Direct torque and flux control of switched reluctance motor with enhanced torque per ampere ratio and torque ripple reduction

P. Krishna Reddy✉, Deepak Ronanki and P. Parthiban

A smooth torque control of switched reluctance motor (SRM) is essential to avoid speed fluctuations causing stability problems in vehicular applications. This can be accomplished by an appropriate motor design and/or use of direct control of torque in SRM. It is reported that high RMS current is required to minimise the torque ripple in the conventional direct torque and flux control (DTFC), thereby reducing the torque per ampere ratio. To overcome this issue, a new DTFC technique with improved torque per ampere ratio while minimising torque ripple in an SRM traction drive is presented. Results demonstrated that the proposed DTFC technique reduces torque ripple with enhanced torque per ampere. Finally, the performance of the proposed scheme is compared with conventional DTFC of a four-phase (8/6) SRM to show the improvement in the traction drive.

Introduction: Switched reluctance motor (SRM) is considered to be one of the promising alternatives to the traditional AC motors due to distinctive features of robust structure, high starting torque, wide constant power region, no shoot through current in inverter, low cost and minimum maintenance. However, it suffers from severe torque ripple, acoustic noise and the requirement of a position sensor for control, which limits the wide usage of SRM in vehicular applications. Moreover, smooth torque control is difficult to achieve due to inherent torque pulsations generated due to the doubly salient SRM structure [1]. Over the past years, a significant research is carried out to minimise aforementioned concerns in SRM by improving the design aspects of the motor and/or employing appropriate control strategies [2]. Several control techniques are developed for SRM such as current profiling techniques (CPTs), flux profiling techniques and torque sharing functions (TSFs). However, these approaches require intensive computation to store machine non-linear characteristics, long settling time and require optimal tuning of control parameters [2, 3].

Alternatively, controlling torque as a direct control variable led to overcome the some of the aforementioned shortcomings through direct torque and flux control (DTFC) [4], which utilises the philosophy of direct torque control (DTC) of conventional AC machines draws more attention due to automatic control, reduced acoustic noise, fast dynamic response, insensitive to motor parameters and does not need information of rotor position. In this scheme, the phase torque is directly controlled based on deceleration/acceleration of the flux linkage vector, where its magnitude is kept constant within a hysteresis band. However, the active phase has to compensate negative torque generated by outgoing phase under negative inductance slope region to maintain the desired torque value, thereby drawing more source current. This results in lowering torque per ampere (T/A), thereby reducing the efficiency of the traction drive [4, 5]. This Letter presents a new DTFC strategy for four-phase SRM to enhance the T/A ratio while minimising the torque ripple. In this scheme, a new switching table is generated based on the sixteen sector partition and the optimised voltage vectors are selected to avoid a negative torque generated by the outgoing phase during a negative inductance slope region. As a result, the proposed strategy not only minimises the torque ripple but also improves the T/A ratio. The results of the SRM drive using the proposed scheme show the improved performance in comparison with the conventional DTFC (CDTFC) strategy.

Conventional DTFC: This scheme is a conventional DTC philosophy developed for AC machines and applied to the SRM [5], named as direct torque and flux control (DTFC). In this scheme, the stator flux and torque magnitudes are controlled in the hysteresis band by accelerating or decelerating the stator flux vector based on the increment and decrement of the torque. The flux linkage vector can be given by

$$\boldsymbol{\psi}_s = \int_0^t (\boldsymbol{V}_s - r_s \times \boldsymbol{i}_s)\,\mathrm{d}t + \boldsymbol{\psi}_{so} \tag{1}$$

Neglecting stator resistance (r_s), (1) becomes

$$\Delta\boldsymbol{\psi}_s = \boldsymbol{V}_s \Delta t \tag{2}$$

Thus, the direction of change in the stator flux linkage vector is in the direction of the applied voltage vector. The block diagram of DTFC of SRM is shown in Fig. 1. The controller needs flux error, torque error, position of flux linkage vector to select appropriate voltage vector as shown in Table 1. The position of flux linkage vector is required to identify the sector. A conventional asymmetric H-bridge (AHB) converter is used with voltage states of $+V_{dc}$ (1), 0 (0) and $-V_{dc}$ (− 1) for both switches on, turning off one switch and turning off both the switches respectively, as shown in Fig. 2.

