Direct Instantaneous Torque Control of Switched Reluctance Motor for Aerospace Applications

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***Abstract*—This paper presents a new Direct Instantaneous Torque Control (DITC) developed to minimize the inherent torque ripple of an aerospace switched reluctance motor (SRM). In addition to good performance, the reliability and robustness of the overall system are of great concern in aerospace and other safety-critical applications. By taking that into consideration, a DITC, that is less prone to the common erroneous operating conditions associated with SRM control such as measurement errors and noise, integration errors and parameter variation errors, is developed and compared with the traditional current chopping control (CCC). The proposed control scheme involves simple torque estimation, distribution, and regulation strategies. The results obtained show that both the proposed DITC and the traditional CCC methods ensure accurate reference tracking. However, the proposed control exhibits better torque ripple reduction capability without compromising the system's reliability and robustness**

***Keywords*—Aerospace, Direct instantaneous torque control, Switched reluctance motor, Torque ripple minimization**

I. INTRODUCTION

The modern switched reluctance motor (SRM) drive is becoming attractive for more-electric airplane applications because of its potential prospects. It has several advantages such as; a robust machine structure, suitability for a hostile environment, a high mean time between failures, wide speed range operation and low system cost [1]-[4]. On the other hand, it generally suffers from large torque ripple, machine nonlinearities and higher acoustic noise [5]-[9]. Such problems can be minimised via machine design methods and/or control strategy approaches. This paper focuses on improving the machine's performance via control strategies.

Control of the SRM to reduce torque ripple and acoustic noise has been an interesting research area. The most well-known approaches adopted by previous researchers include torque sharing function, current profile strategy, commutation strategy, direct torque control, direct instantaneous torque control and indirect instantaneous torque control [10]-[15]. In the aforementioned methods, the control is often achieved via a closed loop current or torque control. In a comparison of torque ripple and current Profile for current control and torque control of an SRM, it was observed that the torque ripple is reduced by 80% with the torque control technique, [16]. This makes the torque control a promising method to solve torque ripple problems.

The dominant SRM torque control to minimize torque ripple can be classified into Indirect Instantaneous Torque Control (IITC) and Direct Instantaneous Torque Control (DITC). In IITC, SRM torque is regulated by controlling the instantaneous phase currents in a cascaded torque to current conversion [17]. A conventional method for IITC is known as current profiling which requires the design of appropriate current waveforms and flux waveform due to the torque-current nonlinear relationship. The accuracy of this method also depends on exact sensing of rotor position [18]. On the other hand, DITC does not require any torque-current conversion because the instantaneous torque of the machine can be directly controlled without the need for an inner current loop. A hysteresis-type direct torque control strategy like hysteresis current controller was reported in [19] where the control switching signals were directly generated from an error narrow band obtained from the difference between the reference torque and the estimated torque. This strategy requires accurate flux estimator and a high sampling frequency to keep the output torque within the narrow band which makes it not suitable for application with limitation in switching frequency. Furthermore, it was noticed that there were large ripples in the SRM current and torque near the unaligned rotor positions. Sahoo *et al*. proposed an Iterative learning control based DITC to correct the drawbacks of the hysteresis-type DITC [20]. A continuous variable voltage between positive and negative DC link voltage is applied to the phase windings via a PWM converter. The method uses an analytical torque estimator, cubic torque sharing function and iterative learning control compensation which makes it relatively complicated and liable to errors.

The main control objective of this paper is to reduce the torque ripple associated with a Magnet-assisted Segmental Switched Reluctance Motor (MSSRM). This machine was designed for an airplane nose-wheel actuator and is designed to produce the same torque density as a permanent magnet motor of the same

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size and mass with an added advantage of being fault tolerant [21].

In this paper, taking into consideration the intended application of the machine, a DITC with no flux estimation is proposed to improve the system reliability and robustness. It consists of an instantaneous torque regulator with a simple torque distributor and a current limiter designed to achieve an optimum torque characteristic. The control algorithm is simulated and compared with a current chopping control using MATLAB/SIMULINK.

