

A Deadbeat Current Control Method for Switched Reluctance Motor

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Abstract—Aiming at high torque ripple of switched reluctance motor (SRM) caused by hysteresis tolerance control, this study proposes a new deadbeat current control based on an SRM rotation coordinate system. The command current is easily calculated on account of the nonlinear deadbeat current controller. For the voltage control, the redefined voltage vectors and space voltage module are discussed to reduce the switching states. Experimental results exhibit that the proposed method can reduce the SRM torque ripple compared with direct torque control and direct instantaneous torque control. In addition, all the results are carried out on a three-phase 12/8-poles SRM.

1. INTRODUCTION

Deadbeat control is a current vector control promised to be a mature prediction control method in traditional motors [1, 2], such as permanent magnet synchronous motor and induction motor. It has the advantages of constant switching frequency, high control accuracy, and good dynamic performance. However, it suffers from the indispensable rotation coordinate system which limits the application in switched reluctance motor (SRM). As a reluctance motor, SRM is applied in many automatic productions, with advantages of a simple structure and strong fault tolerance [3, 4]. SRM torque generation depends on the principle of “minimum magnetoresistance”. Therefore, SRM has unique characteristics, such as severe nonlinearity, high saturation, and lack of rotor flux. These characteristics result in that torque ripple of SRM is high, and it is unable to build a rotation coordinate system.

In recent years, some researches have been undertaken in terms of the rotating frame for SRM. Ref. [5] proposed a SRM rotation coordinate system regarding the DC current of an SRM circuit as virtual “rotor flux”. Ref. [6] proposed the unipolar sinusoidal excited SRM control based on voltage space vector in a d - q coordinate system, improving the operation performance and decreasing the torque ripple of SRM. Ref. [7] discussed the speed sensorless vector control in rotation coordinate system for SRM.

For torque ripple in SRM, direct torque control (DTC) regards torque as direct control variable. The hysteresis control of torque and flux is adopted to overcome high torque ripple, serious noise in DTC [8]. For better torque control, the flux hysteresis loop is abandoned, and the torque hysteresis rules and sector rules are changed in direct instantaneous torque control (DITC) [9]. However, hysteresis control belongs to the bang-bang control, and the switching frequency is unconstant adopting the bang-bang control. The smaller hysteresis width and shorter sampling time can reduce torque ripple accurately, while the corresponding switching frequency is higher. This situation leads to serious losses of experimental platform and switching devices.

Therefore, on the basis of no additional switching devices, a new deadbeat predictive current control is proposed in this letter. The proposed control is adopted to replace hysteresis loops, achieve constant switching frequency, and reduce torque ripple compared with hysteresis control. Moreover,

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the nonlinear function is adopted to well conform SRM electromagnetic characteristics. According to the virtual “rotor flux” theory, an SRM rotating frame is established. Through current controller, the command current can be acquired corresponding to the command torque. And the basic voltage vectors are redefined compared with DTC in order to reduce the frequency of switching states. In addition, the fixed switching frequency of SRM is also analyzed in this letter. In order to access the performance of proposed method and hysteresis control methods, the comparison of torque ripple is tested on a three-phase 12/8-poles SRM.

2. THEORETICAL FRAMEWORK

The torque generation equations of SRM in rotation coordinate system [7] can be expressed as:

$$\begin{cases} \psi_d = \psi_r + \psi_{sd} = \frac{L_{ac}}{\sqrt{2}}i_0 + L_{dc}i_d \\ \psi_q = \psi_{sq} = L_{dc}i_q \end{cases} \quad (1)$$

$$T_e = 2N_r(\psi_d i_q - \psi_q i_d) = \sqrt{2}N_r L_{ac} i_0 i_q \quad (2)$$

where i_d , i_q , i_0 are corresponding to the d -axis, q -axis, and 0-axis current; L_{dc} , L_{ac} are the DC and AC components. Moreover, T_e , N_r are corresponding to the electromagnetic torque and pole-pairs number, respectively. Considering the nonlinear electromagnetic characteristic of SRM, the flux characteristic curves obtained by locked-rotor test are shown in Fig. 1(a), and the simplified flux model is shown in Fig. 1(b).

