Model Predictive Current Control of Dual-Permanent-Magnet Vernier Motor based on Anti-Windup Controller

Yushun Liu1,*, Taiyun Zhu1, Shaolei Wu1, Senlin Li1, Binyu Wu2 and Zhifan Huang2

1 State Grid Anhui Electric Power Research Institute, Heifei 230601, Anhui, China
2 Institute of Information Technology, Yangtze Delta Region Institute of Tsinghua University, Jiaxing 314006, Zhejiang, China
*Corresponding Author: e-mail: ahepri_zjth@126.com

Abstract. Dual-permanent-magnet vernier motor incorporates the merits of high torque density and low cost, suitable for low-speed high-torque applications. Due to integral saturation and high current ripples in dual-permanent-magnet vernier motor control system, a model predictive current control strategy based on Anti-Windup PI controller is proposed. Adaptive adjustment variable structure is adopted in integral segment of the controller, which can quickly eliminate integral saturation in system. Mode predictive current control based on dual vector is adopted in current interior loop of the system, double arbitrary voltage vector can be selected to operate simultaneously in each control cycle that extends selection range of voltage vector and adjustment range of amplitude, which can realize more accurate current control. Meanwhile, considering system delay, current delay compensation is added to predictive control. The simulation results showed that proposed control strategy can effectively restrain integral saturation, reduce current ripples, thus improving dynamic and steady state performance of the control system.

1. Introduction

With the continuous progress of city modernization in China, the demand for urban electricity supply is becoming greater and greater, which puts forward higher requirements for urban power supply system. 10 kV cable is an important constituent part of urban power distribution system, where the cable connector technology has a direct bearing on the quality and safety of the power supply system. In comparison with artificial fabrication, the cable connectors manufactured by automatic robots have the merits of good stability, high safety and short manufacturing period, all of which help to reduce the risk of power supply fault to a great extent. Motor and its control system, which are the core modules of automatic cable connector manufacturing robots, become especially important. In recent years, permanent magnet vernier motor has become a research hotspot among both domestic (Chinese) and foreign scholars by virtue of low velocity and high torque [1-3]. Dual-permanent magnet vernier (DPMV) motor is a new-type permanent magnet vernier motor [4], where permanent magnets are embedded in both stator and rotor to greatly increase the electromagnetic torque density of the motor, and moreover, hybrid magnetic material is used, so the manufacturing cost is lowered. This new-type motor is featured by high torque density and low cost with considerable application prospect in direct-
driven fields with high performance requirements, e.g. computer numerical control machine tools, robots, wind power generation and new energy vehicles [5].

For the speed module in a typical motor control system, the traditional PI controller is generally used to regulate the given value of output quadrature-axis current. Influenced by various factors such as inverter power capacity and limited motor overload capacity, PI control must restrict the output amplitude. When the system speed undergoes sudden change, the controller will output the preset maximum value to adjust the system state, which will generate integral windup phenomenon, lead to excessive speed overshoot and long steady-state time, and then impact the system dynamic performance. In order to overcome the deficiencies of the traditional PI controller and improve the system dynamic performance, Literature [6-7] improved the system starting performance and system robustness by designing a sliding mode controller, but these methods needed to reasonably design the switching surface of the sliding mode, or otherwise buffeting problem would be generated, which would aggravate the system complexity to a certain degree, so it was not easy to realize engineering application of the methods. Some scholars and experts have proposed Anti-Windup PI controller to repress the effect of integral windup on the system. Generally, the anti-windup method is divided into conditional integral method and back-calculation method, where the latter has been extensively to engineering practice with simple design, but the ideal control effect can be achieved only by repeatedly regulating the feedback factor.

As a new-type control strategy in the motion control field, the finite control set model predictive control (FCS-MPC) algorithm takes full consideration of the discrete characteristic of switching devices with merits of multivariable processing, multiple constraint conditions, strong robustness, simple structure and good dynamic performance, etc. However, FCS-MPC also has its limitations. As only a single vector acts in each control cycle, the steady-state performance of the traditional MPC is poor. In order to tackle the deficiencies of the traditional MPC, Literature [8-9] introduced duty ratio modulation into MPC, which improved the system steady-state performance to a certain extent, but the second acting voltage vector was a zero vector, which was difficult to guarantee that acting vector was the global optimum. Double-vector MPC was adopted in Literature [10], but not considering effect of system delay to control system. When calculation was increased, the control performance would be affected.