II. Characteristics of the MSSRM

The performance characteristics of the MSSRM can be analysed using the torque and voltage mathematical equations. Neglecting the mutual inductance between the phases, the instantaneous voltage of the MSSRM can be expressed as:

$$v = iR + \frac{d\psi}{dt} \tag{1}$$

Because of the double salient construction of the MSSRM and effects of magnetic saturation, the flux linked in an SRM phase varies as a function of rotor position, θ, and the motor current, i.Thus, Equation (1) can be expanded as in (2) or (3).

$$v = iR + \frac{\partial\psi}{\partial i}\frac{di}{dt} + \frac{\partial\psi}{\partial\theta}\frac{d\theta}{dt} \tag{2}$$

$$v = iR + L(\theta, i)\frac{di}{dt} + \frac{d\psi(\theta,i)}{d\theta}\ \omega_m \tag{3}$$

where v is the applied phase voltage, R is the winding resistance per phase, L is the inductance, w_m is the angular speed and ψ is the flux linkage due to the phase current *i.*

The torque per phase of the motor under saturation and unsaturation conditions can be expressed as in (4)

$$T \approx \frac{\partial\psi(i,\theta)}{\partial\theta}\ i \tag{4}$$

The instantaneous torque of an SRM is not constant. And is obtained by the summing up the individual phase torques as in (5)

$$T_{instanteneous}(\theta, \mathrm{i}) = \sum_{Phases}^{n} T_{phase}\,(\theta, \mathrm{i}) \tag{5}$$

The torque ripple T_{Ripple} of the machine can be represented as follows:

$$T_{Ripple} = \frac{T_{max} - T_{min}}{T_{Ave}}\ \% \tag{6}$$

where $T_{\max}$ is maximal value of the torque, $T_{\min}$ is minimal torque and T_{Ave} is its average value.

Based on the static analysis of the machine, parameters obtained by means of experiment are used in the creation of a MATLAB/SIMULINK model of the dynamic behaviour of the MSSRM. The dynamic model consist of the machine voltage equation and two lookup tables of the flux linkage and torque characteristics of the machine.

III. Controller Design

Before In this section, a DITC is designed to obtain desired torque characteristics with minimum ripples. In the safety critical application such as aerospace, reliability and robustness of the control system against errors is an important requirement. The sources of errors that are common in motor drive environments include:

i. Measurement errors due to sensor offset error and sensor scaling error,

ii. Measurement noise due to capacitive coupling of measuring circuit, electromagnetic interference from the motor, power circuit and other electronic devices within its vicinity,

iii. Integration errors due to integration offset error, time and amplitude quantization error.

iv. Variation of parameters such as winding resistance due to temperature variation.

Based on these sources of errors, the proposed DITC is designed to operate without the need for a flux linkage of the motor because it is almost impractical to measure it directly. It is often estimated by integrating the resultant voltage across each phase which is prone to the four errors mentioned above. The torque regulator is also designed to use a simple proportional control to eliminate the controller's vulnerability to integration error and measurement error. The control structure is shown in Fig. 1 below.

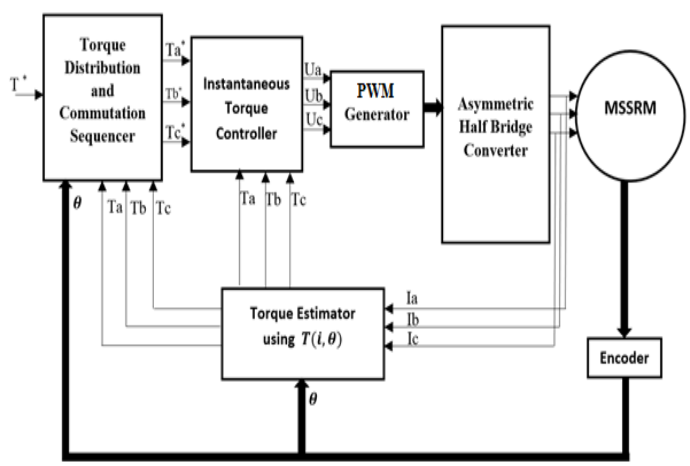


Fig. 1. The control structure of proposed DITC

A. Torque Estimation

A lookup table $T(i, \theta)$ generated from a static test of the machine is used in estimating the torque of each phase via linear interpolation. The data for the lookup table is presented in Fig. 2. The computation involved in such an estimation is less compared to analytical methods.

