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Performance improvement based on adaptive commutation strategy for switched reluctance motors using direct torque control

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Received 10 November 2021; revised 12 January 2022; accepted 13 February 2022

Available online 25 February 2022

KEYWORDS

Switched Reluctance Motors;
 Direct Torque Control;
 Torque Profile Improvement;
 Adaptive Commutation

Abstract This research presents an improved direct instantaneous torque controller (DITC) for switched reluctance motors (SRMs). It incorporates a novel adaptive real-time commutation mechanism. The proposed method can effectively enhance the torque profile and efficiency of the machine by proper real-time adjustment of both the turn-on and the turn-off angles. First, an initial value of the turn-on angle is selected to achieve the highest torque generation capability. Then, with a real-time adjustment around the pre-selected initial angle, the instantaneous torque error can be further compensated. Hence, the torque ripple is minimized.

Regarding the turn-off angle, an initial value is selected to satisfy the minimum required conduction angle of SRM. Then, this value is continuously adjusted at each electrical cycle by utilizing a phase current detector to force the outgoing phase current to decay to a less effective value before the negative slope of the inductance profile. Therefore, this prevents serious negative torque generation. The proposed strategy fully utilizes the torque generation capability of the motor with a minimized torque ripple, besides the phase currents, are generated in optimal conduction range to enhance the motor efficiency. The simulations and experiments have been carried out on a 3-phase 750 W 12/8 SRM to validate the proposed method's feasibility and effectiveness.

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1. Introduction

Due to their simple structure, SRMs offer exceptional robustness and reliability above the other electric machine types. They need no rare-earth materials or windings in their rotary part. Therefore, they provide low cost, high fault tolerance, low maintenance, and wide speed range drives. These significant preferences made them high-potential choices to be utilized in

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

the electric vehicle industry. However, both the rotor and stator poles are salient, leading to undesired ripple in motor torque and noise issues [1–5].

Regarding the torque ripple problem, previous authors proposed two approaches. The first approach is on the basis of adjusting the machine's design, such as winding configurations or optimizing its geometrical dimensions [6–9]. This strategy may minimize the torque ripple and noise produced by the machine, but only to a certain extent. Furthermore, once the machine has been manufactured, it is difficult to make modifications to its dimensions. The second approach relies on advance control strategies [10], such as current chopping control [11–14], average torque control (ATC) [15,16], indirect instantaneous torque control (IITC) [17–20], and direct instantaneous torque control (DITC) [21–25]. Among these techniques, the IITC and DITC can heavily decrease the motor's torque ripple, especially at low and medium speed ranges. In [17], a modified IIT controller is implemented to attain the demands of the electric vehicle, including minimized torque ripple, maximized efficiency, and maximized torque to current ratio. The turn-on angle is obtained analytically to compel phase current to attain its commanded value exactly at the moment when the stator and rotor poles start overlapping. In this way, the maximum torque to current ratio is guaranteed. In [18], an upgraded ant colony optimization is adopted to optimize the turn-on and overlap angles of a pre-selected sinusoidal TSF. The objective of the optimization problem is to reduce both torque ripple and copper loss of SRM while keeping a permissible amount of the average output torque. In [19], the rate of change of the magnetic flux and the RMS value of the current are combined in a multi-objective function and minimized based on a proposed off-line TSF. In [20], different TSFs, including sinusoidal, cubic, linear, and exponential TSFs, are analyzed and discussed. In [21], a Fuzzy Logic Control (FLC) based DITC is implemented and tested under different operating conditions, the torque reference is tracked accurately. Therefore, the torque ripple is reduced. In [22], an adaptive commutation strategy based on optimized DITC has been proposed. The turn-on angle is adjusted in real-time to minimize the torque error at the interference period between two-phase currents. While the turn-off angle is regulated to impose the current phases to decay to zero between two endpoints. However, in low-speed operation, the current decays sharply. Therefore, a considerable amount of current may be attained between the two endpoints. In [23], the DITC is utilized under the base speed while the ATC method is adopted above the base speed. In both cases, the turn-on and turn-off angles are optimally selected. The torque ripple and motor efficiency are improved in a wide speed range. But utilizing two techniques in the same controller will increase the complexity of the controller; besides, the commutation angles may have heavy changes when transitions from the DITC to the ATC, leading to unstable transition operation. In [24], the parameters of DITC have been optimized using an improved version of the firefly algorithm, the torque ripple is largely reduced, and the overall dynamic response is enhanced. In [25], the torque hysteresis controller is replaced by a PWM controller to obtain a fixed switching frequency.

In this research, an improved DITC strategy is proposed to utilize the torque producing capability of SRM fully. It also enhances both the efficiency and torque ripple. At each operating speed and loading condition, initial values for both switch-

ing angles are calculated analytically to make full utilization of the positive slope region of inductance. Then, both angles are adjusted in real-time operation at each electrical cycle by means of two commutation controllers. The turn-on angle is modified to compensate the error between commanded reference torque and the mean torque of SRM. This helps to increase torque tracking accuracy of the proposed DITC and thus reduces torque ripple. A current detector is used to adjust the turn-off angle to restrain serious negative torque production. Hence, it helps to enhance motor efficiency. The introduced DITC based novel adaptive commutation strategies for both switching angles achieve excellent torque ripple suppression and improve motor efficiency.

The layout of this paper is as follows: Section II gives a brief description of the commonly used control techniques in SRM. Section III involves a short analysis about the effect of switching angles on the SRM performance. Sections IV illustrates the commutation strategy of the proposed DITC. Sections V and VI present the simulation and experimental results, respectively. Afterward, Section VII is the conclusions.

2. Torque control schemes in SRM drives

The classical current chopping control (CCC) method is used widely in SRM drives since it can provide a simple and effective controller [11]–[14]. The CCC block diagram is given in Fig. 1.

The reference current is obtained directly from a proportional-integral (PI) speed controller. The CCC aims to track the commanded current by regulating the phase current in the conduction zone between the turn-on and the turn-off instants using a simple two-level states hysteresis controller. The output from the hysteresis controller is the switching signal which is fed to the IGBT power converter to operate the machine. The CCC-based SRM drives suffer from a considerable amount of torque ripple.

On the contrary, the instantaneous torque control strategies can heavily minimize the torque ripple of SRM. They can be divided into indirect (IITC) and direct (DITC) instantaneous torque control. The IITC uses a torque distribution function, commonly known as torque sharing function (TSF), so as to intelligently divide a reference torque value between the machine phases. Each phase reference torque signal is then translated into the reference current signal that corresponds to it. By controlling the obtained current signal, the instantaneous torque of the motor is controlled indirectly. The block diagram of the IITC is shown in Fig. 2.