A new-type multivariable, strong-coupling and multi-constraint DPMW motor was taken as the control object, its current was directly controlled, and model predictive current control (MPCC) was adopted. To solve integral windup and large current fluctuation problems existing in the traditional MPCC system, a dual-vector MPCC control method based on Anti-Windup controller was proposed, two arbitrary vectors were selected in each control cycle, and the compensation link for system current delay was added. The effectiveness of the algorithm was verified through the simulation result.

2. DPMV Motor and its Mathematical Model

2.1. DPMV motor structure
The topological structure of the new-type three-phase DPMV motor is shown in Fig. 1. Two sets of permanent magnets are used in the motor, where one set is embedded into rotor and the other into stator. The motor stator is composed of iron core carrying convex tooth, three-phase armature winding and permanent magnet. Halbach flux gathering array is used for the permanent magnet embedded into stator to reduce magnetic flux leakage to improve the utilization efficiency of permanent magnet, and magnetic barrier is introduced at bottom of the array for magnetic shield. The permanent magnets are made of hybrid magnetic material, thus lowering the processing cost.
2.2. Mathematical Model

The current state equation of DPMV motor under two-phase synchronous d and q-axis coordinates is as below:

\[
\begin{align*}
\frac{di_d}{dt} & = \frac{1}{L_d} \left( -R_i i_d + u_d + L_i i_q \omega_e \right) \\
\frac{di_q}{dt} & = \frac{1}{L_q} \left( -R_i i_q + u_q - L_i i_d - \psi_f - \omega_e \right)
\end{align*}
\]

(1)

Where \(i_d\) and \(i_q\) are the currents of axis \(d\) and \(q\), respectively; \(u_d\) and \(u_q\) are the voltages of axis \(d\) and \(q\), respectively; \(L_d\) and \(L_q\) are the inductances of axis \(d\) and \(q\), respectively; \(R_s\) is stator resistance; \(\psi_f\) is flux linkage of permanent magnet; \(\omega_e\) is electrical angular velocity of the motor.

Eq. (1) is discretized towards the previous-order difference, and then the current equation can be converted into:

\[
\begin{align*}
\frac{1}{T_s}[i_d(k+1) - i_d(k)] & = \frac{T_s}{L_d} [-R_i i_d(k) + u_d(k) + e_d(k)] \\
\frac{1}{T_s}[i_q(k+1) - i_q(k)] & = \frac{T_s}{L_q} [-R_i i_q(k) + u_q(k) + e_q(k)] \\
e_d(k) & = L_d i_d(k) \omega_e(k) \\
e_q(k) & = -\phi_f(k)(L_d i_d(k) + \omega_e(k))
\end{align*}
\]

(2)

Where \(T_s\) is sampling time; \(e_d(k)\) and \(e_q(k)\) are sampling values of counter electromotive forces of axis \(d\) and \(q\) at time \(k\), respectively.

The mechanical motion equation of the DPMV motor is:

\[
T_e - T_l = J \frac{d\omega_r}{dt} + B \omega_r
\]

(4)

Where \(T_e\) is electromagnetic torque of the motor; \(T_l\) is load torque; \(J\) is rotational inertia of the motor; \(\omega_r\) is mechanical angular velocity of the motor; \(B\) is viscous friction coefficient.

3. Dual-vector MPCC based on Anti-Windup controller

3.1. Anti-Windup controller

In a typical DPMV motor MPCC system, the response time of inner current loop is much shorter than that of outer loop of rotary speed, so the dynamic operation process of inner current loop can be neglected in the analysis of rotary speed controller. A saturation limiting module is usually added at the output end of the traditional PI controller to inhibit the influence of nonlinear saturation on the system. When the given rotary speed undergoes great step change or under external disturbance, the integrals will far exceed the integral windup limit due to the continuous accumulation of integration...
elements, thus causing integral windup phenomenon, excessive system overshoot and too long stabilization time, etc.