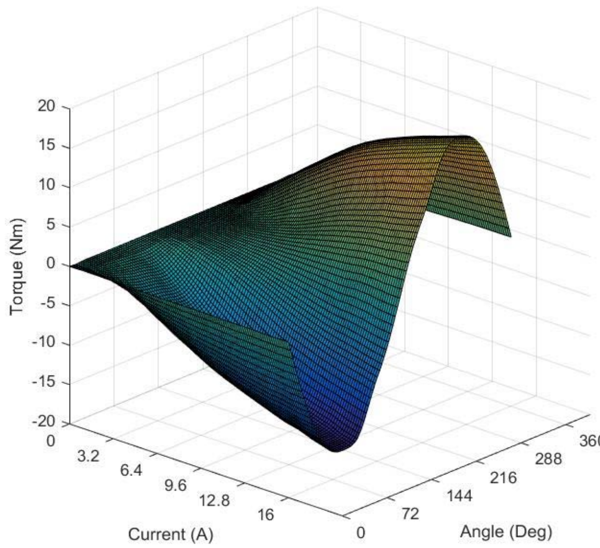


Fig 2: Static torque measurement for different levels of current in each phase of MSSRM

B. Torque Distribution and Commutation Control

The Ensuring desired torque characteristics with minimized ripple can be achieved by right coordination of the individual phase torques during overlapped commutation. Therefore, a simple phase torque distribution control and commutation angle control with no off-line torque sharing profile requirement is proposed to reduce computation errors and increase control flexibility with the assumption that the phases are fully isolated. The control aim is as shown in (7). Based on this a reference phase torque (T^*) is generated for the active phase as in equation (8). Consequently, the phase torque references are defined over the commutation control logic (9).

$$T^* = T_m + T_{m+1} + T_{m-1} \tag{7}$$

$$T_m^* = T^* - T_{m+1} - T_{m-1} \tag{8}$$

$$T_m^* = \begin{cases} T^* - T_{m+1} - T_{m-1} & when\ enabled \\ 0 & when\ not\ enabled \end{cases} \tag{9}$$

Where T^* is the motor desired torque, T_m is the phase instantaneous torque and T^*_m is the phase reference torque.

To obtain the angle of conduction the actual rotor position θ is compared with the commutation angles, which are depending on the actual angular velocity *w*. A conduction signal of 1 is sent if the rotor position is between turn on and turn off angle and a signal of 0 is sent otherwise

C. Instantaneous Torque Regulation

The instantaneous phase torque control of the proposed DITC is regulated using a proportional controller. Each phase torque error is generated from the difference between its corresponding phase reference torque and phase instantaneous torque as expressed in equation (10).

$$U_m = K_P \frac{(T_m^* - T_m)}{(T_r)} \tag{10}$$

where U_m, T_r and K_P, are the per-unit phase torque error, rated torque and proportional gain respectively.

Fig. 3 shows how the reference voltage of each phase is generated from U_m and converted to a switching reference '*d*' (that changes from -1 to 1). The value of '*d'* is used to generate the switching signals of the power switches in an asymmetric half-bridge converter at a switching frequency of 20 kHz.