$$\psi(\theta, i) = i \times L(\theta, i) = i \times [L_{dc}(i) + L_{ac}(i) \cos(N_r \theta + \varphi_n)] \quad (3)$$

where θ and φ_n are corresponding to the electric angle and initial phase of each series. In Eq. (3), L_{dc} , L_{ac} can be represented as:

$$L_{dc}(i) = \frac{L_{\max}(i) + L_{\min}(i)}{2} \quad L_{ac}(i) = \frac{L_{\max}(i) - L_{\min}(i)}{2} \quad (4)$$

$L_{\min}$ is the inductance at unaligned position, which is a constant value.

$$\begin{cases} L_{\max}(i) = \sum_{n=1}^k a_n i^{n-1} \\ L_{\min}(i) = \text{constant value} \end{cases} \quad (5)$$

The nonlinear characteristics can be simplified clearly by Eq. (5). Considering the nonlinear electromagnetic characteristics can achieve accurate torque control in SRM. In torque generation of

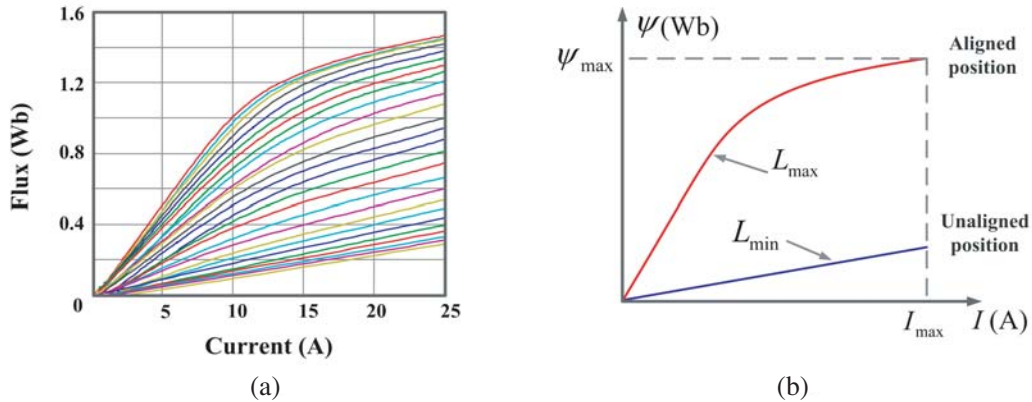


Figure 1. Flux characteristic curves and the simplified flux model.

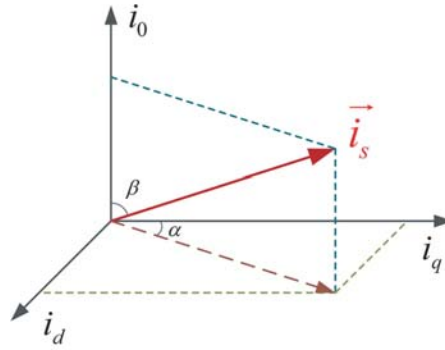


Figure 2. Current diagram in rotation coordinate system.

Eq. (2), the torque is only affected by i_0 and i_q . Besides, i_d has no effect on torque generation, where i_d is zero [6]. The current diagram in rotation coordinate system is shown in Fig. 2.

$$\begin{cases} i_d = I_s \sin \beta \sin \alpha & i_q = I_s \sin \beta \cos \alpha & i_0 = I_s \cos \beta \\ I_s = \sqrt{i_d^2 + i_q^2 + i_0^2} \end{cases} \quad (6)$$

Considering $i_d = 0$, torque expression (2) can be redefined as:

$$T_e = \sqrt{2} N_r L_{ac} i_0 i_q = \sqrt{2} N_r L_{ac} I_s^2 \sin \beta \cos \beta \quad (7)$$

In order to acquire efficiency and reduce losses, the theory of TPA is considered, as lower value of TPA results in higher loss of SRM under the same torque condition. When β is 45 degrees, the value of TPA is maximum. Due to short sampling time, SRM is a discrete system. Therefore, the command current value can be expressed by the torque variation as Eq. (8).

$$\begin{cases} i_q^*(k) = i_0^*(k) & i_d^*(k) = 0 \\ T_e^*(k) - T_e(k) = \sqrt{2} N_r L_{ac} i_0^*(k) i_q^*(k) \end{cases} \quad (8)$$

