

Research Article

A Duty Cycle-Based Model Predictive Control of Matrix Converter-Fed PMSM Using Rotating Vectors

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Abstract: To address technical challenges such as insufficient steady-state performance and common-mode voltage interference in the Matrix Converters (MC), this paper proposes a duty cycle-based Model Predictive Control (MPC) strategy that utilizes the rotating vectors of MC, which are characterized by generating zero Common-Mode Voltage (CMV). This strategy predicts the motor's operating state in real time, selects the optimal reference vector, and synthesizes a virtual vector in the same direction as the reference vector by combining two adjacent rotating vectors, whose duty cycles are then calculated based on the position of the virtual vector. Experimental results demonstrate that the proposed control strategy fully leverages the fast response advantage of MPC while effectively suppressing CMV amplitude and reducing current harmonic distortion, significantly improving the system's steady-state performance.

Keywords: Model Predictive Control (MPC), Matrix Converters (MC), rotating vector, Common-Mode Voltage (CMV)

1. Introduction

Permanent magnet motor systems powered by matrix converters offer significant advantages in power density and speed control performance and are consequently increasingly adopted in Alternating Current (AC) variable-frequency speed control systems for high-end equipment such as aerospace, rail transport, and marine propulsion [1]-[5]. As equipment and motor systems continue to increase in capacity, common-mode voltages can cause issues such as motor bearing damage and electromagnetic interference. These problems not only reduce the reliability of motor systems but, in severe cases, may even threaten the safety of the equipment. Consequently, the suppression of common-mode voltages has become a major focus, and numerous hardware and software methods have been proposed [6]-[9].

Since the rotating vector of the matrix converter inherently has zero common-mode voltage, driving the motor solely with the Matrix Converters (MC) rotating vector completely eliminates common-mode voltage without altering the hardware circuitry, making it the simplest and most efficient solution for common-mode voltage suppression. Consequently, various control and modulation strategies based on the rotating vector have been proposed by scholars in the field of electrical engineering, both domestically and internationally, including model predictive control and other control strategies. The effectiveness of these methods in eliminating common-mode voltage has been fully demonstrated [10]-[15]. Among these, model predictive control has attracted particular research attention because of its outstanding dynamic performance and inherent multiple control objectives. However, the steady-state performance of traditional

model predictive control based on rotating vectors is relatively poor, which is not fit for high-performance motor drive applications. To improve steady-state performance whilst ensuring zero common-mode voltage and good dynamic performance, a duty-cycle-based model predictive control strategy with MC rotating vectors is put forward in this paper.

2. Rotating vector of a matrix converter

The relationship between the three-phase voltages on the input side and on the output side of the matrix converter, i.e., a, b, c, and A, B, C, respectively, is shown in Equations (1) and (2):

$$\mathbf{V}_o = \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \mathbf{M}_T \mathbf{V}_i, \quad (1)$$

$$\mathbf{V}_i = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} V_{in} \cos(\theta_{Vi}) \\ V_{in} \cos\left(\theta_{Vi} - \frac{2\pi}{3}\right) \\ V_{in} \cos\left(\theta_{Vi} + \frac{2\pi}{3}\right) \end{bmatrix}. \quad (2)$$

In the equation, $\mathbf{V}_i$ and $\mathbf{V}_o$ represent the input and output voltage vectors, respectively. S_{pq} denotes the switching function of the bidirectional switch connecting phase p on the output side to phase q on the input side; $S_{pq} = 1$ indicates the switch is closed, and $S_{pq} = 0$ indicates the switch is open, where $p \in \{A, B, C\}$ and $q \in \{a, b, c\}$. V_{in} represents the magnitude of the input phase voltage, and $\mathbf{M}_T$ denotes the transfer matrix of the matrix converter. Since the input side of the MC cannot be short-circuited and the output side cannot be open-circuited, there are 27 switching combinations, corresponding to 27 voltage vectors. Among these, the six vectors whose magnitudes remain constant whilst their phase angles continuously vary are called rotating vectors, as shown in Table 1.