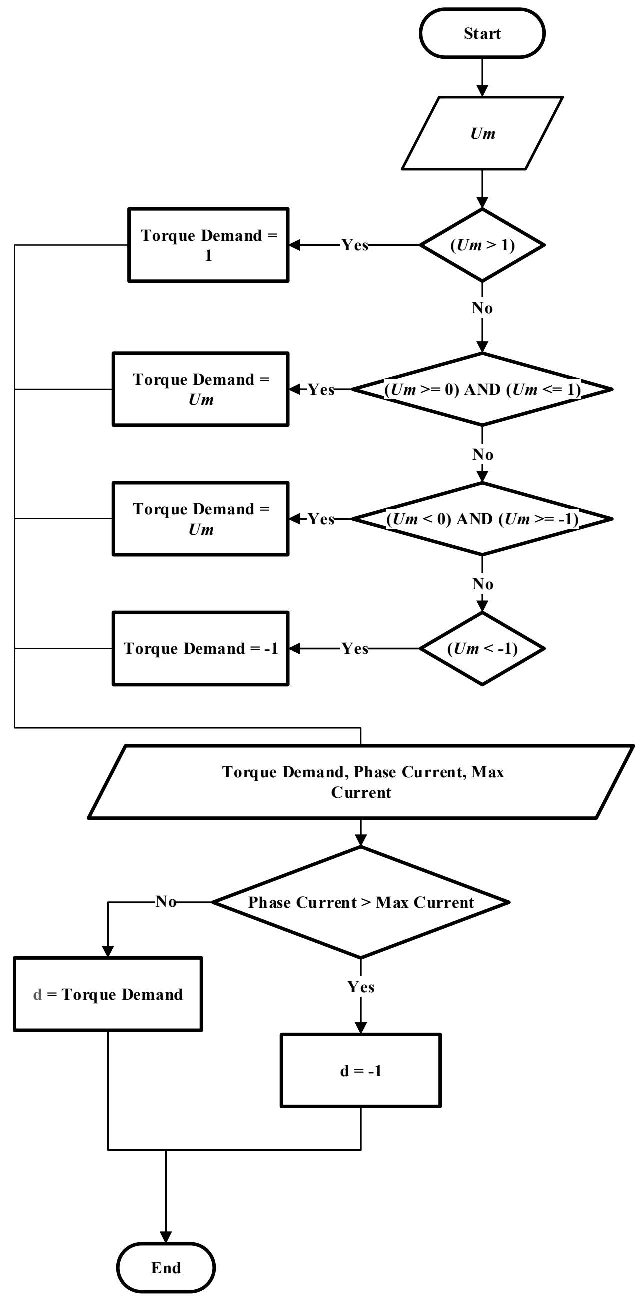
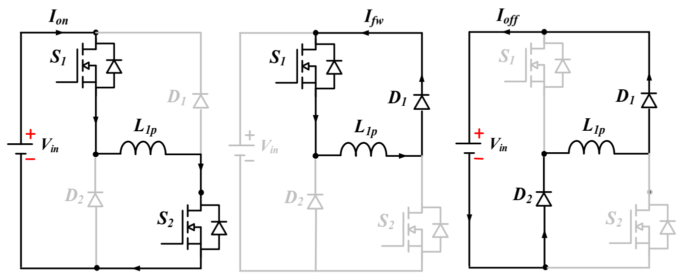


Fig. 3: Flowchart of PWM demand

TABLE I. CONVERTER SWITCHING CONDITION

Switching reference per cycle	Phase voltage per cycle
d ≥ +1	Vm = Von
0 < d < +1	Vm = |d| × Von + (1 - d) Vfw
d = 0	Vm = Vfw
0 > d > -1	Vm = |d| × Voff + (1 - d) Vfw
d ≤ -1	Vm = Voff



(a) (b) (c)

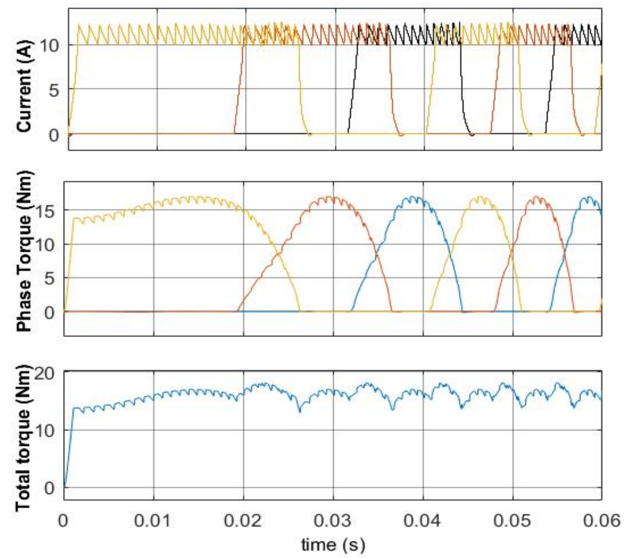
Fig. 4: One phase cconverter States. (a) On-state. (b) Freewheeling State. (c) Off-state.

