A torque control strategy for a two-phase switched reluctance motor based on dynamic ranking of voltage vectors

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Abstract. Switched reluctance motor (SRM) suffers from high torque ripple which limits its application in many areas. In order to improve the control performances of SRM, a novel torque control strategy based on dynamic ranking of voltage vectors is developed in the paper. Multiple voltage vectors are selected as candidates at any control instant to enhance the control flexibility, and they are evaluated by a ranking process to determine their suitability to be finally applied to the power converter. The ranking evolves dynamically based on the prediction of motor output torque change rate, phase torque change rate, current change rate, and flux vector change at the next control instant. Several control rules are developed and finally the scheme is applied to a two-phase SRM. The control performances are analysed in the simulation which shows the validity of the proposed scheme.

1. Introduction
Switched reluctance motor (SRM) has some prominent merits such as structural simplicity, easy manufacturability and fault tolerance capability that make it suitable in many applications [1-2]. However, due to the salient structure and high nonlinearity, torque ripple is high when applying conventional control strategies. Various control scheme has been developed for SRM to solve this issue, such as current profiling [3] and torque sharing function [4].

Direct torque control (DTC) for SRM using conventional asymmetric half bridge converter is first developed in [5] with the inherent nature of torque ripple reduction. And similar to the ac motor drives, it uses a switching table to pick out appropriate voltage vector based on torque error and flux error. DTC scheme for SRM with three phases and higher number of phases has been reported in [6-8]. However, it has not yet been applied to a two-phase SRM in published papers. One of the possible difficulties is that the number of available voltage vectors of a two-phase asymmetric half bridge converter are much fewer than that for the SRM with higher number of phases. The topology of this power converter is shown in figure 1, and there are 3 possible operations for each phase in figure 2. There are only 32 possible operating states of this converter, which correspond to 9 voltage vectors, whereas the available number for three-phase and four-phase converter is 33 and 34, respectively, which implies the limitation while developing DTC for a two-phase SRM. Therefore, the control flexibility is significantly reduced, and it is more difficult to fabricate an appropriate switching table. Besides, the traditional DTC scheme lacks the available formulas of torque control.
Unlike the motor with three or higher phases, the rotor structure of a two-phase SRM needs to take the form of stepped air gap to achieve self-starting ability and eliminate the torque dead zone [9]. The parameters of the motor are shown in table 1, and the flux linkage characteristics are shown in figure 3.

To overcome the shortcoming of DTC for the two-phase SRM, a novel torque control scheme is proposed in this paper. The detailed control strategy is developed in section 2, and multiple ranking rules of voltage vectors are explained. In section 3, the proposed scheme is simulated in commercial software MATLAB/Simulink, and some conclusions are drawn in section 4.

**Table 1.** Parameters of the two-phase 8/4 SRM.

| Parameter          | Value | Unit |
|--------------------|-------|------|
| DC-link voltage    | 310   | V    |
| Power              | 750   | W    |
| Rated torque       | 1.3   | Nm   |
| Rated speed        | 5500  | rpm  |
| Resistance         | 0.726 | Ohm  |
| Unaligned inductance| 7.84  | mH   |
| Aligned inductance | 41.8  | mH   |

**Figure 1.** Two-phase asymmetric half-bridge converter.  
**Figure 2.** Possible operations in each phase of an asymmetric half-bridge converter.

**Figure 3.** Flux linkage characteristics of the two-phase 8/4 SRM.

2. **Principles of the proposed torque control scheme**

The proposed control scheme is illustrated in figure 4. Instead of using a fixed switching table with limited flexibility in the traditional DTC to determine one candidate voltage vector, the proposed control scheme is highlighted with a dynamic ranking process, where multiple voltage vector will be as the candidates. At each control instant, the voltage vectors are evaluated via the ranking rules based on the real time operating conditions of the motor, hence the ranking is a dynamic sequence, and the position of voltage vectors in the ranking represents their suitability to be finally applied.

The structure of the proposed control scheme might seem similar to the conventional one at first sight because of the closed-loop control for torque and flux, the fundamental ideas of them are quite different, however. The amplitude of the flux vector is strictly maintained, and derivation of torque control does not have a solid foundation in the conventional scheme, whereas in the proposed scheme, the information of the torque change rate at the next control instant is made use of to properly control the torque, and flux control has little importance.
2.1. Ranking rule 1: Total torque change rate

The most direct approach to control the torque is to make the upcoming change of torque to have the correct polarity, in other words, the increase or decrease of the torque requires the positive or negative torque change rate, respectively.