Table 1. Rotating vectors of 3×3 MC

State	On devices			Magnitude (V_{out})	Phase	Common-Mode Voltage (CMV) (V_{com})
+10	S_{Aa}	S_{Bb}	S_{Cc}	V_{in}	θ_{Vi}	0
-10	S_{Aa}	S_{Bc}	S_{Cb}	V_{in}	$-\theta_{Vi}$	0
+11	S_{Ab}	S_{Bc}	S_{Ca}	V_{in}	$\theta_{Vi} - 2\pi/3$	0
-11	S_{Ab}	S_{Ba}	S_{Cc}	V_{in}	$-\theta_{Vi} + 2\pi/3$	0
+12	S_{Ac}	S_{Ba}	S_{Cb}	V_{in}	$\theta_{Vi} + 2\pi/3$	0
-12	S_{Ac}	S_{Bb}	S_{Ca}	V_{in}	$-\theta_{Vi} - 2\pi/3$	0

In Table 1, V_{out} represents the magnitude of the output voltage vector, θ_{Vi} represents the phase angles of the input voltage vectors, and V_{com} represents the common-mode voltage, i.e., the average of the three-phase voltages on the output side. It is apparent that the rotating vectors generate zero V_{com} . Based on the phase angles of the rotating vectors in Table 1, it can be seen that the distribution of the six rotating vectors and the shape of the hexagon they form vary with θ_{Vi} , as shown in Figure 1.

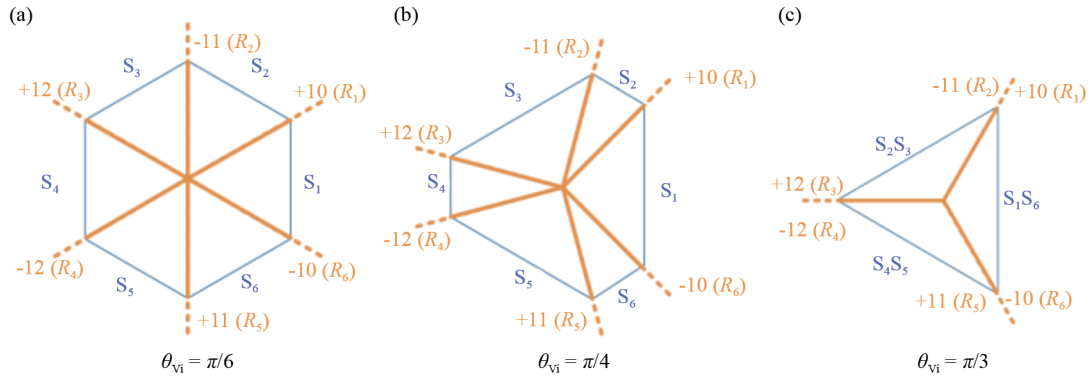


Figure 1. Rotating vector distribution diagram

When the values of θ_{vi} varies, the order of the rotating vectors in the plane varies according. For the sake of convenience in discussion and calculation, this paper rennumbers and reorders the rotating vectors. Starting with the vector closest to the positive x-axis, they are numbered in counterclockwise order as $R_1 \sim R_6$. As shown in Figure 1a, when $\theta_{vi} = \pi/6$, the rotating vectors corresponding to R_1 - R_6 are, in order, (+10), (-11), (+12), (-12), (+11), and (-10). Using the above rules, the rotating vectors corresponding to R_1 - R_6 can be determined for different ranges of θ_{vi} values, as shown in Table 2.

Table 2. Rotating vector arrangement table

θ_{vi}	$(0, \frac{\pi}{3})$	$(\frac{\pi}{3}, \frac{2\pi}{3})$	$(\frac{2\pi}{3}, \pi)$	$(\pi, \frac{4\pi}{3})$	$(\frac{4\pi}{3}, \frac{5\pi}{3})$	$(\frac{5\pi}{3}, 2\pi)$
R_1	+10	-11	+11	-12	+12	-10
R_2	-11	+10	-12	+11	-10	+12
R_3	+12	-12	+10	-10	+11	-11
R_4	-12	+12	-10	+10	-11	+11
R_5	+11	-10	+12	-11	+10	-12
R_6	-10	+11	-11	+12	-12	+10

The six vectors R_1 to R_6 divide the vector plane into six sectors, which are labelled S_1 to S_6 in anti-clockwise order, as shown in Figure 1.