In order to mitigate the influence of nonlinear saturation on the system and realize better control performance, an Anti-Windup adaptive variable-structure PI controller as shown in Fig. 2.

![Fig. 2 Anti-Windup adaptive variable-structure PI controller](image)

By judging the state of the saturation limiting module before and after the output, the controller uses the feedback compensation system \( \eta \) to realize adaptive compensation of integral terms, and the adaptive change law is as follows:

\[
\eta = \begin{cases} \frac{\beta}{K_i} [(u_a - u_s) - e_s], & u_a \neq u_s, e(u_a - u_{avg}) > 0; \\
e_s, & u_a = u_s. \end{cases}
\]

(5)

Where \( \beta \) is integral feedback time constant, satisfying \( \beta >> \frac{B}{J} \); \( e_p = (u_{pm} - u_{fs}) \); \( u_{avg} = (I_{max} + I_{min})/2 \).

### 3.2. Double-vector MPCC

Based on the discretization of switching devices and mathematical motor model, the FCS-MPC algorithm mainly consists of predictive model, cost function and traversal optimization modules, etc. The current taken as the control object in this study, Eq. (2) can be selected as predictive model. For the sake of optimal control, an index which can describe the effects of different voltage vectors should be defined, that is, cost function \( g \). By traversing the cost functional values after all candidate vectors take effect, the vector with the minimum cost functional value is selected as the actuating quantity at the next time, so as to realize the optimal control.

However, the sampling and control may not be completely synchronous due to large calculated quantity during the practical application of the FCS-MPC algorithm, and consequently, the system delay will be caused, and ideal control effect cannot be reached. An effective compensation method for system delay is extrapolation method, which predicts the controlled quantity at time \( k+1 \) in advance at time \( k \). Through forward one-step extrapolation according to Eq. (2), the cost function after delay compensation can be obtained as follow:

\[
g = \|i_d^* - i_d^*(k+2)\|^2 + \|i_q^* - i_q^*(k+2)\|^2
\]

(6)

Where \( i_d^* \) and \( i_q^* \) are the reference values of current vectors of axis \( d \) and \( q \), respectively; \( i_d^*(k+2) \) and \( i_q^*(k+2) \) are the predicted values of current vectors of axis \( d \) and \( q \), respectively.

As the control is realized by the traditional MPCC only through a single vector within one control cycle, and there are only 8 voltage vectors (6 effective voltage vectors and 2 zero vectors) with fixed amplitude, the traditional MPCC can be understood as the optimal control under the local conditions at the current time, but not global optimal control. Therefore, in the traditional MPCC system, especially when the control cycle is long, the steady-state performance of motor control is poor and large current fluctuation.
The duty ratio modulation technique is adopted in the double-vector MPCC system. Two basic voltage vectors, which realize the minimization of cost function, and different duty ratio selected to constitute the reference voltage vector, which will act on switching devices to realize motor control and improve the control performance. The comparison between the traditional MPCC and double-vector MPCC in the range of choice of voltage vector is presented in Fig. 3. From Fig. 3 (a), the range of choice of voltage vector in traditional MPCC is only composed of 8 amplitudes and basic voltage vector of fixed direction. It can be observed from Fig. 3 (b) that the double-vector MPCC combines any two voltage vectors to greatly enlarge the range of choice of synthetic voltage vector, including all dotted lines on circumscribed hexagon and two inscribed triangles, and on this basis, more accurate and flexible control can be realized.

The double-vector MPCC algorithm combines two voltage vectors at different duty ratios to synthesize a reference voltage vector, and the key of this algorithm lies in how to determine the duty ratio. The change rate $\delta_x$ of current vector corresponding to an arbitrary voltage vector $u_x$ can be obtained through Eq. (1) as follow:

$$
\delta_x = \frac{1}{L} (-Ri_x^* + u_{ix} + L_i \omega)
$$

$$
\delta_q = \frac{1}{L} (-Ri_q^* + u_{iq} - L_i \omega_q - \psi \omega)
$$

Assume that the duty ratio of the first acting voltage vector is $d_{p1}$, $\delta_1$ and $\delta_2$ are the current change rates of acting voltage vectors $u_1$ and $u_2$, respectively. Through the combined action of two voltage vectors, the predicted value of the current vector at time $k+2$ can be obtained as below:

$$
\hat{i}_x^{*}(k+2) = \hat{i}_x^{*}(k+1) + \delta d_{p1} T + \delta_2 (1-d_{p1}) T
$$

Where $\hat{i}_x^{*}(k+2)$ is the predicted value of current vector at time $k+2$, and its components are current vectors of axis $d$ and $q$.