For a switched reluctance motor, the phase torque can be expressed as the function of current and rotor position in (1).

\[ T = T(i, \theta) \]  

The change rate of phase torque can be derived as

\[ \frac{dT}{dt} = \frac{\partial T(i, \theta)}{\partial i} \frac{di}{dt} + \frac{\partial T(i, \theta)}{\partial \theta} \frac{d\theta}{dt} \]  

(2)

Voltage equation for one phase is show in (3), and the derivative of flux linkage is derived in (4).

\[ u = Ri + \frac{d\psi(i, \theta)}{d\theta} \]  

(3)

\[ \frac{d\psi(i, \theta)}{dt} = \frac{\partial \psi(i, \theta)}{\partial i} \frac{di}{dt} + \frac{\partial \psi(i, \theta)}{\partial \theta} \frac{d\theta}{dt} \]  

(4)

The current change rate is extracted from (4) as

\[ \frac{di}{dt} = \left( \frac{\partial \psi(i, \theta)}{\partial i} \right)^{-1} \left( u - Ri - \frac{\partial \psi(i, \theta)}{\partial \theta} \frac{d\theta}{dt} \right) \]  

(5)

Therefore, the change rate of phase torque can be rewritten as

\[ \frac{dT(i, \theta)}{dt} = \frac{\partial T(i, \theta)}{\partial i} \left( \frac{\partial \psi(i, \theta)}{\partial i} \right)^{-1} \left( u - Ri - \frac{\partial \psi(i, \theta)}{\partial \theta} \frac{d\theta}{dt} \right) + \frac{\partial T(i, \theta)}{\partial \theta} \frac{d\theta}{dt} \]  

(6)

And the output torque change rate is the sum of each phase.

\[ \frac{dT_{\text{sum}}}{dt} = \frac{dT_A}{dt} + \frac{dT_B}{dt} \]  

(7)

Equations (6) and (7) indicate that the output torque change rate can be explicitly expressed as a function of voltage vector, and each voltage vector will correspond to a specific value of torque change rate.
The partial derivatives in (6) can be replaced by difference quotients calculated from discrete data in \( i(\psi, \theta) \) look-up table and \( T(i, \theta) \) look-up table used in SRM model, which are shown in (8-11).

\[
\begin{align*}
\frac{\partial T(i_0, \theta_0)}{\partial i} &= \frac{\Delta T}{\Delta i} [T(i_0 + \Delta i, \theta_0) - T(i_0, \theta_0)] \\
\frac{\partial T(i_0, \theta_0)}{\partial \theta} &= \frac{\Delta T}{\Delta \theta} [T(i_0, \theta_0 + \Delta \theta) - T(i_0, \theta_0)] \\
\frac{\partial \psi(i_0, \theta_0)}{\partial i} &= \frac{\Delta \psi}{\Delta i} [\psi(i_0 + \Delta i, \theta_0) - \psi(i_0, \theta_0)] \\
\frac{\partial \psi(i_0, \theta_0)}{\partial \theta} &= \frac{\Delta \psi}{\Delta \theta} [\psi(i_0, \theta_0 + \Delta \theta) - \psi(i_0, \theta_0)]
\end{align*}
\] (8)

(9)

(10)

(11)

In order to correctly control the torque, multiple voltage vectors with correct torque change rate would meet the requirements. Despite of the enhanced control flexibility brought about by the multiple voltage vector candidates to be chosen from, new question emerges of how to decide the final candidate that will be applied.

A simple way here is to sort the voltage vectors by their corresponding torque change rate either from small to large or conversely. There is a greater opportunity for the ones in the front of the sequence to be selected. Simply put, the voltage vectors with correct polarity of torque change rate will rank ahead of those with wrong polarity. This rule exhibits the key concept of a hysteresis torque controller, and has relatively higher priority compared with other rules.

The torque control is supposed to be correct if the correct torque change rate is assigned. However, the actual situation is rather complicated if there is only one closed-loop control for motor output torque and no other supplementary techniques and restrictions. In the following sections, multiple auxiliary rules are developed.