The control block diagram of proposed method is shown in Fig. 3. The voltage function based on Kirchhoff's law can be expressed as:

$$\vec{u}_s = R \vec{i}_s + \frac{d\psi(\theta, i)}{dt} \quad (9)$$

In one sampling period, the current controller outputs the command current based on the proposed scheme. In the next period, the current can be set to the value of command current, which is known

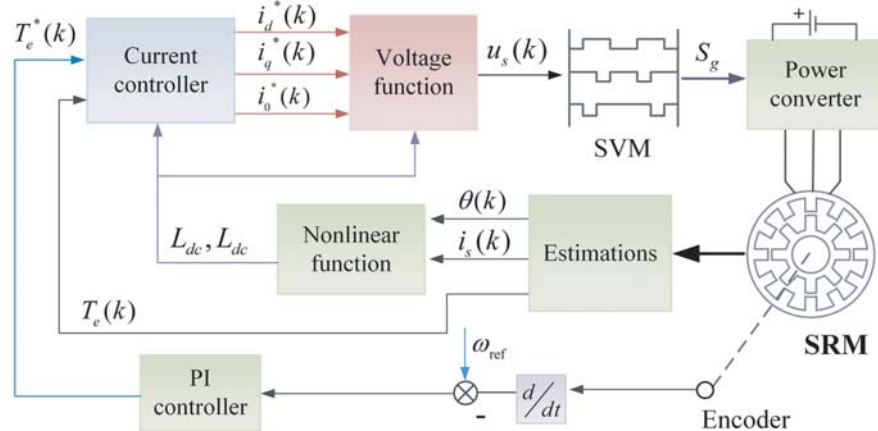


Figure 3. Control block diagram of the proposed method.

as deadbeat performance. Through the voltage function and space vector modulation (SVM), voltage vectors corresponding to command torque can be applied to SRM.

Adopting the proposed method, the hysteresis loops are replaced by the deadbeat theory, and the bang-bang tolerance issue can be solved. Based on current controller, the relation between command torque and command current is obtained to achieve precise torque control. Additionally, SVM is applied to fix switching frequency in this method.

3. FIXED SWITCHING FREQUENCY

The power converter of SRM adopts a three-phase asymmetric half bridge structure, and there are three switching states, turn-on state ($S_g = 1$), freewheeling state ($S_g = 0$), and turn-off state ($S_g = -1$). Different combinations of the three-phase switching states can be described as a voltage vector $S = [S_1, S_2, S_3]$. Based on the process of SVM by traditional voltage vectors, three switching states are required at the step of inserting zero voltage vectors. As for the basic voltage vectors, they are redefined compared with DTC as shown in Fig. 4. Based on redefined voltage vectors, only two switching states change in every switching instant. In this way, the switching frequency is fixed, and the loss of switching devices is also reduced through SVM.

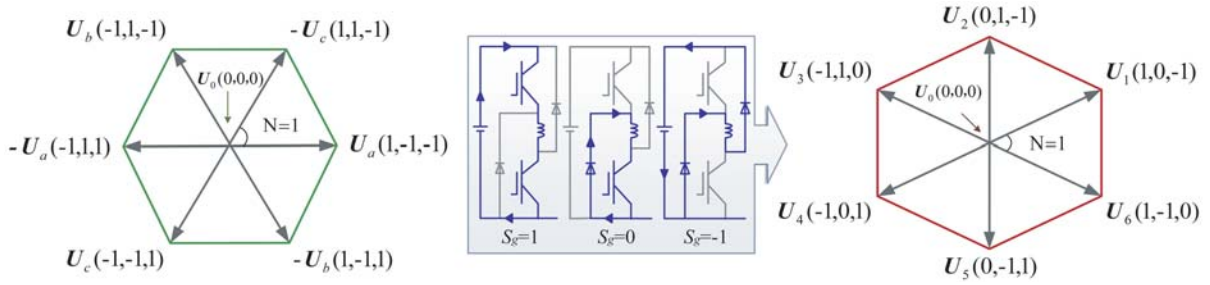


Figure 4. Redefined voltage vectors in space voltage modulation.