3. Model predictive control of rotating vectors with duty cycles

This paper proposes a novel rotating vector-based model predictive control strategy to improve the system's steady-state performance.

3.1 Predicting model

If we establish a coordinate system with the x-axis aligned with the direction of the stator flux Ψ_s , the stator voltage equation for a permanent magnet synchronous motor is:

$$v_x = R_s i_x + d|\Psi_s|/dt,$$

$$v_y = R_s i_y + \omega_s |\Psi_s|. \quad (3)$$

In the equation, $v_s = [v_x, v_y]^T$ represents the stator voltage vector; $\Psi_s = [\Psi_x, \Psi_y]^T$ represents the stator flux vector; and $i_s = [i_x, i_y]^T$ represents the stator current vector.

The stator current for the next sampling period is predicted, using the equation:

$$\begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \begin{bmatrix} \left(1 - \frac{T_s R}{L_d}\right) i_d(k) + \frac{T_s}{L_d} u_d(k) + T_s \omega_e i_q(k) \\ \left(1 - \frac{T_s R}{L_q}\right) i_q(k) + \frac{T_s}{L_q} u_q(k) - \frac{T_s}{L_q} \omega_e \Psi_m - T_s \omega_e i_d(k) \end{bmatrix}. \quad (4)$$

In the equation, R , L_q , and L_d represent the stator resistance, the q-axis inductance, and the d-axis inductance, respectively; u_d and u_q are the d-axis and q-axis voltage, respectively; i_d and i_q are the d-axis and q-axis current, respectively; ω_e is the rotor angular velocity.

By substituting the reference value for the predicted current in Equation (4), we obtain the reference voltage vector required to make the current error in the next cycle approach zero:

$$\begin{bmatrix} u_d^*(k) \\ u_q^*(k) \end{bmatrix} = \begin{bmatrix} R i_d(k) + L_d \frac{i_d^* - i_d(k)}{T_s} - L_q \omega_e i_q(k) \\ R i_q(k) + L_q \frac{i_q^* - i_q(k)}{T_s} + L_d \omega_e i_d(k) + \omega_e \Psi_m \end{bmatrix}. \quad (5)$$

3.2 Calculation of the duty cycle of a rotating vector

Virtual vectors synthesized using rotating vectors can only lie within or on the boundary of the rotating vector hexagon. When the reference vector is located on the boundary, it can be synthesized by two rotating vectors. However, when it is located inside the hexagon, it is not possible to synthesize an exact match with only two vectors; in this case, a virtual vector located on the boundary of the hexagon which is close to the reference vector is synthesized. In this paper, the virtual vector with the same angle as the reference vector is selected. Denote the reference vector as V_s and the selected virtual vector as V_M .

First, consider the case where $\theta_{V_i} \in (0, \pi/3)$ and the reference vector V_s lies in sector S_1 , as shown in Figure 1b. Let A and B denote the endpoints of the two adjacent rotating vectors, R_1 and R_6 , such that vectors OA and OB represent R_1 and R_6 , respectively. To find the point on the boundary AB that is in line with the endpoint of vector V_s , draw a ray from the endpoint of V_s toward the line segment AB. The resulting intersection point M is the one sought, as shown in Figure 2a.

In Figure 2a, point M is on the line segment AB, which connects the endpoints of vectors OA and OB . Vector OM can be synthesized by vectors OA and OB , with their coefficients summing to 1:

$$OM = k_1 OA + k_2 OB. \quad (6)$$

Where, k_1 and k_2 are positive numbers less than 1 that satisfy $k_2 + k_1 = 1$. Thus, during one control cycle, virtual vector OM is synthesized by combining the rotating vectors OA and OB , using duty cycles k_1 and k_2 , respectively.

