. Therefore, some scholars have combined different observers or added filters to improve the accurate estimation of the rotor position and speed [13].

This article first studies the MPCC of the induction motor. Based on the vector control, the current inner loop is transformed into a model predictive current controller, and the optimal voltage vector is directly selected and output to the converter to control the induction motor. In view of the error of current tracking caused by traditional MPC single vector control, duty cycle modulation is introduced, which reduces the current harmonic content and the pulsation of torque and flux linkage to a certain extent. Then, based on the duty cycle MPCC, in view of the shortcomings of poor robustness of the traditional MRAS speed estimation, it is combined with the sliding mode controller, the PI control law in the MRAS is replaced by the sliding mode control law, and the sliding mode control is replaced. The sign(s) switching function in is replaced with sat(s) saturation function to reduce chattering. Finally, the simulation analysis proves that the duty cycle MPC is more superior than the traditional MPC and vector control, and can greatly reduce the harmonic content of the stator current. Compared with the traditional MRAS and the improved SMC-MRAS speed estimation results, the improved algorithm can be more accurately identify the speed and have a strong robust conclusion.

2. Model prediction direct current control system design
This article adopts the direct current control (FCS-MPCC) method based on finite set model prediction, and its control block diagram is shown in Figure 1.

![Figure 1 Block diagram of predictive current control of induction motor model.](image-url)
After the error signal of the rotor flux linkage amplitude and speed passes through the corresponding PI regulator, the reference value of the stator d-q axis current is generated. In order to improve the performance of the control system, a delay compensation link is added to the system, and then the predicted value of the stator current is obtained from the current prediction model, and finally the value function is evaluated to obtain the optimal switching vector.

2.1 Traditional single vector MPC algorithm

The forward Euler method is used to discretize the current state equation to predict the value of the stator current at the next moment. The prediction model is:

\[
\begin{align*}
    i_{ad}(k+1) &= (1 + a_{11} T_s) i_{ad}(k) + T_s a_{11} i_{sd}(k) + a_{14} \varphi_r \\
    i_{aq}(k+1) &= (1 + a_{22} T_s) i_{aq}(k) + T_s a_{22} i_{sq}(k) + a_{24} \varphi_r
\end{align*}
\]

The control target of MPCC is to expect the stator current of the motor to quickly follow its reference value, and construct the deviation of the d-q axis component of the stator current from the reference value. Cost function, namely

\[ J = (i_{ad}(k+1) - i_{ad}^*)^2 + (i_{aq}(k+1) - i_{aq}^*)^2 \]

The core idea of traditional MPCC is to select the voltage vector that minimizes the error between the predicted current and the given current through the value function as the optimal voltage vector. Substituting the seven effective switching vectors into the cost function in turn, the one with the smallest result is the optimal switching vector, and the corresponding switching state is input into the frequency converter to realize the control of the generator.

2.2 Duty Cycle Model Predictive Current Control

It can be seen from the traditional MPCC control process that the optimal voltage vector acts on the entire control cycle. When the predicted current after acting is not equal to the given value, as shown in Figure 2(a), the control amount will fluctuate greatly. The steady-state performance of the system is poor. Therefore, this article borrowing ideas from references [1], introducing the duty cycle MPCC algorithm proposed therein to control the induction generator, which improves the steady-state performance of MPCC to a certain extent. The duty cycle MPCC is based on the traditional MPCC, which introduces duty cycle control, that is, calculates the action time of the optimal voltage vector selected by the value function, so that the optimal voltage vector only acts on a part of the control cycle, and the rest of the time is zero voltage The vector effect is shown in Figure 2(b).