2.2. Ranking rule 2: Rotating reference frame

The amplitude of flux vector is necessary to be restricted within certain range to keep a stable operation of the motor. By using the direction of flux vector as the reference direction of the space plane, two sectors can be defined in figure 5. All the voltage vectors defined in figure 6 fall into these two sectors, and by applying the voltage vectors in sector I will increase the amplitude of flux vector while the ones in sector II have the opposite effect.

![Figure 5. Rotating reference frame. Two sectors can be defined, in which the voltage vectors can have different effects on flux vector.](image)

![Figure 6. Voltage vectors of the two-phase asymmetric half-bridge converter.](image)

Similar to the ranking rule in section 2.1, the voltage vectors can be ranked by the sectors. The rule is that based on the difference between reference flux vector and actual flux vector, the voltage vectors in the appropriate sector will be put in the front of the ranking, which means there is higher opportunity to control the flux correctly.

The flux vector and the output torque are both the composition of its phase component. Since the phase torque has nonlinear relationship with the phase flux linkage, the relationship between total torque and flux vector is extremely complex and dynamic. Therefore, there is not a clear guideline of
how to keep the value of flux amplitude. The rule for flux control is relatively nonsignificant and is subject to other rules.

2.3. Ranking rule 3: To reduce negative phase torque
The total motor torque is the sum of each phase torque, negative phase torque does not contribute to the motor output, yet it has the negative impact which will further reduce the motor efficiency. For conventional control strategies such as current chopping control, the information of rotor position is utilized, and the phase is not excited in the negative inductance slope region. If the current dynamic is included in the calculation of turn off angle, negative phase torque can be fully eliminated. In the proposed control strategy, the rotor position is only used in the calculation of the necessary motor variables such as torque change rate and current change rate, rather than exciting the phase according to rotor position. Therefore, negative phase torque is inevitable. On the other hand, if the negative phase torque is regarded as the compensation for the too high positive torque of the other phase, it can be used to maintain a constant output torque. For a two-phase motor, if the phase is fully turned off in the negative torque region, there will be only one phase contribute to the total torque, and the other phase have no effect on torque production, which limits the control flexibility. Another reason to limit the amplitude of negative phase torque is that under some circumstances it keeps increasing and finally cause the motor operation to be unstable in the proposed control scheme.

When the amplitude of negative torque of any phase exceed the pre-set limit, corresponding phase torque change rate of each voltage vector will be predicted by (6), the ones with negative sign will be assigned low priority, i.e. they are moved to the end of the ranking.

2.4. Ranking rule 4: To limit maximum current
Since there is not a current controller for the proposed control strategy, over current might happen and exceed the tolerance of the motor winding and the power converter to damage the motor drive system, where actions should be taken to prevent the further increase of the current. It is necessary to predict the corresponding current change rate of each candidate vector in order to know if the phase current will further increase at the next control instant.

This rule has the highest priority, any candidate which increases the phase current further over the pre-set limit will be immediately removed from the ranking, even though it will reduce the control flexibility. The current change rate is predicted by (5).

2.5. Ranking rule 5: To prevent uncertain voltage
Generally, for a SRM using asymmetric converter, there are 3 certain states of the phase voltage, i.e. positive voltage, zero voltage and negative voltage. The amplitude of the phase voltage is assumed to be equal to the DC-link voltage or zero if voltage drops on the switches and diodes are neglected. However, during demagnetizing, the phase voltage will drop dramatically if the current is very small because the diodes tend to be turned off, and the value will be far different from the DC-link voltage. As stated above, the calculation of motor output torque change rate, phase torque change rate, flux change and current change rate are all based on the accurate phase voltage, and they are not reliable with an uncertain argument. This situation can be avoided by making a ranking rule which assign low priority to the candidate vectors that invoke uncertain voltage.

3. Simulation results and discussions
In order to verify the validity and performances of the proposed torque control strategy, simulation model is built in MATLAB/Simulink. Figure 7 shows the torque characteristics, it can be seen that there are multiple levels of hysteresis band to restrict the torque error. Reference torque is obtained from the speed PI controller. The maximum torque error is around 0.4 Nm. In figure 8, current wave forms of each phase are shown, the pre-set current limitation is 10A. Inductance tendency is plotted here only to show the positive and negative inductance slope region, corresponding to the rising edge and falling edge. In the simulation, the pre-set negative torque limit is 0Nm. Negative phase torque
can be observed here because the ranking rule for phase torque does not have the highest priority. However, the negative phase torque is compensated by the positive peak torque produced by the incoming phase. The motor runs at 1000 rpm in figure 7 and 8.