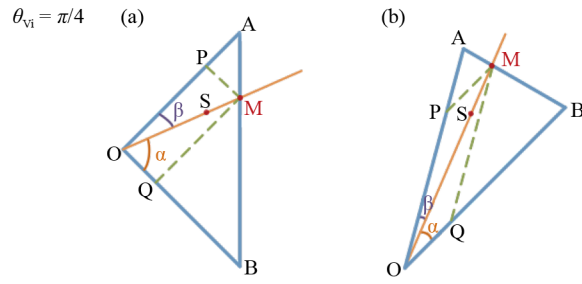


Figure 2. Virtual vector decomposition

To calculate duty cycles, decompose **OM** into lines through **OA** and **OB**. Draw lines parallel to **OB** and **OA** through **M**, intersecting **OA** and **OB** at **P** and **Q**, forming parallelogram **OPMQ**. It follows that:

$$\mathbf{OP} = k_1 \mathbf{OA},$$

$$\mathbf{OQ} = k_2 \mathbf{OB},$$

$$\mathbf{OM} = \mathbf{OP} + \mathbf{OQ}. \quad (7)$$

Using the coordinates of reference vector V_s , which can be expressed as $V_s e^{j\theta_s}$, we obtain $\alpha = \theta_s - \theta_{R_2}$ and $\beta = \theta_{R_1} - \theta_s$.

From the law of sines, we obtain:

$$\frac{OM}{\sin \alpha} = \frac{PM}{\sin \beta}. \quad (8)$$

From the similar isosceles triangles ΔPMA and ΔOBA , **PM** equals **PA**. Therefore,

$$\frac{OP}{OA} = \frac{OP}{OP + PM} = \frac{OP}{OP + \frac{\sin \beta}{\sin \alpha} QM}. \quad (9)$$

As **QM** equals **OP**, we obtain

$$k_1 = \frac{OP}{OA} = \frac{\sin \alpha}{\sin \alpha + \sin \beta},$$

$$k_2 = 1 - k_1 = \frac{\sin \beta}{\sin \alpha + \sin \beta}. \quad (10)$$

When the reference vector is located in another sector, the virtual vector in line with the reference vector, as well as the duty cycle of the rotating vector required to generate that virtual vector, can be determined in the same way. Figure

2b illustrates the situation in which the reference vector lies in sector S_2 ; in this case, **OA** and **OB** correspond to the two adjacent rotating vectors R_2 and R_1 , respectively.

3.3 Driving signals

Once the rotating vector's duty cycle has been obtained, it must be converted into driving signals for the nine bidirectional switching devices in the matrix converter. The rotating vector is selected based on the sector of V_s and the value range of θ_{V_i} . The on/off states of each switch corresponding to the selected rotating vector are then determined using Table 1. By combining this with the duty cycle of the rotating vector, the driving signal for each switch can be obtained. For example, when $\theta_{V_i} = \pi/4$ and the reference vector are located in sector S_1 , the sector boundaries **OA** and **OB** correspond to rotating vectors of $+10$ and -10 respectively. The driving signals for all switching devices are shown in Figure 3. In the figure, the duty cycles for switches S_{Bb} and S_{Cc} are both k_1 ; those for S_{Bc} and S_{Cb} are both k_2 , S_{Aa} is constantly high, and the other switches are constantly low.

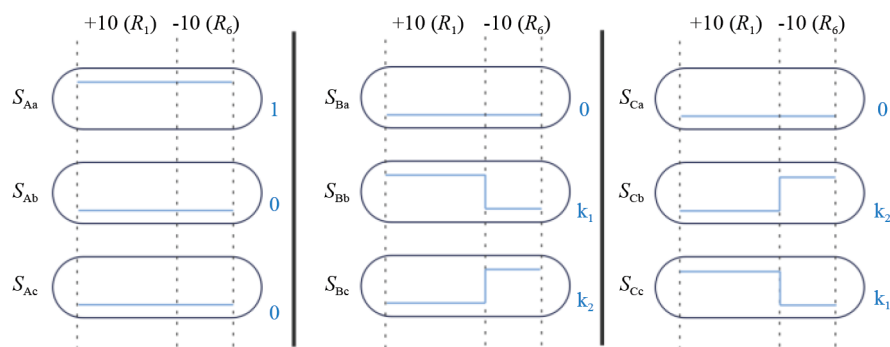


Figure 3. Driving signals of switching devices

When the value of θ_{V_i} falls within different intervals, and V_s is located in different sectors, the rotating vectors corresponding to the sector boundaries **OA** and **OB** will also change accordingly. Figure 4 shows the duty cycles of the various switches in the MC when **OA** and **OB** correspond to different rotating vectors.