First, select the optimal voltage vector \( V_{opt} \) according to the method similar to the traditional MPCC. The difference is that the duty cycle MPCC has a zero vector in each sampling period. Therefore, the zero vector is not considered when selecting \( V_{opt} \). The vector library contains only six valid voltage
vectors. The choice of the zero vector $V_0$ is based on the principle of minimum switching frequency. Then calculate the action time of $V_{opt}$ and $V_0$ in a cycle. In this paper, the $q$-axis current deadbeat is used to calculate the duty cycle. When the two vectors act separately, the rate of change of the $q$-axis current is:

$$
\begin{align*}
S_0 &= p_i q |i_{q}=0 = a_{22}i_{sq} + a_{23}i_{sd} + a_{24}i_{sr} \\
S_{opt} &= p_i q |i_{q}=q_{opt} = a_{23}u_{sqq} + S_0
\end{align*}
$$

(3)

According to the principle of deadbeat current, in a sampling period, the optimal voltage vector and zero voltage vector action time are allocated to make $i_q$ reach a given value $i_q^*$ at $k+1$

$$
i_q(k+1) = i_q^*(k) = S_{opt}t_{opt} + S_0t_0
$$

(4)

Combining equations (3) (4), the optimal voltage vector action time can be obtained as:

$$
t_{opt} = (i_q^* - iq(k) - S_0T_s)(S_{opt} - S_0)^{-1}
$$

$$
t_0 = T_s - t_{opt}
$$

(5)

Finally, the optimal voltage vector and zero vector are output to the inverter according to their duty cycle to control the operation of the induction generator.

3. Model reference adaptive flux observation and speed identification

Model reference adaptive algorithm for speed estimation mainly has three typical links: building a reference model, building an adjustable model, and designing an adaptive law. Generally in induction motors, a model based on the stator static two-phase coordinate system is used to design the algorithm. In this paper, the voltage-current and current-speed models calculated by the rotor flux linkage are used as the reference model and the adjustable model, respectively. The former has better Parameter robustness, and no speed information is included when outputting the flux linkage, and the flux linkage needs to be output based on the rotation speed information. In the process of operation, by real-time adjusting the parameter to be identified of the adjustable model, that is, the motor speed, the output value of the adjustable model is approximately equal to the output value of the reference model, so as to realize the observation of the parameter to be identified.

According to the state equation of the induction motor in the two-phase static coordinate system, the reference model can be easily derived as

$$
\begin{align*}
\psi_{ra} &= \frac{L_s}{L_m} \left[ (u_{ra} - R_i_{ra}) dt - L_s \sigma i_{ra} \right] \\
\psi_{r\beta} &= \frac{L_s}{L_m} \left[ (u_{r\beta} - R_i_{r\beta}) dt - L_s \sigma i_{r\beta} \right]
\end{align*}
$$

(6)

The adjustable model is

$$
\begin{align*}
\psi_{ra} &= (T_s s + 1)^{-1} \left[ -T_s \sigma \psi_{r\beta} + L_m i_{ra} \right] \\
\psi_{r\beta} &= (T_s s + 1)^{-1} \left[ -T_s \sigma \psi_{ra} + L_m i_{r\beta} \right]
\end{align*}
$$

(7)

The Popov superstability theory is used to design the adaptive law. The specific design process refers to the reference [11], and the motor angular velocity is identified by the following formula:

4
The rotor angle estimation value \( \hat{\theta}_m \) can be obtained directly from the rotor estimated speed integral, and the rotor flux linkage amplitude and angle can also be obtained by calculation. So far, the MRAS-based speed sensorless control model has all been deduced. Combining the reference model, the adjustable model and the adaptive law, the MRAS speed and flux linkage observation model based on the rotor flux linkage can be obtained as shown in Figure 3.

![Figure 3 MRAS velocity observation model based on rotor flux.](image)

Because the above-mentioned traditional MRAS speed observer uses the motor itself as the reference model, the control performance is greatly affected by the motor parameters, and the PI controller is used to obtain the estimated speed, the PI parameters are not easy to adjust, and the robustness is poor. Therefore, a sliding mode observer is used here instead of the PI controller to determine the sliding mode control mechanism by estimating the deviation, so that the system state is stabilized on the sliding mode surface and the system's dependence on parameters is reduced.