![Figure 7](image1.png) ![Figure 8](image2.png)

**Figure 7.** (a) Reference torque. (b) Motor output torque. (c) Torque error.

**Figure 8.** (a) Phase current. (b) Phase torque. (c) Inductance tendency.

The influence of the variation of the reference flux to the torque control performance is shown in figure 9 and 10. It can be seen that the amplitude is not strictly kept and varies greatly, which indicates that flux control has a very low priority. The waveforms of amplitude of flux vector and output torque nearly remain the same in the two conditions, despite the large variation of reference from 0.02Wb to 0.2Wb, therefore, the proposed control strategy is not sensitive to the reference flux.

![Figure 9](image3.png) ![Figure 10](image4.png)

**Figure 9.** (a) Waveform of the flux vector amplitude with the reference at 0.02Wb. (b) Waveform of the flux vector amplitude with the reference at 0.2Wb.

**Figure 10.** (a) Output torque with the reference flux vector amplitude set to 0.02Wb. (b) Output torque with the reference flux vector amplitude set to 0.2Wb.

Figure 11 and 12 show how the variation of pre-set maximum current limit will affect the control performance. As can be seen that the torque error does not change much when the current limit varies,
therefore, lower limit can be selected to reduce the copper loss and increase the efficiency. It should be noted that to limit the current will also limit the flexibility due to the reduction of available vectors.

![Image](image1.png)

**Figure 11.** (a) Phase current with the current limit set to 10A. (b) Phase current with the current limit set to 15A. (c) Phase current with the current limit set to 20A.

![Image](image2.png)

**Figure 12.** (a) Torque error with the current limit set to 10A. (b) Torque error with the current limit set to 15A. (c) Torque error with the current limit set to 20A.

4. Conclusions
In this paper, a novel torque control strategy using dynamic ranking rules of voltage vectors is proposed for a two-phase SRM, and it can be easily extended to SRM with higher phase numbers by increasing the number of voltage vector candidates. Control flexibility is increased in the proposed scheme by using multiple voltage candidates rather than a fixed switching table in conventional DTC. The information of motor output torque change rate, phase torque change rate, current change rate, angle of flux vector and uncertain voltage is used to determine the priority of each voltage vectors. Simulation results show that the torque control performances are acceptable at relatively low speed, and related to multiple control parameters. Due to the abundant controllable parameters, the performances of the proposed scheme can be further improved by evaluating their influences.

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References
[1] Öksüztepe E 2017 In-wheel switched reluctance motor design for electric vehicles by using a pareto-based multiobjective differential evolution algorithm *IEEE Trans. Veh. Technol.* 66 4706-15
[2] Powell D J, Jewell G W, Calverley S D and Howe D 2005 Iron loss in a modular rotor switched reluctance machine for the "More-Electric" aero-engine *IEEE Trans. Magn.* 41 3934-6
[3] Shaked N T and Rabinovici R 2005 New procedures for minimizing the torque ripple in switched reluctance motors by optimizing the phase-current profile IEEE Trans. Magn. 41 1184-92

[4] Xue X D, Cheng K W E and Ho S L 2009 Optimization and evaluation of torque-sharing functions for torque ripple minimization in switched reluctance motor drives IEEE Trans. Power Electron. 24 2076-90

[5] Cheok A D and Fukuda Y 2002 A new torque and flux control method for switched reluctance motor drives IEEE Trans. Power Electron. 17 543-57

[6] Sau S, Vandana R and Fernandes B G 2013 A new direct torque control method for switched reluctance motor with high torque/ampere 39th Annual Conf. of the IEEE Industrial Electronics Society Vienna 2518-23

[7] Ye M, Jiao S J and Yi X G 2010 Direct torque control for four phase switched reluctance motor, Int. Conf. on Computer, Mechatronics, Control and Electronic Engineering Changchun 531-4

[8] Feyzi M R, Ebrahimi Y and Zeinali M 2009 Direct torque control of 5-phase 10/8 switched reluctance motor by using fuzzy method Int. Jour. of Engineering and Technology 1 256

[9] Wu C, Xu Y, Fu D and Zhang Y 2015 Development of 8/4-pole high-speed two-phase SRM used in a grinding machine 18th Int. Conf. on Electrical Machines and Systems (ICEMS) Pattaya 584-7