Fig. 3 presents the block diagram of DITC. The real-time rotor position is estimated through a position encoder, and the motor speed is obtained by differentiating the rotor position. Each phase current is measured directly using a current sensor. The SRM torque has highly non-linear variations with rotor position and current, and thus, it's very challenging to obtain an accurate analytical expression [26–28]. Therefore, in this work, the motor torque data is obtained using finite elements method (FEM) and then these data are verified experimentally using static torque transducer. Where, at each combination of rotor position and phase current the corresponding torque is recorded and saved in look-up table and then this table is used to estimate the motor torque. The

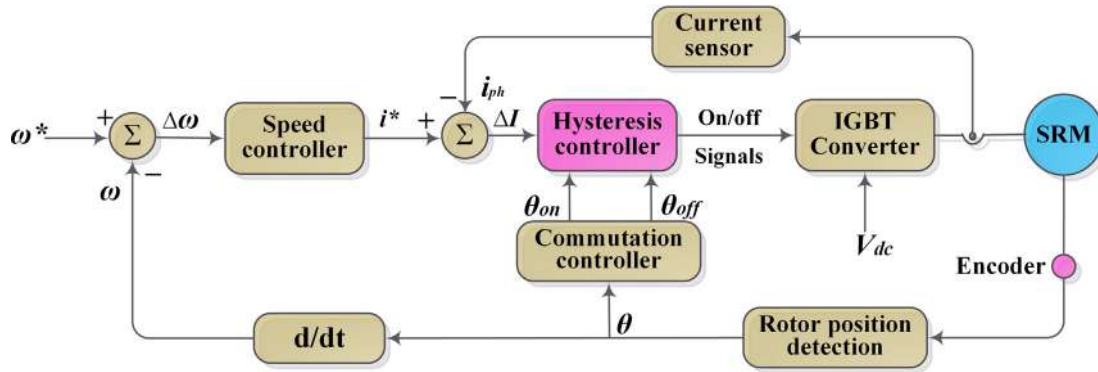


Fig. 1 Block diagram of the current chopping control of SRMs.

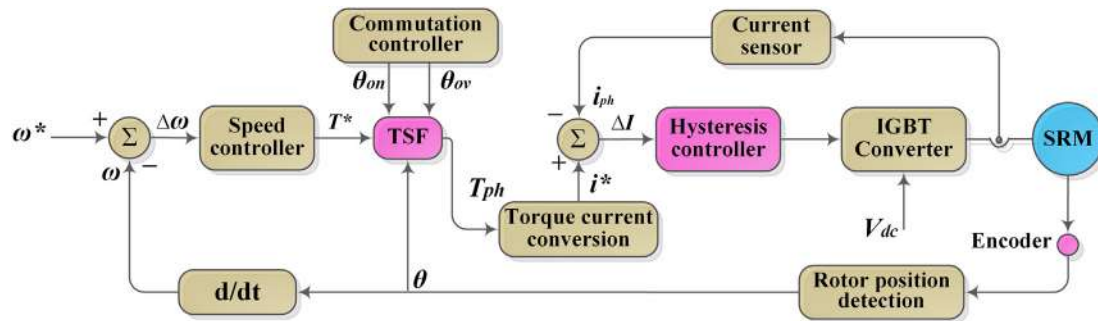


Fig. 2 Diagram of indirect torque control for SRMs.

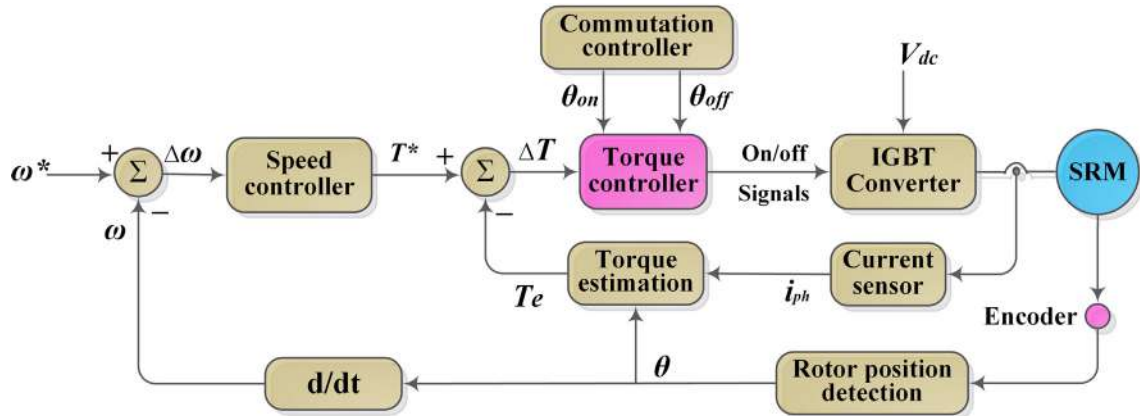


Fig. 3 Block diagram of direct torque control for SRMs.

procedures of SRM modelling are explained in detail in previous authors' work in [11]. A PI controller is utilized to perform a closed-loop speed control. It generates the commanded reference torque.

Unlike the IITC, the DITC controls the commanded torque directly by comparing it to the instantaneous estimated torque. The obtained torque error signal is fed to a torque controller or switching unit. The output switching signal of the switching unit is then used to operate the power converter and to run the machine. The turn-on and the turn-off angles are obtained from a commutation controller. They have a direct effect on

the performance of the SRM drive. Because of the highly non-linear inductance, magnetic flux, and torque characteristics of SRM, optimal selection of the switching angles is a challenging task, as will be illustrated in the next section.

The DITC is adopted in this work because controlling the instantaneous torque directly gives advantages to DITC over IITC. The conversion from torque to current is eliminated, and therefore, there will be no need for a current controller. Besides, the DITC deals with the torque error immediately, resulting in a better dynamic response with reduced torque ripple.

3. Commutation analysis in SRM drives

The inductance profile (L) along with the current (I_{ph}) of one phase of the machine against the position θ of the rotor is depicted in Fig. 4.

where θ_{on} and θ_{off} are the turn-on and turn-off angles, θ_m and θ_z are the angles when the rotor and stator start and finish overlap, respectively. I_z is the sampled current at θ_z .

In SRMs, the output torque is a non-linear function of current and rate of inductance change against the rotor position. Hence, to generate positive torque, each phase should be switched-on during the positive slope zone of the inductance profile ($dL/d\theta > 0$). Alternatively, if the phases are exited during the negative slope region ($dL/d\theta < 0$), a negative torque will be produced, or if the phases are excited in the fully aligned or unaligned positions ($dL/d\theta = 0$) then no torque will be generated, and therefore, the motor efficiency will be reduced. As a result, the turn-on and turn-off angles should be selected carefully to attain a high-performance machine. For instance, if the phases are switched on too early before θ_m as shown in Fig. 4a, then a large amount of current will be needed to generate the required torque because the rate of change of inductance in that region is very low, leading to poor motor efficiency. On the other hand, if the phases are turned on too late after θ_m (Fig. 4b), then the positive inductance region will not be utilized entirely, and therefore, the average out torque will be reduced.

Regarding the turn-off angle, if the phases are switched off too early before the aligned position, as depicted in Fig. 4a, they will be completely demagnetized before the negative slope region (θ_z). Thus, I_z will be zero, i.e., there will be no negative torque production. However, in this case, the positive inductance region will not be utilized entirely, and therefore, the average out torque will be reduced. On the other hand, if the phases are turned off at the fully aligned position, the current will not be utterly demagnetized before θ_z , and there will be a considerable amount of I_z leading to a negative torque production as shown in Fig. 4b. A short summary can be seen in Table 1.

Besides, the switching angles also have a significant influence on the machine torque ripple. The torque ripple is a crucial factor that should be considered, especially when utilizing the SRM for electric vehicles (EVs). To enhance the torque ripple of the machine, the switching angles can be optimized off-line or on-line. This paper proposes a novel real-time (on-line) commutation method based on the DITC aiming to improve torque profile and motor efficiency.

Table 1 Summary of the effect of the switching angle on SRM performance.