4. RESULTS ANALYSIS

SRM structure parameters are listed in Table 1. Line charts of torque ripple coefficient and torque per ampere based on the experimental results are shown in Fig. 5. According to the line charts, the torque ripple is higher based on torque hysteresis control, especially in high speeding region. The proposed

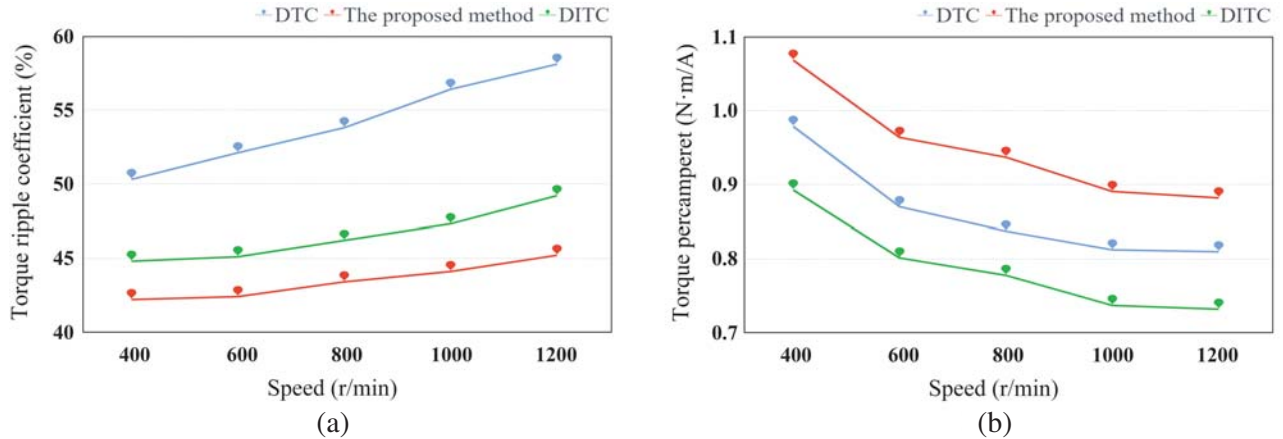
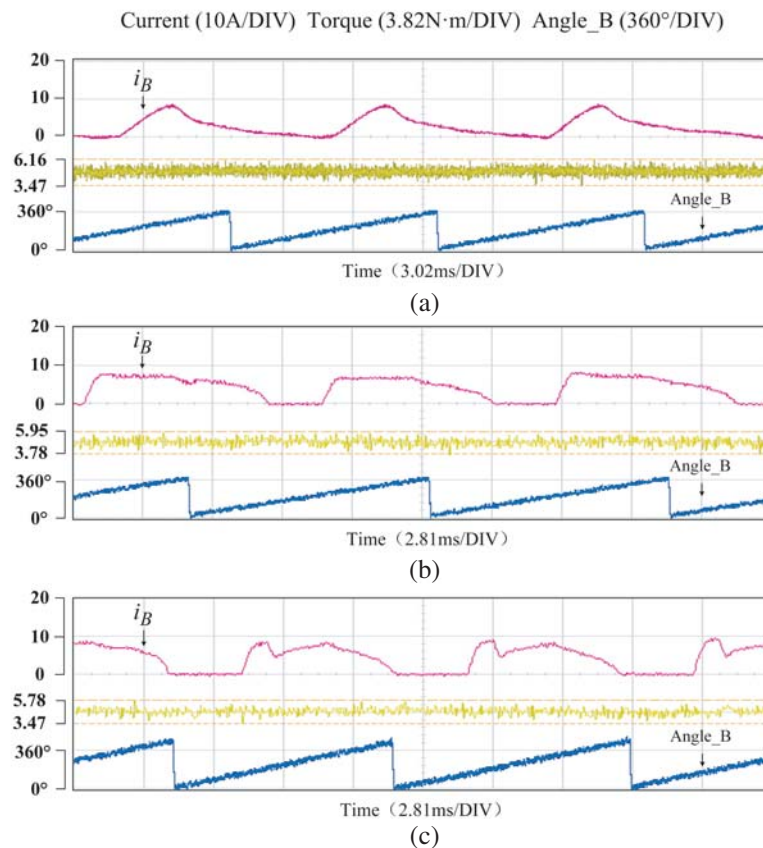


Figure 5. $T_L = 5 \text{ N}\cdot\text{m}$. (a) Torque ripple coefficient. (b) Torque per ampere.