The switching function of constructing the SMC-MRAS speed identifier is:

\[
\hat{s} = \hat{\psi}_{ra} \hat{\psi}_{rb} - \psi_{ra} \psi_{rb}
\]

(9)

The saturation function \( \text{sat}(s) \) is used to replace the traditional switching function \( \text{sign}(s) \) to reduce the influence of the sliding mode surface chattering on the control effect.

4. Simulation result analysis

The simulation in this paper is mainly divided into two parts. First, the feasibility and superiority of the proposed duty cycle FCS-MPC are verified by comparing the vector control of the induction generator, the traditional FCS-MPC, and the duty cycle FCS-MPC algorithm. Then on the basis of the proposed duty cycle MPC control strategy, a comparison simulation uses the traditional MRAS speed estimation algorithm and the improved SMC-MRAS speed estimation algorithm to verify the feasibility and robustness of the proposed speed estimation algorithm.

4.1 Comparative analysis of vector control, traditional MPC and duty cycle MPC algorithm guidelines

Figure 4 shows the simulation waveforms of the stator A-phase current, speed, torque, and flux of the vector control algorithm, the traditional FCS-MPC algorithm, and the duty cycle FCS-MPC algorithm. The simulation conditions are: the motor starts without load, the initial given speed is 800r/min, the speed step is set to 1200r/min at 0.3s, and the 0.6s simulation ends. The flux linkage setting is the rated value 0.96Wb unchanged, the speed and the flux linkage outer loop output current setting value is limited to [-50,50]A, and the outer loop PI parameters are the same.
Figure 4 Waveform of stator current, speed, torque and flux linkage.
It can be seen from Figure 4 that all three control strategies have good dynamic and steady-state performance. From the FFT analysis results of the three phase A stator current waveforms, it can be seen that the duty cycle MPC stator current harmonic content is less than that of the traditional MPC, and both are less than the vector control harmonics. The THD is 8.49%, 5.70%, and 5.11. %. It can be seen from the three speed waveforms that the speed can track the set value without difference, and can quickly reach the stable value. Due to the limitation of the set value of the current output from the outer loop, the dynamic performance of the three is not much different. It can also be seen from the reference waveform that the torque ripple of the two MPC algorithms is smaller than that of the vector control algorithm. Finally, it can be seen from the circular waveforms of the three flux linkages that after the initial dynamic process, they can all reach a given value, and the dynamic processes of the flux linkage of the three are getting faster and faster in sequence in Figure 4(a)(b)(c), And the ripple becomes smaller and smaller when it is stable.

4.2. Rotation speed estimation based on duty cycle MPC

This paper combines the duty cycle MPC algorithm speed estimation control strategy, and proposes the SMC-MRAS speed estimation algorithm on the basis of the traditional MRAS algorithm. The feasibility of applying traditional MRAS and SMC-MRAS in duty cycle MPC is verified, and its dynamic performance is compared and simulated. The simulation conditions are similar to 4.1. The simulation conditions are: the motor starts at no load, the initial given speed is 800r/min, the speed step is 1200r/min at 0.3s, and a load of 50N·m is applied for 0.6s. The flux linkage setting is the rated value 0.96Wb unchanged, the speed and the flux linkage outer loop output current setting value is limited to [-50,50]A, and the outer loop PI parameters are the same. The simulation results are shown in Figure 5.

![Waveform of traditional MRAS and improved SMC-MRAS speed estimation](image)

*Figure 5* Waveform of traditional MRAS and improved SMC-MRAS speed estimation.