Switching angles	Early switching	Delayed switching
Turn-on angle	Higher average torque, lower efficiency	Lower average torque, higher efficiency
Turn-off angle	Lower average torque, no negative torque	Higher average torque, negative torque

4. Proposed DITC strategy and commutation method

To take full advantage of torque producing capability of SRM and to enhance both the torque ripple and operation efficiency, an improved DITC strategy is proposed. At each operating point, defined by the speed and torque, initial values for both switching angles are calculated analytically, aiming to fully utilize the positive slope region of inductance. Then, both angles are adjusted in real-time operation by means of two commutation controllers to obtain further improvements on torque ripple and motor efficiency.

4.1. Proposed Turn-on angle controller

An initial value of the turn-on angle $\theta_{on}^{(0)}$ is selected to compel phase current to attain its commanded reference value precisely at the instant when rotor and stator poles start overlapping (θ_m). In this case, maximum torque production with a lower phase current will be achieved. The optimum excitation angles are illustrated in Fig. 5.

This can be done analytically by calculating $\theta_{on}^{(0)}$ backward from θ_m as shown:

$$\theta_{on}^{(0)} = \theta_m - \Delta\theta = \theta_m - \omega \cdot tr \quad (1)$$

where, ω is the speed of the motor and t_r is the time needed for the phase current to reach its commanded value, and it can be calculated from (2).

$$tr = \frac{L_u}{R + K_b\omega} \ln \left[1 - I^* \left(\frac{R + K_b\omega}{V_{dc}} \right) \right] \quad (2)$$

where, L_u is the inductance of the unaligned position, and its a function of rotor position only, K_b is its derivative, R is phase resistance, I^* is the reference current, and V_{dc} is the dc voltage supplied from the power converter. The turn-on angle

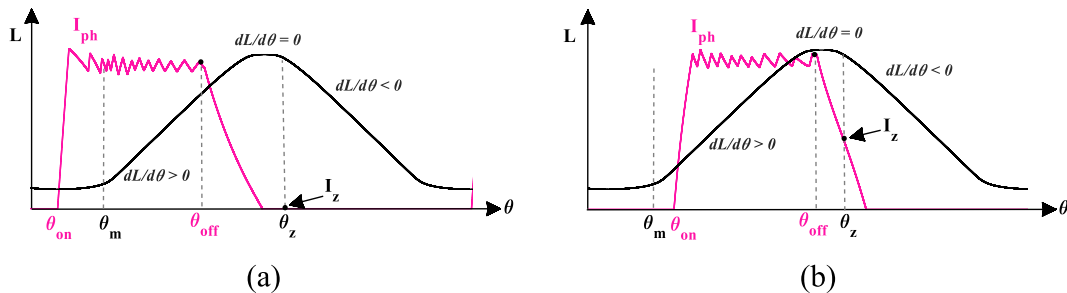


Fig. 4 Inductance profile of SRM along with the current at different switching angles.

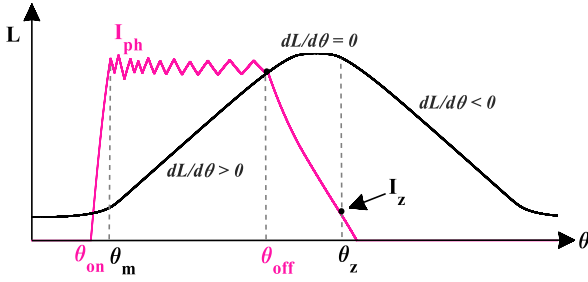


Fig. 5 Inductance profile of the SRM along with the phase current at initial switching angles.

is then updated at each electrical cycle in real-time operation by a proposed torque error compensator in order to eliminate the average torque error ΔT_{ave} given in equation (3) and thus, improve the torque tracking capability of the proposed DITC. As a result, the torque ripple will be effectively minimized.

$$\Delta T_{ave} = T^* - T_{ave} \quad (3)$$

where, T^* is the commanded reference torque obtained from the PI speed controller. T_{ave} is the average torque over one electrical cycle. Fig. 6. depicts the diagram of the proposed turn-on angle controller.

T_{ave} is updated at each electrical cycle (τ) of the motor operation as:

$$T_{ave} = \frac{1}{\tau} \int_0^\tau T_e(t) dt \quad (4)$$

Therefore, the corresponding average torque error is continuously updated in real-time operation and fed to the compensator. If the torque error is positive, i.e., the mean value of the motor torque in an electrical cycle is less than the commanded torque reference, a proper negative angle decrement ($-\Delta\theta_{on}$) should be provided, and the resultant turn-angle is advanced in order to generate higher torque that makes up the inadequate torque.

On the other hand, if the torque error is negative, a proper positive angle increment ($\Delta\theta_{on}$) must be provided, and the resultant turn-angle is delayed generating lower torque, as shown in table 1. In this way, the turn-on angle is continuously updated until a near-zero average torque error is achieved. Therefore, the torque ripple is minimized. The detailed flowchart of the proposed turn-on angle controller is presented in Fig. 7.

where, the notation (n) indicates the n^{th} electrical cycle, k is a small constant. In practice it is challenging to obtain zero

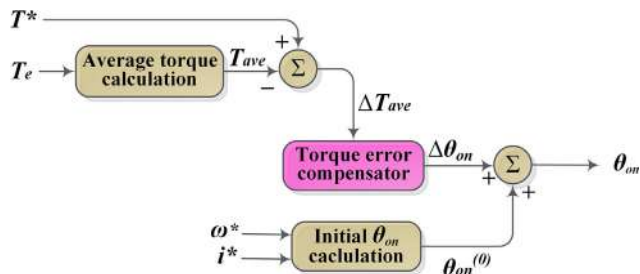


Fig. 6 The diagram of the proposed turn-on angle controller.

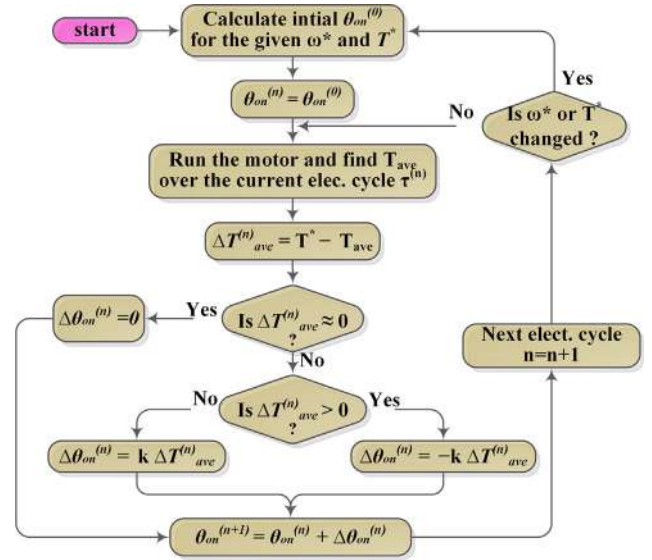


Fig. 7 Detailed flowchart of the proposed turn-on angle controller.

ΔT_{ave} , and thus a minimal pre-selected tolerance is allowed between T^* and T_{ave} .