Table 1. SRM structure parameters.

Parameter	Value
Stator resistance	$0.6\ \Omega$
Stator/rotor poles	12/8
Rated current	31 A
Rated speed range	1500 rpm
Outer diameter of the stator	258 mm
Outer diameter of the rotor	159 mm
Inner diameter of the stator	160 mm
Inner diameter of the rotor	83 mm
Stator slot depth	27 mm
Rotor slot depth	23 mm
Aligned inductance	104.3 mH
Unaligned inductance	11.44 mH

**Figure 6.** $\omega = 800\text{ r/min}$, $T_L = 5\text{ N}\cdot\text{m}$. (a) DTC. (b) The proposed method. (c) DITC.

method shows a better performance in the aspect of torque ripple coefficient and torque per ampere compared with DTC and DITC. In addition, Fig. 6 shows the experimental waveforms in detail, and the results are similar to that in Fig. 5. The position signal represents the electrical angle of the phase B in Fig. 6.

5. CONCLUSION

In this letter, a deadbeat current control method is proposed based on a rotation coordinate system for SRM. Aiming to reduce torque ripple and fix the system switching frequency, the hysteresis loops are replaced by deadbeat algorithm. According to nonlinear deadbeat current controller, high torque ripple caused by hysteresis tolerance can be optimized. In order to reduce the loss of switching devices, the basic voltage vectors are redefined compared with DTC, and the switching states in SVM process are also analysed. Additionally, the new strategy is verified on a three-phase 12/8-poles SRM. The proposed method shows better results in terms of lower torque ripple than DTC and DITC.

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REFERENCES

1. Wang, Y., S. Tobayashi, and R. D. Lorenz, "A low-switching-frequency flux observer and torque model of deadbeat-direct torque and flux control on induction machine drives," *IEEE Trans. Ind. Appl.*, Vol. 51, No. 3, 2255–2267, 2015.
2. Dastjerdi, R. S., M. A. Abbasian, H. Saghaei, and M. H. Vafaie, "Performance improvement of permanent-magnet synchronous motor using a new deadbeat-direct current controller," *IEEE Trans. on Power Electron.*, Vol. 34, No. 4, 3530–3543, 2019.
3. Bostanci, E., M. Moallem, A. Parsapour, and B. Fahimi, "Opportunities and challenges of switched reluctance motor drives for electric propulsion: A comparative study," *IEEE Trans. Transport. Electrification*, Vol. 3, No. 1, 58–75, 2017.
4. Chiba, A., K. Kiyota, N. Hoshi, M. Takemoto, and S. Ogasawara, "Development of a rare-earth-free SR motor with high torque density for hybrid vehicles," *IEEE Trans. Energy Conversion*, Vol. 30, No. 1, 175–182, 2015.
5. Nakao, N. and K. Akatsu, "Vector control specialized for switched reluctance motor drives," *2014 Int. Conf. on Elect. Mach.*, 943–949, 2014.
6. Kuai, S., H. Zhang, X. Xia, and K. Li, "Unipolar sinusoidal excited switched reluctance motor control based on voltage space vector," *IET Electric Power Appl.*, Vol. 13, No. 5, 670–675, 2019.
7. Khan, Y. A. and V. Verma, "Novel speed estimation technique for vector-controlled switched reluctance motor drive," *IET Electric Power Appl.*, Vol. 13, No. 8, 1193–1203, 2019.
8. Shinohara, A., Y. Inoue, S. Morimoto, and M. Sanada, "Maximum torque per ampere control in stator flux linkage synchronous frame for DTC-based PMSM drives without using q -axis inductance," *IEEE Trans. Ind. Appl.*, Vol. 53, No. 4, 3663–3671, 2017.
9. Inderka, R. B. and R. W. A. A. De Doncker, "DITC-direct instantaneous torque control of switched reluctance drives," *IEEE Trans. Ind. Appl.*, Vol. 39, No. 4, 1046–1051, 2003.