The minimal value of cost function is calculated by solving the equation $\partial g/\partial d_{p1} = 0$, and then the duty ratio $d_{p1}$ is solved as below:

$$
d_{p1} = \frac{(\delta_1 - \delta_2)(i_x^*(k+1) - i_{x}^{*}(k+1) - \delta_2)T}{|\delta_1 - \delta_2|^2 T}
$$

As the DPMV motor satisfies $L_d = L_q$, $i_d = 0$ control strategy is adopted. Fig. 4 is the block diagram of the double-vector MPCC control based on Anti-Windup controller, and its main implementation process is: First, the given current value $i_{q}^*(k)$ of axis $q$ is obtained after the given deviation of rotary speed is processed by the Anti-Windup PI controller; The first optimal voltage vector $u_1$ is acquired after traversal processing through the traditional MPCC algorithm; The duty ratio is calculated using Eq. (9) and already selected $u_1$, and the secondary traversal optimization is conducted for the second optimal voltage vector $u_2$ and duty ratio $d_{p1}$ through the cost function $g$; In the end, the reference voltage vector is synthesized by the selected two optimal voltage vectors and duty ratio, which is then used to act on switching devices to realize the motor control.
4. Simulation Verification

The simulation model for the motor control system is conducted in Matlab/Simulink to verify the effectiveness of the proposed double-vector MPCC algorithm based on Anti-Windup controller. The parameters of the DPMV motor used in the system simulation are seen in Tab. 1. In the simulation, the system control cycle is 50 μs, $K_p$ and $K_i$ in the Anti-Windup PI controller are 10 and 50, respectively, and the integral feedback time constant $\beta$ is taken as 2.

| Parameters                  | Value | Parameters                  | Value |
|-----------------------------|-------|-----------------------------|-------|
| Rated current $I_n$/A       | 5.0   | Stator resistor $R_s$/Ω     | 0.46  |
| Rated torque $T_n$/Nm        | 15.0  | d-axis inductance $L_d$/mH  | 5.9   |
| Rated speed $n$/rpm          | 600   | q-axis inductance $L_q$/mH  | 5.9   |

Fig. 5 shows the comparison result of velocity simulation waveforms between traditional PI controller and Anti-Windup controller. At 0.4 s when the given velocity suddenly increases from 300 rpm to 600 rpm, the velocity response overshoot of the traditional PI controller is about 10.0%, and the velocity response of Anti-Windup PI controller is of steady transition almost without overshoot. As the given velocity sharply declines from 600 rpm at 0.5 s to 300 rpm, and experiences reverse step change to -300 rpm at 0.6 s and then forward step change to 300 rpm at 0.7 s, the traditional PI controller undergoes overshoot to different degrees, but the Anti-Windup controller does not. Hence, the Anti-Windup PI controller can effectively eliminate the integral windup, reduce the system overshoot and improve the system dynamic performance.

Fig. 5 Contrastive velocity simulation waveform of traditional PI and Anti-Windup PI
When the DPMV motor operates under rated velocity and rated torque, the comparison results of steady-state simulation waveforms between traditional MPCC and double-vector MPCC are presented in Fig. 6. At 0.3 s, the control system is switched from the traditional MPCC algorithm to double-vector MPCC algorithm. It can be observed that when the MPCC algorithm dominates the control within 0.2 s-0.3 s, the three-phase stator current fluctuates a lot with many burrs and high harmonic content; In the meantime, the currents of axis d and q are 1.5 A and 1.6 A, respectively; The fluctuation of electromagnetic torque is 4.8 Nm and that of rotary speed is 3.1 rpm. When the system control is switched to double-MPCC algorithm control within 0.3 s-0.4 s, the fluctuation of three-phase stator current is obviously reduced, the waveform is smoother and the harmonic content is evidently reduced; The current fluctuations of axis d and q are also reduced to 0.7 A and 0.5 A; The fluctuation of electromagnetic torque is reduced by 1.8 Nm, and that of rotary speed is decreased to 1.0 rpm; Meanwhile, the duty ratio under the action of the first optimal voltage vector is adjusted from the previous value 1 according to the control requirement. Obviously, the double-vector MPCC algorithm proposed in this study can effectively relieve the current fluctuation and improve the steady-state system performance.