4.2. Proposed Turn-off angle

An adoptive turn-off angle controller has been proposed to attain the maximum possible utilization of the positive inductance zone without generating considerable negative torque. This can be done by a phase current detector that detects the sampled current I_z at θ_z continuously, where, if I_z is higher than a pre-determined allowed value I_z^{max} , then, a serious negative torque will be generated, and the turn-off angle should be advanced by a proper negative decrement ($-\Delta\theta_{off}$). On the other hand, if I_z is zero, this means the phase current is switched off early, and the positive slop inductance zone is not fully utilized; as a result, the turn-off angle must be delayed by a positive increment ($\Delta\theta_{off}$). In this manner, the turn-off angle is continuously adjusted at each electrical cycle until a small positive value of I_z is attained between zero and I_z^{max} . Noting that I_z^{max} has only a slight influence and can generate ignorable negative torque, as depicted in Fig. 5. The initial turn-off angle is obtained from the initial turn-on ($\theta_{on}^{(0)}$) using equation (5):

$$\theta_{off}^{(0)} = \theta_{on}^{(0)} + 15^\circ \quad (5)$$

The block diagram of the proposed turn-off angle controller is given in Fig. 8.

The detailed flowchart of the proposed turn-off angle controller is presented in Fig. 9

where, $I_z^{(n)}$ is the sampled current I_z at the n^{th} electrical cycle, and k is constant.

Under high speed operation (constant power region), the ability for current control reduces. As a result, the torque ripple increases. Hence, the DITC has the best performance over the low and medium speed ranges. The control of turn-on angle still functional till $\theta_{on} < -\theta_m$. This could happen for a very high operating speed that may exceed the maximum allowable speed. By other means it is not an operating region

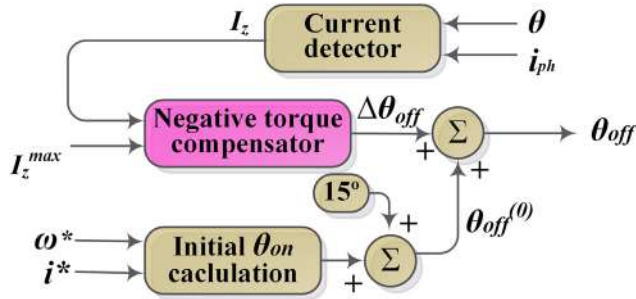


Fig. 8 Block diagram of the proposed turn-off angle controller.

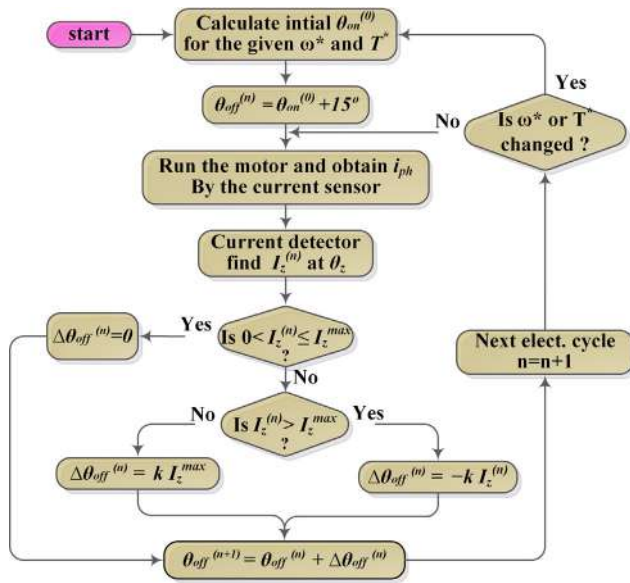


Fig. 9 Detailed flowchart of the proposed turn-off angle controller.

to be considered within the control algorithm. It is beyond the operating speed region for a well-designed SRM. The control of turn-off angle still functional with no limits.

5. Simulation results

Simulations have been carried based on MATLAB/Simulink. The magnetic characteristics (flux and torque) of SRM are obtained using Finite Element Analysis (FEA) and verified experimentally [11]. Fig. 10 shows a screen shot for the Simulink model. The parameters of the adopted SRM prototype are listed in Table 2.

Fig. 11 gives the dynamic results of the system when subjected to step speed changes from 500 to 1000 r/min. Fig. 12 shows the dynamic results of the proposed approach when subjected to a step load change from 1 to 2 Nm. As depicted, a very good torque profile is obtained by the proposed controller.

To investigate the on-line response of the proposed commutation controllers within the DITC, a case study is selected.

Table 2 List of parameters of the selected SRM prototype.

SRM Parameter	Value
Number of phases	3
Stator / rotor poles	12/8
Rated power	750 W
Rated speed	1500 r/min
Phase resistance	0.166 Ω
Stator outer/ bore diameters	138/ 82 mm
Rotor outer/ inner diameters	81.5/ 62.4 mm
Stack/ Air-gap lengths	70 / 0.25 mm
Stator/ rotor pole arcs	15°/ 18°
Turns/ pole	24

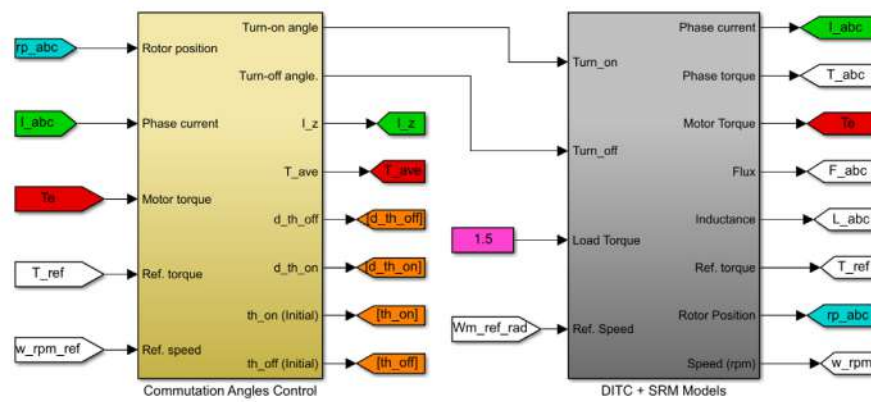
The on-line variations of both switching angles and real-time average torque (T_{ave}) and the sampled current (I_z) are presented. Fig. 13 shows the obtained results at 1000 r/min and a commanded torque of 1.5 Nm.

As shown in Fig. 13a, the average torque error between the commanded torque and the on-line estimated average torque ΔT_{ave} is compensated to pre-defined small tolerance by adjusting the turn-on angle (see Fig. 13c). The sampled current (I_z) is kept below the pre-determined I_z^{max} by means of the turn-off angle controller as illustrated in Fig. 13b and Fig. 13d respectively. I_z^{max} is set between 0.25 A and 0.5 A in this work.

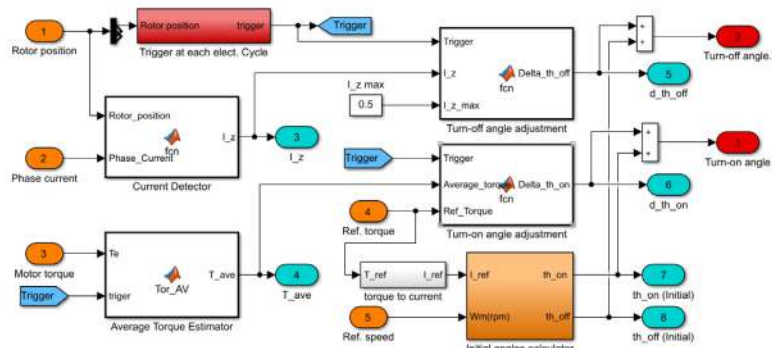
Fig. 13e depicts the electromagnetic torque of SRM, noting that the initial torque ripple (indicated by a small arrow) is compensated, and therefore, the torque profile of the machine is improved. The torque ripple is seen in Fig. 13g. As noted, the ripple decreases as the switching angles are adjusted. The generated torque by each phase is presented in Fig. 13f. Noting that the initial amount of negative torque (indicated by small arrows) is considerable and, therefore, minimized to less effective values. The efficiency is shown in Fig. 13h.