Aa							Ba							Ca						
OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12
OB							OB							OB						
+10	-	1	-	k_2	-	k_2	+10	-	0	-	k_1	-	0	+10	-	0	-	0	-	k_1
-10	1	-	k_2	-	k_2	-	-10	0	-	0	-	k_1	-	-10	0	-	k_1	-	0	-
+11	-	k_1	-	0	-	0	+11	-	0	-	k_1	-	0	+11	-	k_2	-	k_2	-	1
-11	k_1	-	0	-	0	-	-11	k_2	-	k_2	-	1	-	-11	0	-	k_1	-	0	-
+12	-	k_1	-	0	-	0	+12	-	k_2	-	1	-	k_2	+12	-	0	-	0	-	k_1
-12	k_1	-	0	-	0	-	-12	0	-	0	-	k_1	-	-12	k_2	-	1	-	k_2	-

Ab							Bb							Cb						
OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12
OB							OB							OB						
+10	-	0	-	k_1	-	0	+10	-	k_2	-	k_2	-	1	+10	-	k_1	-	0	-	0
-10	0	-	k_1	-	0	-	-10	k_1	-	0	-	0	-	-10	k_2	-	k_2	-	1	-
+11	-	k_2	-	1	-	k_2	+11	-	0	-	0	-	k_1	+11	-	k_1	-	0	-	0
-11	k_2	-	1	-	k_2	-	-11	k_1	-	0	-	0	-	-11	0	-	0	-	k_1	-
+12	-	0	-	k_1	-	0	+12	-	0	-	0	-	k_1	+12	-	1	-	k_2	-	k_2
-12	0	-	k_1	-	0	-	-12	1	-	k_2	-	k_2	-	-12	0	-	0	-	k_1	-

Ac							Bc							Cc						
OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12	OA	+10	-10	+11	-11	+12	-12
OB							OB							OB						
+10	-	0	-	0	-	k_1	+10	-	k_1	-	0	-	0	+10	-	k_2	-	1	-	k_2
-10	0	-	0	-	k_1	-	-10	k_2	-	1	-	k_2	-	-10	k_1	-	0	-	0	-
+11	-	0	-	0	-	k_1	+11	-	1	-	k_2	-	k_2	+11	-	0	-	k_1	-	0
-11	0	-	0	-	k_1	-	-11	0	-	k_1	-	0	-	-11	1	-	k_2	-	k_2	-
+12	-	k_2	-	k_2	-	1	+12	-	k_1	-	0	-	0	+12	-	0	-	k_1	-	0
-12	k_2	-	k_2	-	1	-	-12	0	-	k_1	-	0	-	-12	k_1	-	0	-	0	-

Figure 4. Duty cycle of switching devices

For a switch with a duty cycle k_1 , the high level occurs earlier in a control cycle. For a switch with a duty cycle k_2 , the low level occurs earlier. Thus, for k_1 , the PWM module uses direct comparison between the modulated wave and the carrier, whereas for k_2 , it uses reversed comparison.

3.4 Overall process and discussion

The procedure for the rotating vector model predictive control described in this paper is as follows:

- Calculate the real-time phase angles of the six rotating vectors based on the phase angle of the input voltage;
- Determine the sector in which the reference voltage vector lies based on its phase angle, and identify the rotating vectors at the sector boundaries;
- Calculate the duty cycle values k_1 and k_2 using Equation (10);
- Determine the duty cycles for each switch of the MC based on the table in Figure 4;
- Generate the drive signals for each switch.

Compared with traditional Model Predictive Control (MPC) that uses only one rotating vector within each control period, the proposed duty cycle-based MPC with rotating vectors can employ a virtual vector of any phase angle within a control period, and therefore will improve the performance of the motor system, including lower current Total Harmonic Distortion (THD) and lower torque ripple.