D. PWM Generation

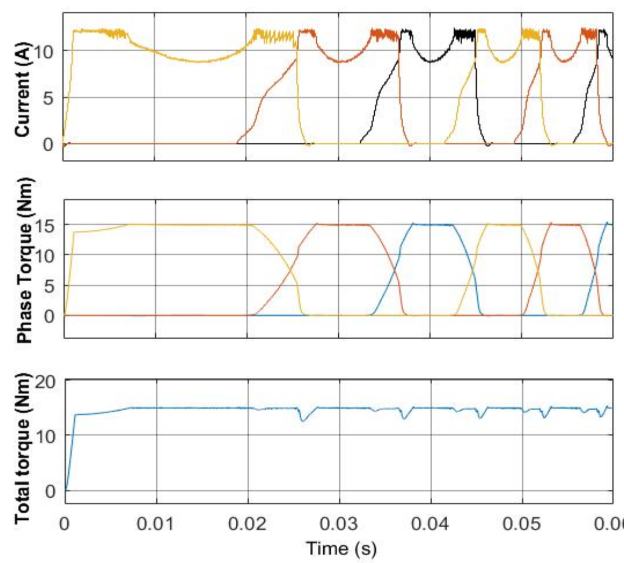
The phase voltage of each phase is determined in accordance with the functionality of the asymmetric half-bridge converter whom switching states are on-state, freewheeling-state and off-state as shown in Fig. 4. When the torque is to be increased, both power devices of the active phase are turned on (on-state) for the time equals to the absolute value of '*d*' and then the phase turns into the freewheeling-state. When the torque is to be decreased, both power devices of the active phase are turned off (off-state) for the equals to the absolute value of '*d*' and then the phase turns into the freewheeling-state. The polarity of d determines which device to modulate. TABLE I shows how the reference phase voltage is obtained. Where V_m, V_{on}, V_{fw}, V_{off} are the phase voltage, on-state voltage, freewheeling-state voltage and off-state voltage respectively.

IV. RESULTS

In this section, the simulation result of the proposed DITC is presented. For performance comparison CCC as one of the traditional control method was also simulated and recorded. Depicted in Fig. 5 are phase current, phase torque and total torque of the MSSRM controlled by the proposed DITC methods at reference torque of 15Nm (machine's rated torque) and the CCC method at reference current of 11A (machine's rated current). Comparing the results it can be found that the proposed DITC and CCC both produced good results in tracking the desired references. Meanwhile, the DITC produced the best result with regards to torque ripple reduction. Also, by observing the current waveforms, the DITC schemes tend to require current that is more than the maximum current of the machine at the beginning and end of the conduction period, but the included current restriction control described in Fig. 3 limits it within the allowed value.