From the dynamic and steady-state processes of the two algorithms in Figure 5 when the speed changes stepwise, both can track the given value quickly and without difference. The performance of the two algorithms is similar, and the estimated speed is consistent with the actual speed. When the load torque step increases to 50N·m at 0.6s, both speeds decrease first and then rise quickly. However, after the traditional MRAS algorithm stabilizes the speed again, there is a significant error between the estimated speed and the actual speed, while the improved SMC-MRAS algorithm can accurately estimate the
motor speed, thus verifying the traditional model reference adaptive algorithm and sliding mode variable structure control algorithm. The combination has better speed estimation performance.

5. Conclusion
Aiming at the problem of large current fluctuations in the traditional MPCC strategy of induction motors, this paper proposes a duty cycle MPCC strategy. This strategy has a zero vector and a non-zero vector in each control cycle, which reduces the error caused by traditional MPCC to a certain extent, and better steady-state performance can be obtained; in addition, this paper introduces MRAS on the basis of the duty cycle MPCC strategy to estimate the motor speed and rotor position, and combine The SMC strategy improves the robustness of the estimation system. The simulation results show that the duty cycle MPCC has the same rapid speed and flux response as the traditional MPCC and vector control, and the current harmonic content of the former is significantly reduced, which verifies the effectiveness and feasibility of the proposed algorithm; through MRAS and SMC-MRAS under the interference of the torque jump, the simulation results of the speed estimation show that the two have the same fast dynamic response, but the latter tracks more accurately when reaching the steady state, which proves the robustness of the proposed speed estimation method stronger.

6. References
[1] Xu Y, Zhang B and Zhou Q 2017 PMSM two-vector model predictive current control Trans. Chi. Electro. Soc. 32(20) pp 222-30.
[2] Zhang Y, Xia B and Yang H 2017 Induction motor three vector model predictive flux control Jour. Electric. Eng. 12(003) pp 1-9.
[3] Zhang X and Yang J 2019 The predictive torque control technique of asynchronous motor model based on duty cycle modulation Electro. 19 pp 18-25.
[4] Sun W, Yu Y and Wang G 2014 Predictive current control algorithm for asynchronous motor based on vector control Proc. CSEE. 34(021) pp 3448-55.
[5] Jonggrist J 2021 Multivariable model predictive control for a virtual synchronous generation-based current source inverter International Journal of Electrical and Electronic Engineering & Telecommunications. 10(3) pp 196-202.
[6] Dharanirajan T, Gowri Sankar K, Surya Kumar K and Renukadevi G 2015 Open loop response of inverter-fed three phase induction motor drive International Journal of Electrical and Electronic Engineering & Telecommunications.1(1) pp 148-53.
[7] Mariethoz, Sébastien, Domahidi A and Morari M 2013 High-bandwidth explicit model predictive control of electrical drives IEEE Trans. Ind. Appl. 48(6) pp 1980-92.
[8] Kashyap N, Patidar S 2017 Model predictive direct torque control of neutral point clamped induction drive. International Conference on Power and Embedded Drive Control. pp 202-7
[9] Zhang X, Hou B 2017 Double vectors model predictive torque control without weighting factor based on voltage tracking error. IEEE Trans. Pow. Electro. 33(3) pp 2368-80.
[10] Castro A , Pereira W , Almeida T , et al. 2018 Improved Finite Control-Set Model-Based Direct Power Control of BLDC Motor with Reduced Torque Ripple. IEEE Trans. Ind. Appl. 54(5) pp 4476-84.
[11] Zhang Y and Yang H 2014 Model Predictive Torque Control of Induction Motor Drives With Optimal Duty Cycle Control IEEE Trans. Pow. Electro. 29(12) pp 6593-603.
[12] Zhang Y, Xia B and Yang H 2017 Induction motor three vector model predictive flux control. Jour. Electric. Eng. 12(003) pp 1-9.
[13] Swati S and Ankita K 2015 Comparative study of integer order PI-PD controller and fractional order PI-PD controller of a DC motor for speed and position control. International Journal of Electrical and Electronic Engineering & Telecommunications, 4(2) pp 22-6.