4. Experiment verification

To verify the effectiveness of the model predictive control strategy proposed in this paper, experiments were conducted under identical conditions using both the traditional MPC with rotating vectors proposed in [13] and the proposed duty cycle-based MPC with rotating vectors in this paper. The control period of the traditional strategy is $100\ \mu\text{s}$ while the proposed one is twice, so that both strategies employ two rotating vectors within $200\ \mu\text{s}$. The controlled motor in the experiment is a Permanent Magnet Synchronous Motor (PMSM), whose parameters are shown in Table 3.

Table 3. Parameters of PMSM

Parameters	Symbol	Value
Number of pole pairs	p	4
Permanent magnet flux	Ψ_f	0.25 Wb
Stator resistance	R_s	0.65 Ω
Stator inductance	L_s	1.3 mH
Rated power	P_N	0.8 kW
Rated torque	T_N	15 N·m

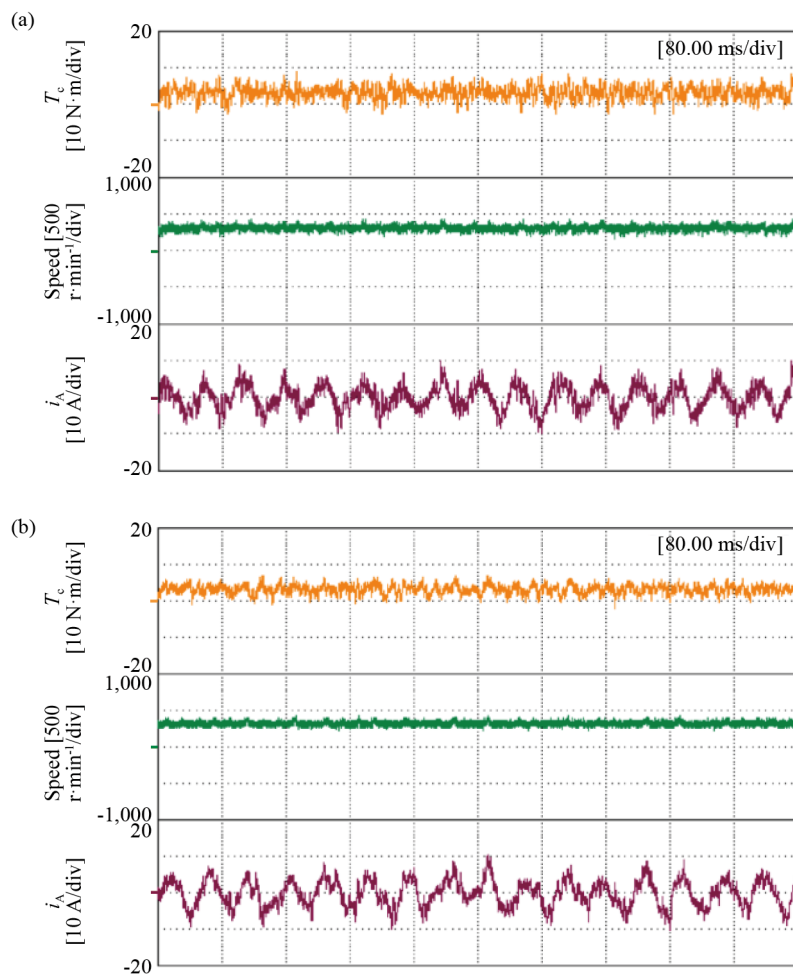
**Figure 5.** Steady state performance (a) Traditional Rotating Vector (RV)-MPC; (b) Proposed RV-MPC

Figure 5 shows the waveforms of the torque, motor speed and phase current under both the traditional and the proposed strategy at 300 r/min. The torque and current waveforms demonstrate that, compared with the traditional MPC, the proposed strategy improves the quality of torque and current waveforms, thereby improving steady-state performances. To compare their performance quantitatively, current THD and torque ripple results under both strategies are provided in Table 4. The results in Table 4 validated the superior performance of the proposed method. In addition, switching

frequency under both strategies are also provided in Table 4, and the results show that the switching frequency under the proposed MPC is close to that of the traditional one.