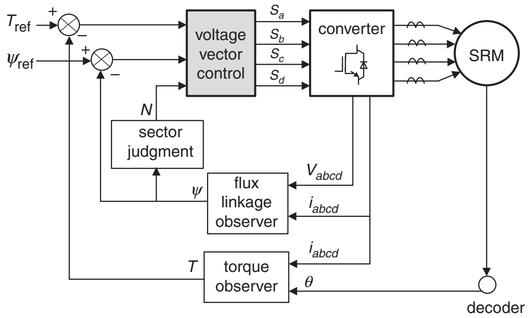

Fig. 1 *Control block diagram of DTFC*

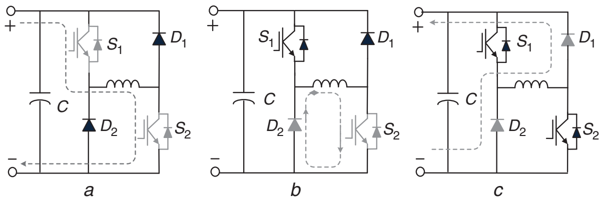

Fig. 2 *AHB converter*

a Magnetising state (+1)
b Freewheeling state (0)
c Demagnetising state (− 1)

Table 1: Voltage vector selection for k^{th} sector in the CDTFC

$T\Uparrow \psi\Uparrow$	$T\Uparrow \psi\Downarrow$	$T\Downarrow \psi\Uparrow$	$T\Downarrow \psi\Downarrow$
V_{k+1}	V_{k+3}	V_{k-1}	V_{k-3}

The DTFC controller selects the suitable voltage vector based on control algorithm to reduce torque and flux errors, as shown in Fig. 3*a*. However, the active phase need to generate more positive torque to maintain the desired torque during the negative inductance slope region of the outgoing phase, thereby lowers T/A ratio.

Proposed DTFC (PDTFC): The existence of current in any phase during dead zones (zero torque production regions) leads to reduction of T/A in the CDTFC. In order to avoid this problem, the CDTFC scheme is modified to enhance T/A by maintaining the current at zero level during dead zones by dividing into 16 sectors and voltage vector selection as shown in Fig. 3*b*. In the CDTFC scheme, the selected vector for the simultaneous increase of torque and flux is the vector existing in the next sector, which is 67.5° ahead of the stator flux vector and the same vector is maintained up to 45° of stator flux vector rotation. In this method, as the flux vector is moving, the angle difference between stator flux vector and selected voltage vector decreases from 67.5° to 22.5° at the instant reaching next sector. This improper selection voltage vector increase the torque ripples and reduces the T/A ratio. However, the most appropriate voltage vector which is right angles to the stator flux vector and ahead of it, can be selected in order to increase both torque as well as flux for faster dynamic response in the PDTFC scheme. In the same way, the most appropriate voltage vector which is right angles to the stator flux vector and lags behind it, can be selected in order to decrease both torque as well as flux. This appropriate selection is realised in the proposed method so that the phase difference between stator flux vector and selected voltage vector at all rotor positions is maintained at 90° approximately under simultaneously decrease or increase in flux and torque. To achieve this, the total 360° space is divided into 16 sectors (each sector of 22.5°) and voltage vector selection is performed as shown in Table 2.

Results: To validate the effectiveness of the PDTFC scheme, detailed studies are performed on a four-phase 8/6 SRM. An accurate non-linear

SRM model is developed using magnetisation and torque characteristics, which was obtained by performing experimental test as shown in Fig. 4. In this test, the current waveforms are captured at each rotor position from unaligned to aligned with the application of dc voltage. The rotor is locked at each position against the torque produced using dividing head. The captured current and voltages waveforms are further processed into computer to determine flux linkages using (1). A non-linear SRM model is developed using these experimental characteristics and the PDTFC scheme is implemented in real-time digital simulator using OPAL-RT platform.

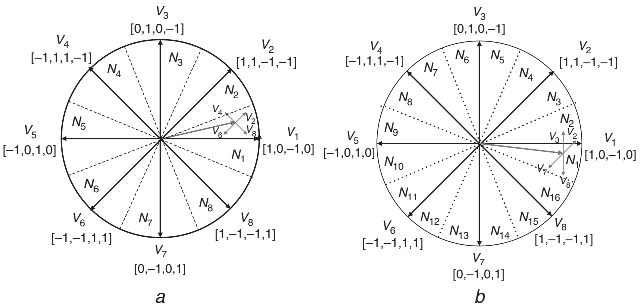

Fig. 3 *Vector selection for*

a CDTFC
b PDTFC

Table 2: Voltage vector selection for k^{th} sector in the PDTFC

$T \Uparrow \psi \Uparrow$	$T \Uparrow \psi \Downarrow$	$T \Downarrow \psi \Uparrow$	$T \Downarrow \psi \Downarrow$
V_{k+1}	V_{k+2}	V_{k-1}	V_{k-2}