Comparative analysis in both simulations and experimental measurements is presented to verify the proposed controller's effectiveness and feasibility. The traditional current chopping control (CCC) is employed for this purpose since it is widely used in literature. Figs. 14-16 give a comparison between the proposed DITC and CCC. They show the current and torque profiles at three different speeds of 500 r/min, 1000 r/min, and 1500 r/min. The DITC optimizes the switching angles as discussed earlier, while the CCC uses an analytical solution for both switching angles using equations (1) and (5). As observed, the proposed DITC strategy has a significant improvement of torque profile over the CCC method.

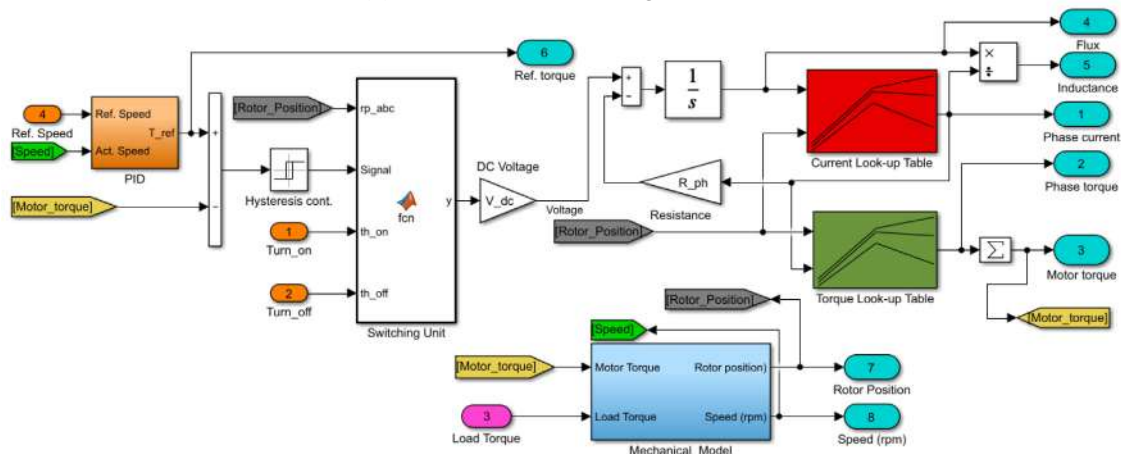
Fig. 17 gives the performance indices when employing the proposed DITC and CCC over the whole speed range of the SRM. The performance indices include torque ripple, average output torque, torque to current ratio, and motor efficiency. As illustrated, the proposed DITC shows clear superiority over the traditional CCC strategy. Where, the torque ripple is significantly reduced, as depicted in Fig. 17a. The proposed method also gives a noticeable higher average output torque (see Fig. 17b) and higher operation efficiency (see Fig. 17c). However, it possesses a bit lower torque to current ratio at high-speed (see Fig. 17d), But it gives a much preferable overall performance.



(a) The complete system model

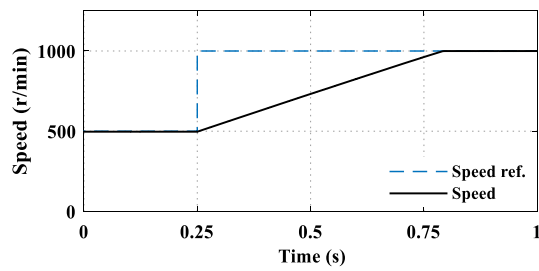


(b) The commutation angles control

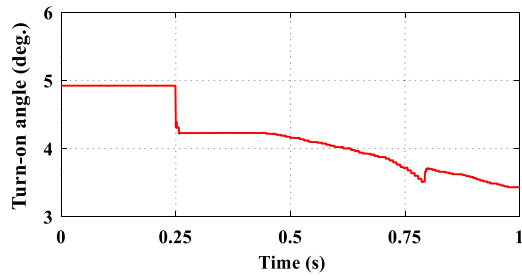


(c) PID speed controller, DITC algorithm, and electrical and mechanical motor models

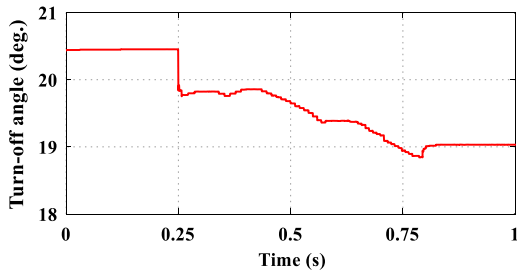
Fig. 10 MATLAB Simulink model of the proposed system.