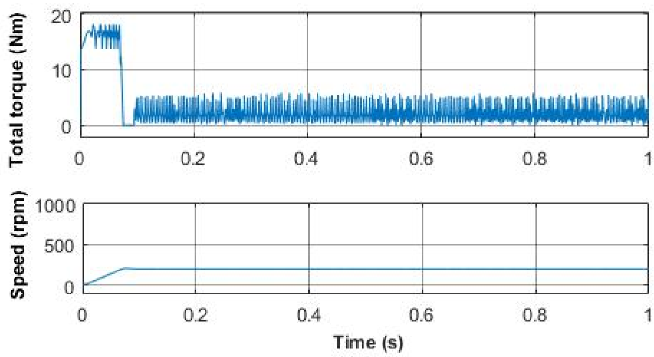
(a) CCC method



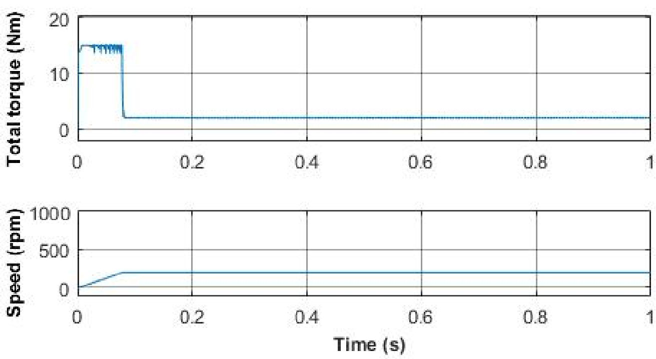
(b) Proposed DITC Method

Fig. 5: Comparison of control methods

Furthermore, the CCC and DITC have been analyzed with the motor set to run at a reference speed of 200rpm, 500rpm, and 900rpm under 2Nm load torque as shown in Fig. 6, 7, and 8. It can be seen that the proposed DITC method significantly shows less torque ripple than the CCC method in all the speed ranges. From Fig. 6, the result shows that the proposed DITC offers better performance at low speed as the difference in torque ripple between the two methods is very significant both during transient and steady state. From Fig. 7 and 8 the proposed DITC did not show very much difference compared to the CCC during the transient state as it shows during steady state. It can be observed that the torque ripple starts to increase at a speed beyond the motor's base speed (400 rpm) and then the proposed control algorithm continues to reduce the torque ripple once steady-state is attained. This is because the back EMF is higher above the base speed of the machine and limits the current. The turn-on angle of the converter switch is set to advance as a function of the rotor speed, that is the higher the rotor speed, the larger the advancing of turn-on angle is required but it reaches a critical speed at which both turn-on and turn-off position reach their limit values. Therefore, no phase advancing is allowable and the torque ripple due to commutation can no longer be further reduced by changing the advance angle.

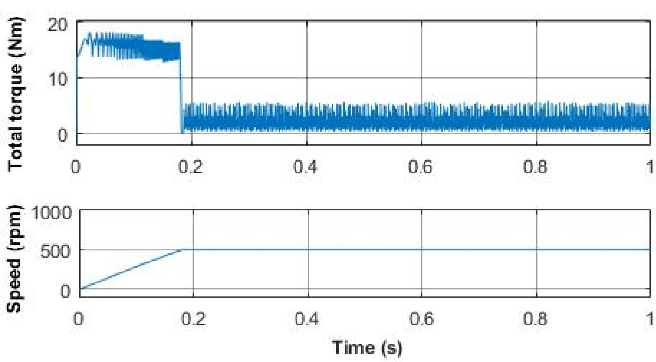


(a)

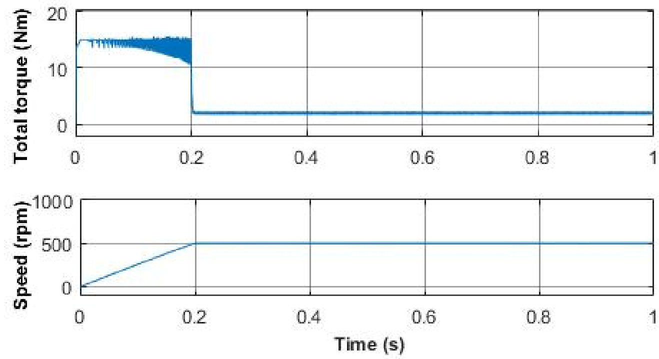


(b)

Fig. 6: MSSRM running at 200rpm under 2Nm load torque (a) CCC method (b) Proposed DITC method.