Fig. 7 shows the simulation waveform of dynamic torque response of the double-vector MPCC when the DPMV motor operates under rated rotary speed. It can be seen from the figure that at 0.4 s, the given load sharply increases from 15 Nm to 20 Nm, and the response time of electromagnetic torque is 1.9 ms; The given load suddenly declines from 20 Nm to 15 Nm at 0.6 s, and the response time of electromagnetic torque is 1.8 ms. As the motor load sharply increases (decreases), the motor speed can rapidly return to the given rotary speed and operate steadily after undergoing slight disturbance. The simulation results indicate that the double-vector MPCC is of high velocity and excellent dynamic torque performance.
5. Conclusion
In view of integral windup and great current fluctuation problems of DPMV motor control system, a double-vector model predictive current control algorithm based on Anti-Windup controller was put forward in this study. The feedback compensation was realized in the integration element of this controller by using the variable structure with adaptive adjustment, and this can rapidly eliminate the integral windup. Following the analysis of insufficient traditional model predictive current control, the current control was predicted using a double-vector model in the inner current loop, and two voltage vectors were randomly selected within one control cycle and combined with duty ratio to further expand the range of choice of voltage vector and the adjustable range of amplitude. According to the simulation results, the proposed control algorithm can effectively repress the integral windup, reduce current fluctuation, and improve the system steady-state performance, and what’s more, it is of preferable dynamic performance.

Acknowledgements
This work was supported by science and technology project of State Grid Anhui Electric Power Co., Ltd: key automated field manufacturing technology research and application for 10 kV single-core cable connector (52120518001R).

References
[1] Zhao, W., Du, K., Xu, L, et al. (2020) Design consideration of fault-tolerant permanent magnet vernier machine. J. Sci. IEEE Trans. Ind. Electron., 67: 7290–7300.
[2] Liu, Y., Li, H., Zhu, Z. Q. (2018) A high-power factor vernier machine with coil pitch of two slot pitches. J. Sci. IEEE Trans. Magn., 54: 8105405.
[3] Du, Z., Lipo, T. A. (2020) Design of an improved dual-stator ferrite magnet vernier machine to replace an industrial rare-earth IPM machine. J. Sci. IEEE Trans. Energy Convers., 34: 2062–2069.
[4] Zhao, W., Sun, X., Ji, J, et al. (2016) Design and analysis of new Vernier permanent-magnet machine with improved torque capability. J. Sci. IEEE Trans. Appl. Supercond., 26: 5201505.
[5] Shi, C., Qu, R., Gao, Y, et al. (2018) Design and analysis of an interior permanent magnet linear vernier machine]. J. Sci. IEEE Trans. Magn., 54: 8106805.
[6] Zhang, X., Li, Z. (2016) Sliding-mode observer-mechanical parameter estimation for permanent magnet synchronous motor. J. Sci. IEEE Trans. Power Electron., 31: 5732–5745.
[7] Zhang, X., Sun, L. (2013) Nonlinear speed control for PMSM system using sliding-mode control and disturbance compensation techniques. J. Sci. IEEE Trans. Power Electron., 28: 1358–1365.

Fig. 7 Simulation waveform of dynamic torque response of double-vector MPC
[8] Zhang, Y., Yang, H. (2014) Model predictive torque control of induction motor drives with optimal duty cycle control. J. Sci. IEEE Trans. Power Electron., 29: 6593–6603.
[9] Zhang, Y., Yang, H. (2014) Model predictive torque control of induction motor drives with optimal duty cycle control. J. Sci. IEEE Trans. Power Electron., 29: 6593–6603.
[10] Vafaie, M., Dehkordi, B, Moallem, P. (2016) A new predictive direct torque control method for improving both steady-state and transient-state operations of the PMSM. J. Sci. IEEE Trans. Power Electron., 31: 3738–3753.