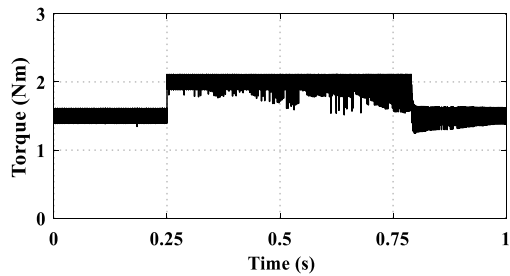
(a) Speed



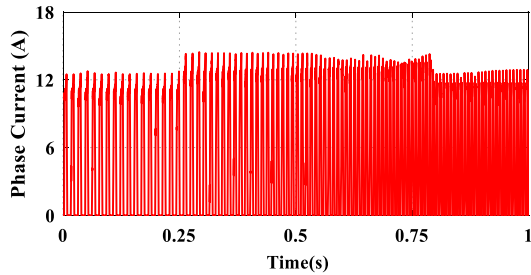
(b) Turn-on angle



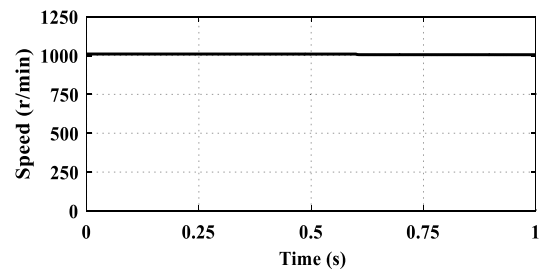
(c) Turn-off angle



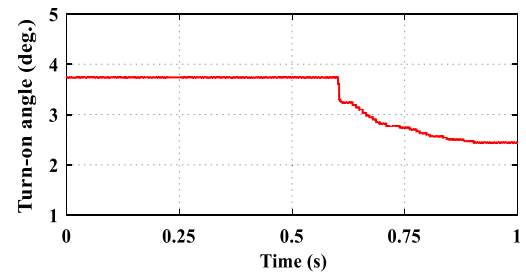
(d) Torque



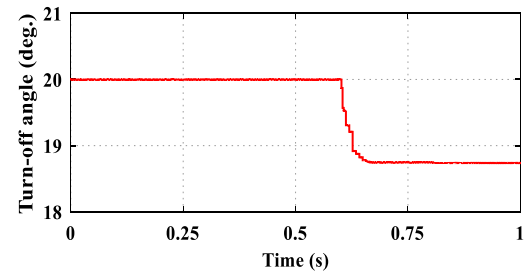
(e) Phase current



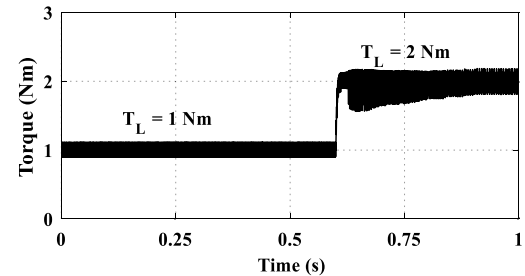
(a) Speed



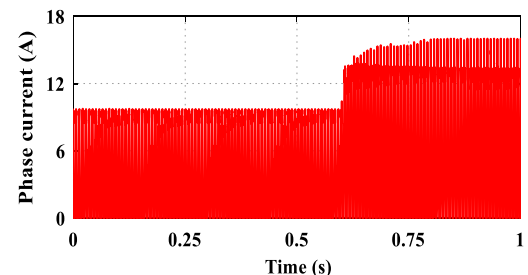
(b) Turn-on angle



(c) Turn-off angle



(d) Torque



(e) Phase current

Fig. 11 Dynamic response with speed changes.

Fig. 12 Dynamic response with load change.

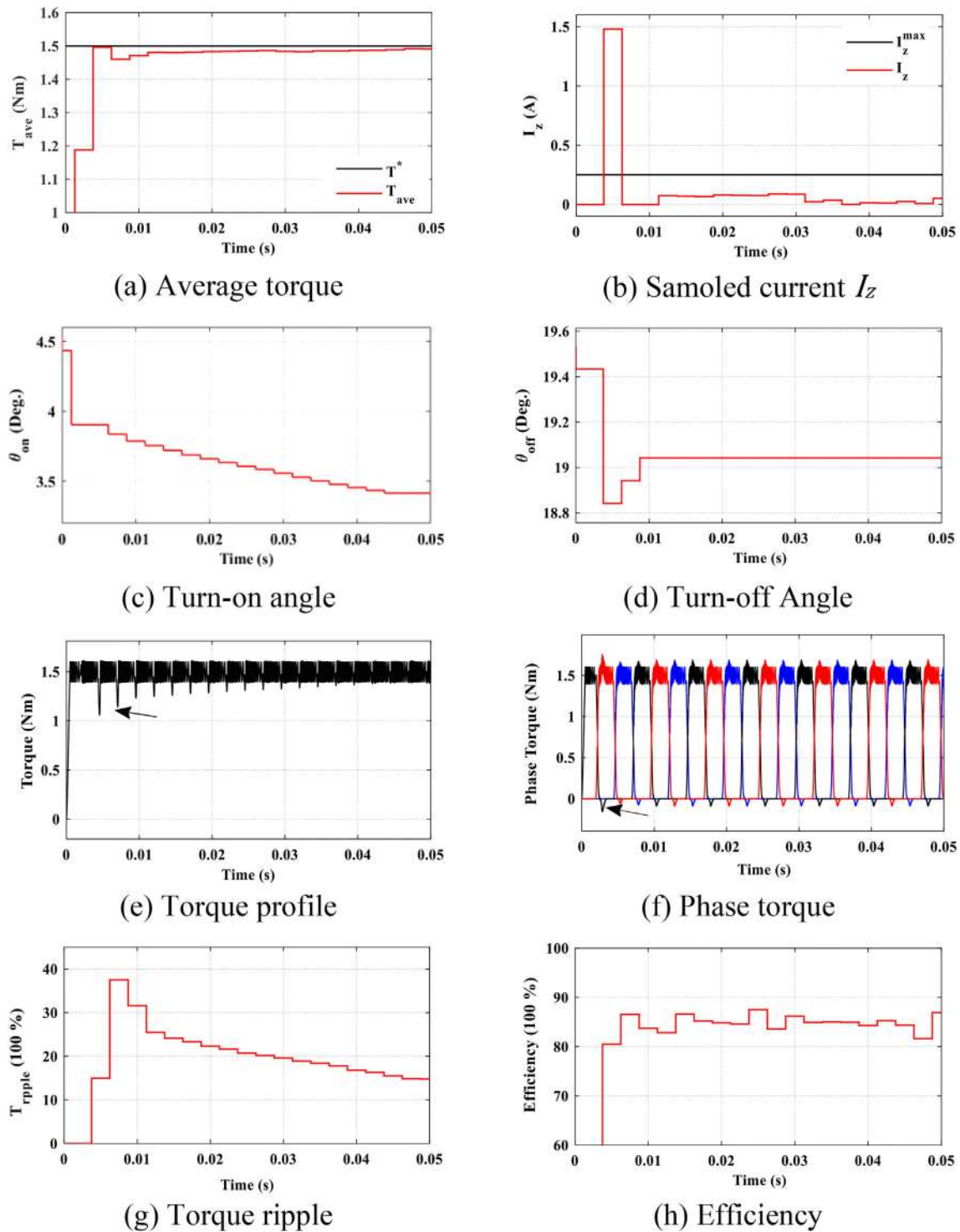


Fig. 13 Response of the proposed DITC at 1000 r/min speed and 1.5 Nm torque reference.

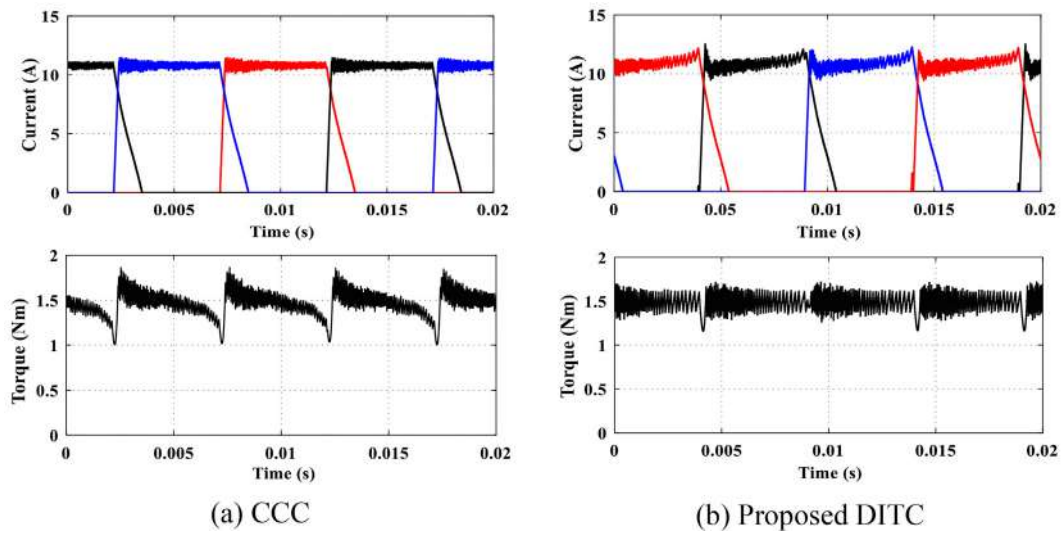


Fig. 14 Simulation results at a speed of 500 r/min and 1.5 Nm torque.