Table 4. Steady state performance results

RV-MPC method	Conventional	Proposed
Current THD (%)	66.25	8.2
Torque ripple (N·m)	1.82	1.38
Switching frequency (kHz)	0.73	0.76

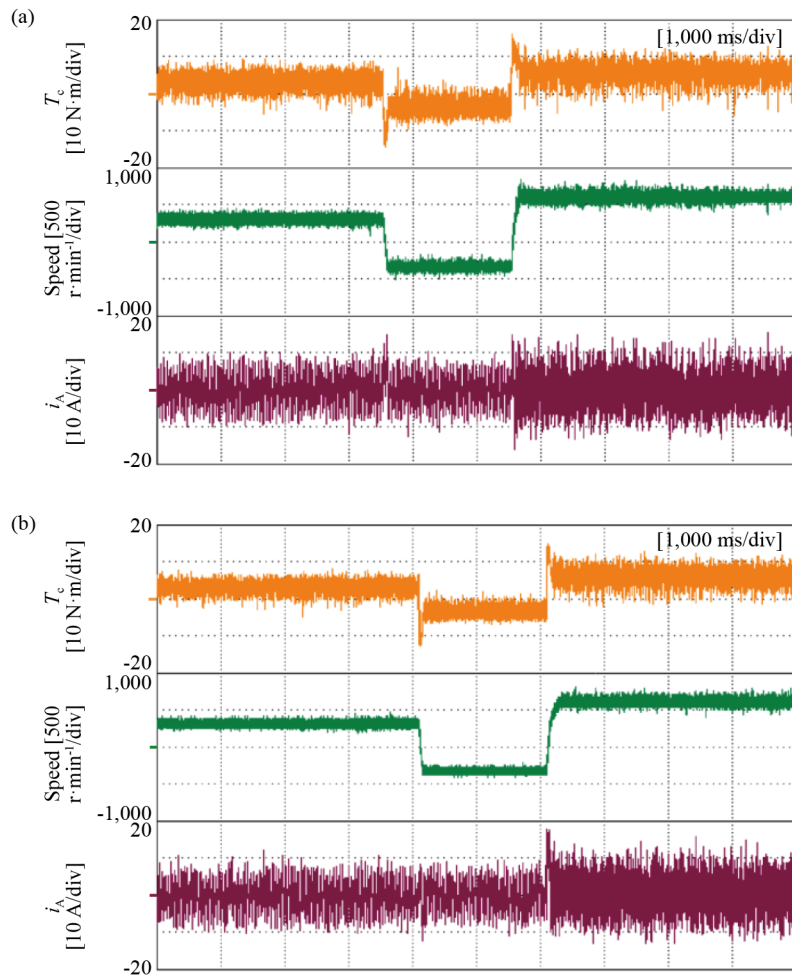


Figure 6. Dynamic performance (a) Traditional RV-DTC; (b) Proposed RV-DTC

Figure 6 presents the dynamic waveforms under both the traditional and the proposed MPC strategies. During the experiment, the motor speed steps from 300 r/min to -300 r/min firstly, and back to 600 r/min after 2 seconds. Under both control strategies, the electromagnetic torque reaches a steady-state value after a brief adjustment period, with torque fluctuations smaller under the proposed MPC. Therefore, the above dynamic response results show that the proposed MPC maintains excellent dynamic performance.

5. Conclusion

A novel rotating vector model predictive control strategy with duty cycles is proposed in this paper. The merits of this strategy include:

- (i) Zero CMV characteristic of the rotating vector is preserved;
- (ii) Steady state performance is enhanced due to the utilization of duty cycles;
- (iii) Dynamic performance of the model predictive control is preserved.

Hardware experiments validated the feasibility of the proposed MPC.

Author contributions

All authors contributed to the study conception and design. Software, F.Z.; validation, F.Z.; formal analysis, S.Z.; investigation, B.Y.; writing—original draft preparation, F.Z.; writing—review and editing, W.D. All authors have read and approved the final manuscript.

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Data availability

The data are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no competing financial interest.