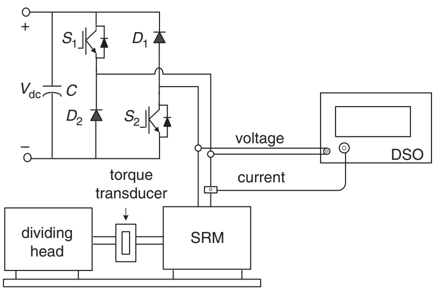

Fig. 4 *Test setup to determine magnetisation and torque characteristics*

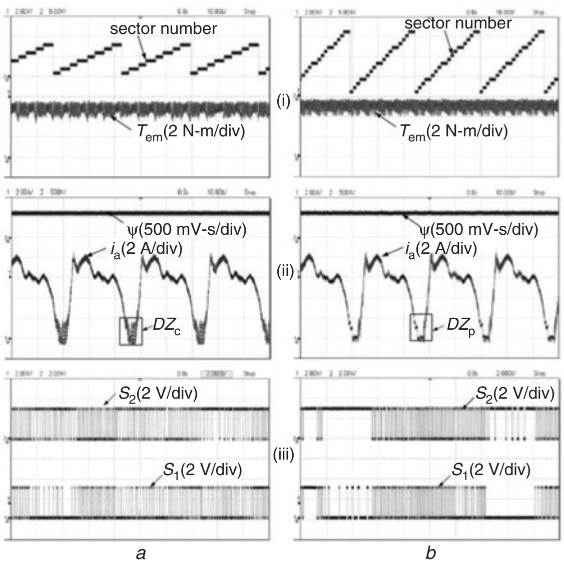

Fig. 5 *Results at 500 rpm*

a CDTFC
b PDTFC. Scope i: CH1: Torque (N-m) and CH2: Sector number; Scope ii: CH1: Phase-A current (A) and CH2: Flux linkage vector (Wb-turns); Scope iii: CH1: Gate signal for S_1 and CH2: Gate signal for S_2; Time scale: 2 ms/div

The performance of the proposed scheme is compared with the CDTFC scheme to show the improvement. Figs. 5*a* and *b* show the results of CDTFC and the PDTFC scheme under a torque reference of 5 N-m. It is observed that both the torque and flux are well regulated at their nominal values in the PDTFC scheme and performs better in minimising torque ripple as well as improving T/A. In Fig. 5(ii), it is shown that the phase current is maintained at zero-level during dead zone (DZ), thereby reducing the source current using the PDTFC scheme. This is achieved by applying a freewheeling/demagnetising mode of either an active phase or an incoming phase under positive slope inductance region. As a result, torque ripple is reduced with enhanced T/A ratio compared to the CDTFC scheme. This scheme does not allow the magnetisation state of any phase in the DZ region. Thus, it is observed in Fig. 5(iii) that the number of switchings of the active switches S_1 and S_2 for 'A' phase are less using the PDTFC, thereby reducing switching frequency as well as switching losses. The comparison of the proposed scheme with the CDTFC scheme in terms of torque ripple and T/A ratio is listed in Table 3. From the analysis, it is concluded that the proposed scheme offers better performance in terms of minimising torque ripple with enhanced T/A ratio.

Table 3: Comparison between the PDTFC and the CDTFC

Speed (rpm)	Method	Torque ripple (%)	T/A (N-m/A)
100	CDTFC	26.8	0.8107
	PDTFC	25.1	1.2041
250	CDTFC	31.1	0.8289
	PDTFC	28.1	1.1804
500	CDTFC	38.4	0.8321
	PDTFC	33.1	1.1071

Conclusion: A new DTFC technique with enhanced torque per ampere in an SRM drive is introduced. In this scheme, 16 sector partition method is employed and then most appropriate voltage vectors are selected to increase torque per ampere ratio while minimising torque ripple. The PDTFC strategy is verified on a 8/6 four-phase SRM drive system and the results confirm that the proposed strategy not only minimises the torque ripple but also improves the T/A compared to CDTFC scheme. As a result, a smooth torque control as well as improvement in efficiency of traction drive is achieved.

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One or more of the Figures in this Letter are available in colour online.

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