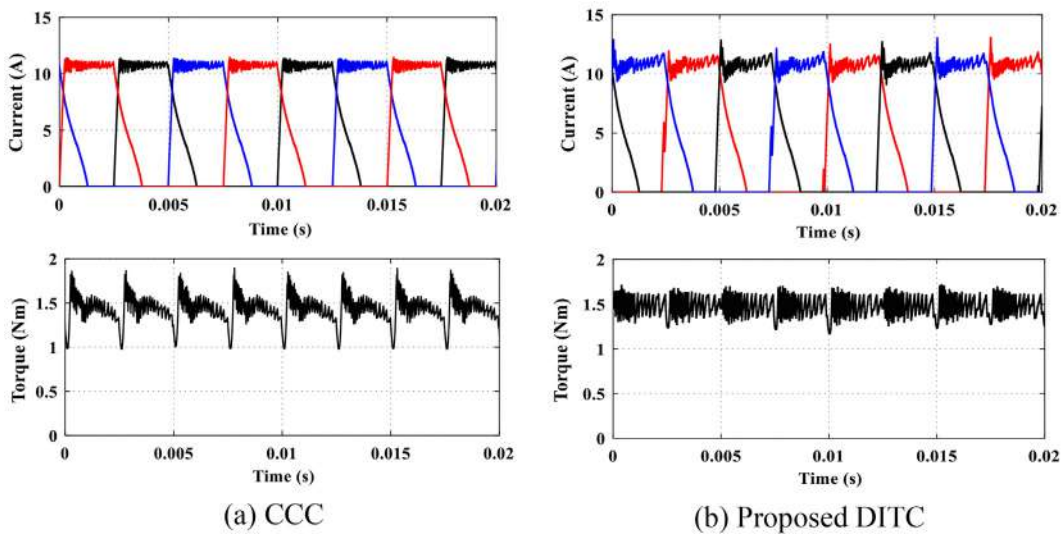


Fig. 15 Simulation results at a speed of 1000 r/min and 1.5 Nm torque.

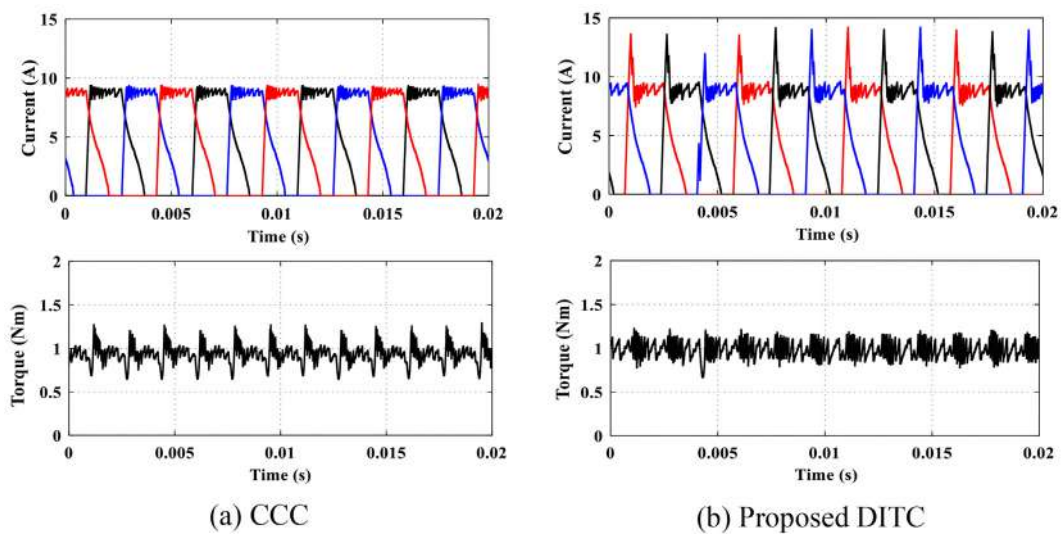


Fig. 16 Simulation results at a speed of 1500 r/min and 1 Nm torque.

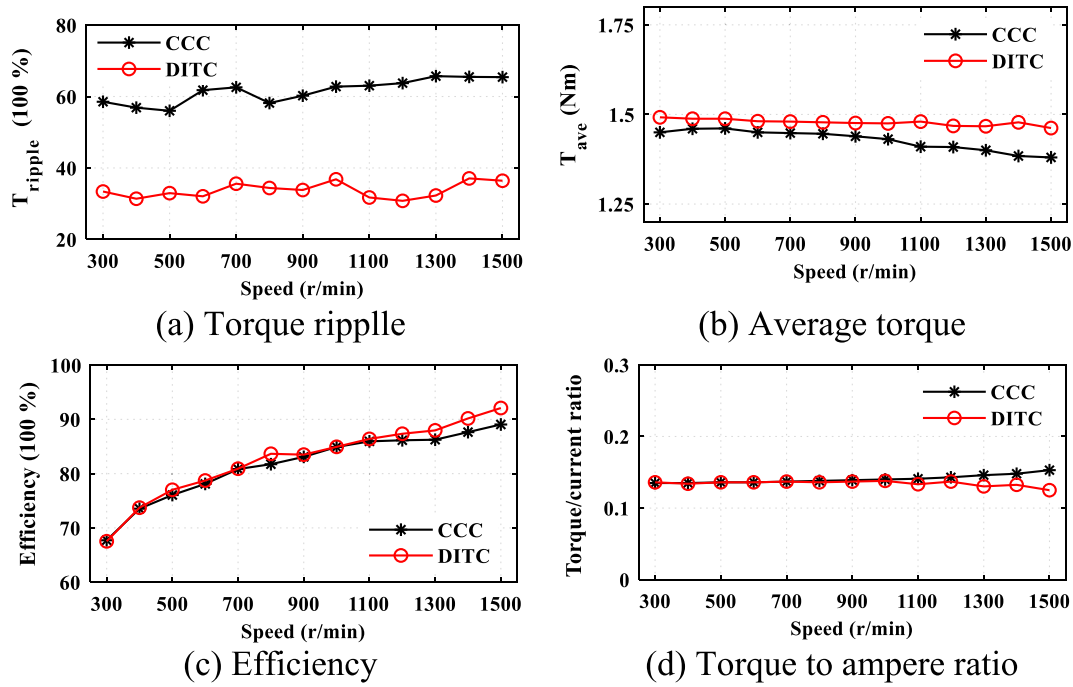


Fig. 17 Comparison of performance indices between the proposed DITC and conventional CCC schemes.

6. Experimental verification

The experimental platform shown in Fig. 18 is built to validate the simulation findings. The SRM is mechanically coupled to an electromagnetic brake. The SRM drive system involves an asymmetrical bridge IGBT converter, TMS320F28335 DSP control board, current transducers, incremental encoder, data acquisition unit (DAQ NI USB-6009).

The experimental results involve the steady state performance of the proposed control method compared to the conventional CCC methods. Besides, they include the dynamic system performance under step change in speed and step change in loading torque.

Figs. 19–21 show the experimentally measured current and torque waveforms obtained from the proposed DITC and the conventional CCC at three different operating speeds of 500 r/min, 1000 r/min, and 1500 r/min.