References

- [1] M. A. Waghmare, B. S. Umre, M. V. Aware, A. Iqbal, and A. Kumar, “Dual stage single-phase to multiphase matrix converter for variable frequency applications,” *IEEE Transactions on Power Electronics*, vol. 38, no. 2, pp. 1372–1377, 2023. Available: <https://doi.org/10.1109/TPEL.2022.3207515>.
- [2] S. Raju and N. Mohan, “Switching optimized modulation for direct three-level matrix converter,” *IEEE Transactions on Power Electronics*, vol. 39, no. 3, pp. 3313–3328, 2024. Available: <https://doi.org/10.1109/TPEL.2023.3339480>.
- [3] C. Xia and Y. Yan, “Matrix converter–permanent magnet synchronous motor drives,” *Transactions of China Electrotechnical Society*, vol. 30, no. 23, pp. 1–9, 2015.
- [4] A. D. Arioni, T. S. Padilha, and S. V. G. Oliveira, “Expanded space vector modulation of direct matrix converters including hidden rotating pairs,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 11, pp. 8296–8307, 2019. Available: <https://doi.org/10.1109/TIE.2018.2890489>.
- [5] S. Ichiki, “New modulation method for three-phase matrix converter: mathematical theory and demonstration test results,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 4, pp. 3959–3966, 2022. Available: <https://doi.org/10.1109/TIE.2021.3075878>.

- [6] D. Jiang, Y. Xiong, K. Liu, Z. Liu, R. Wang, and K. Yang, "Common mode suppression method of current source back-to-back converter based on five-segment space vector modulation," *IEEE Transactions on Industry Applications*, vol. 59, no. 1, pp. 1035-1043, 2023. Available: <https://doi.org/10.1109/TIA.2022.3211486>.
- [7] Z. Ma, H. Niu, X. Zhang, X. Wu, and X. Cai, "Virtual space vector overmodulation strategy for NPC three-level inverters with common-mode voltage suppression," *IEEE Transactions on Power Electronics*, vol. 39, no. 6, pp. 6877-6888, 2024. Available: <https://doi.org/10.1109/TPEL.2024.3375348>.
- [8] Z. Gong, P. Dai, J. Li, D. Su, and X. Su, "Topology and modulation for a new indirect matrix converter to reduce the common-mode voltage," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 7, pp. 6518-6529, 2023. Available: <https://doi.org/10.1109/TIE.2022.3203745>.
- [9] M. Su, G. Zhang, Y. Sun, H. Dan, and X. Li, "Improved space vector modulation to reduce the common mode voltage for indirect matrix converters," *Proceedings of the CSEE*, vol. 34, no. 24, pp. 4015-4021, 2014.
- [10] H.-N. Nguyen and H.-N. Lee, "An enhanced SVM method to drive matrix converters for zero common-mode voltage," *IEEE Transactions on Power Electronic*, vol. 30, no. 4, pp. 1788-1792, 2015. Available: <https://doi.org/10.1109/TPEL.2014.2348019>.
- [11] J. Lei, S. Feng, B. Zhou, H.-N. Nguyen, J. Zhao, and W. Chen, "A simple modulation scheme with zero common-mode voltage and improved efficiency for direct matrix converter-fed PMSM drives," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 3712-3722, 2020. Available: <https://doi.org/10.1109/JESTPE.2019.2934730>.
- [12] T. N. Mir, B. Singh, and A. H. Bhat, "Delta-sigma modulation based common-mode voltage elimination in direct matrix converter," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 2, pp. 1048-1057, 2021. Available: <https://doi.org/10.1109/TII.2020.2987918>.
- [13] L. Wang, H. Dan, Y. Zhao, Q. Zhu, T. Peng, Y. Sun, et al., "A finite control set model predictive control method for matrix converter with zero common-mode voltage," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 1, pp. 327-338, 2018. Available: <https://doi.org/10.1109/JESTPE.2017.2727501>.
- [14] W. Deng, J. Tang, and W. Cheng, "An enhanced rotating vector-based direct torque control for matrix converter-fed PMSM drives using virtual pulsating vectors," *CPSS Transactions on Power Electronics and Applications*, vol. 8, no. 1, pp. 65-73, 2023. Available: <https://doi.org/10.24295/CPSSTPEA.2023.00007>.
- [15] G. Zhang, J. Yang, Y. Sun, M. Su, Q. Zhu, and F. Blaabjerg, "A predictive-control-based over-modulation method for conventional matrix converters," *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 3631-3643, 2018. Available: <https://doi.org/10.1109/TPEL.2017.2710909>.