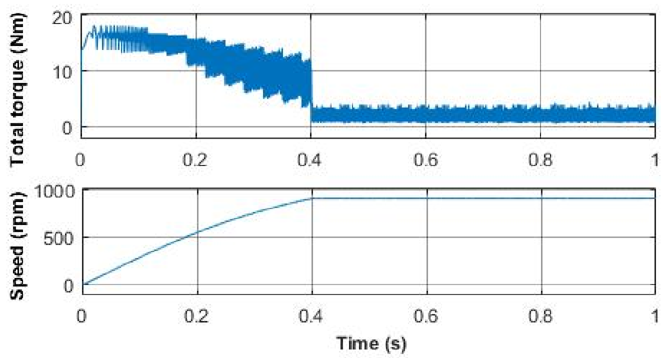


(a)

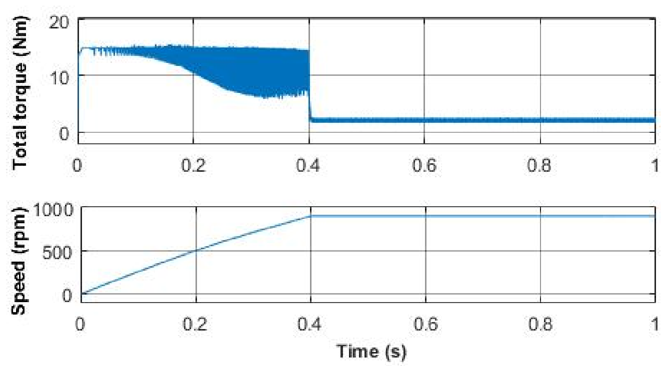


(b)

Fig. 7: MSSRM running at 500rpm under 2Nm load torque (a) CCC method (b) Proposed DITC method



(a)



(b)

Fig. 8: MSSRM running at 900rpm under 2Nm load torque (a) CCC method (b) Proposed DITC method

Fig. 9 depicts the torque ripple and speed relation of the CCC and the proposed DITC covering the operation regions of the MSSRM, namely the constant-torque operation, constant-power operation, and natural operation, which are desirable for low-speed, medium-speed, and high-speed operation, respectively. The toque ripple has been calculated using equation (6). It can be seen that the proposed DITC produced less torque ripple than the CCC at 200rpm (low-speed), 500rpm (medium-speed) and 900rpm (high-speed) respectively but with larger settling time. In summary, the set of results depicted above clearly shows that the proposed DITC method is ideal to achieve good torque characteristics in a switched reluctance motor.

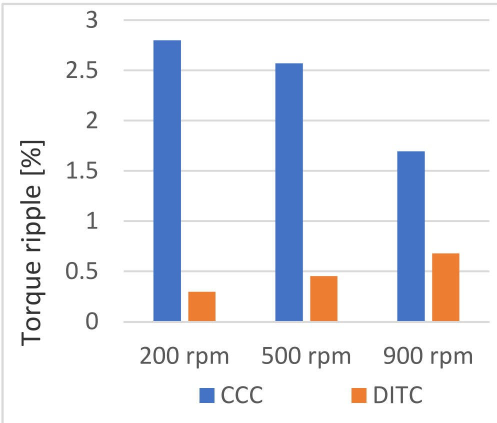


Fig. 9: Torque ripple comparison between proposed DITC and CCC methods at steady state

V. CONCLUSION

In this paper, a new DITC of switched reluctance motor for an aerospace application has been proposed. For analysis and controller design, a dynamic model of the switched reluctance has been developed using static experimental data and the motor's voltage equation. By considering the reliability requirement of the motor's intended application, a DITC scheme that is less susceptible to the common erroneous operating conditions associated with SRM control is proposed and simulated with MATLAB/SIMULINK. Comparison of this method with the CCC has been presented from the aspect of desired reference tracking and torque ripple minimization at different operating conditions of the motor. The simulation results shows that both methods produce the same average torque but the torque ripple of the proposed DITC method is significantly less than that of a CCC method. Based on the proposed DITC method, improving the reliability of the system by eliminating the need for rotor position is an objective for the future study of torque optimization of the aerospace MSSRM.

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