As depicted in the figures, by implementing the proposed DITC strategy, the torque ripple is reduced, and thus, the torque profile of the machine is highly improved. However, in the simulation results, torque ripple minimization is more visible than in the experimental results. These differences are mostly impacted by several types of experimental noise/error. Also, the modelling error of motor torque will affect the ripple amount. However, both findings in MATLAB simulations and experimental measurements con-

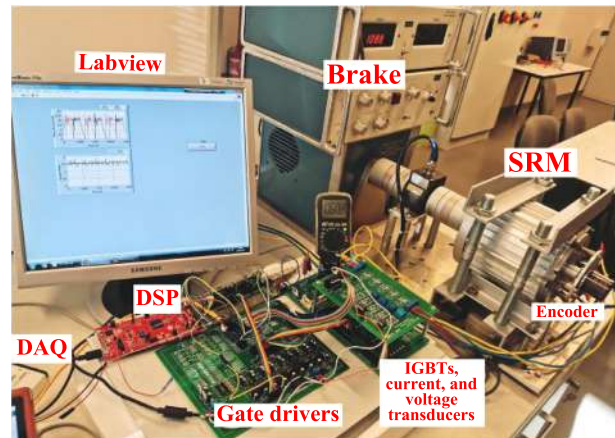


Fig. 18 The experimental platform.

firm the feasibility and effectiveness of the proposed strategy.

The experimental dynamic tests of the system including speed step response and torque step response are depicted in Fig. 22 and Fig. 23, respectively. As shown in both tests the switching angles are automatically adjusted during the transit period by means of the proposed controller. a very good torque profile is seen in Fig. 22d and Fig. 23d.

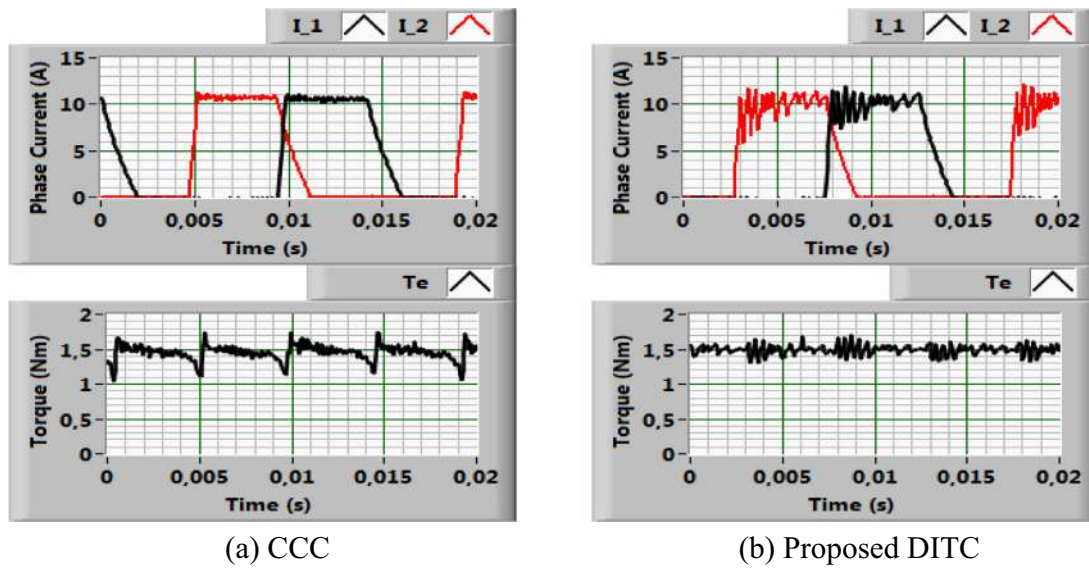


Fig. 19 Experimental results at a speed of 500 r/min and 1.5 Nm torque.

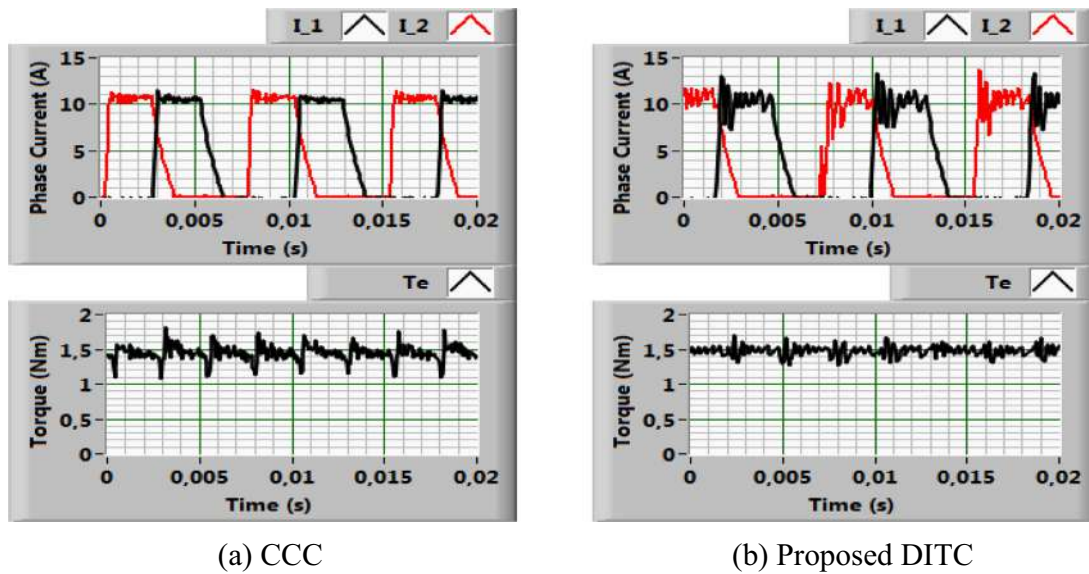


Fig. 20 Experimental results at a speed of 1000 r/min and 1.5 Nm torque.

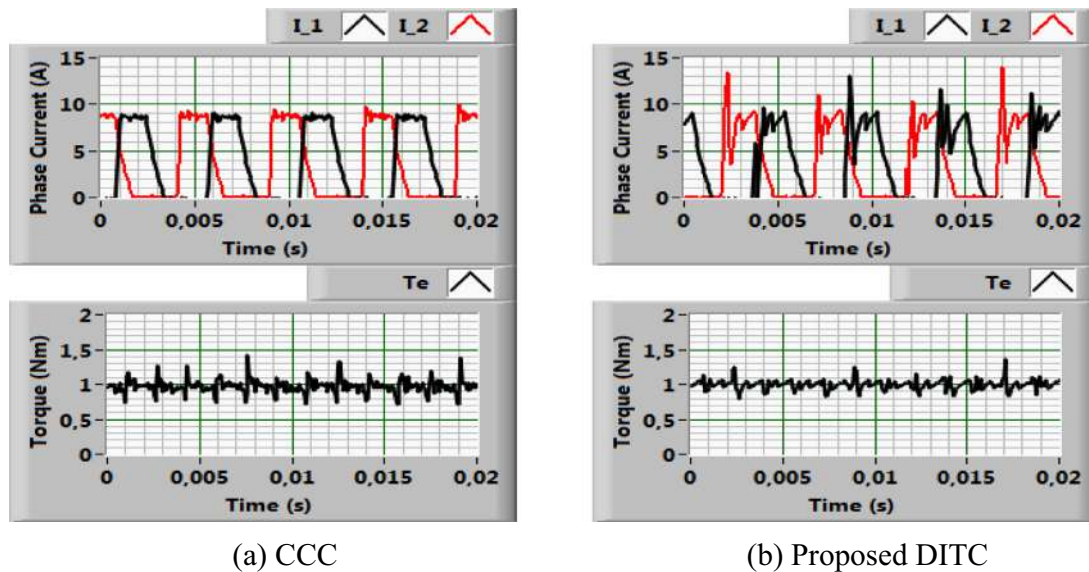
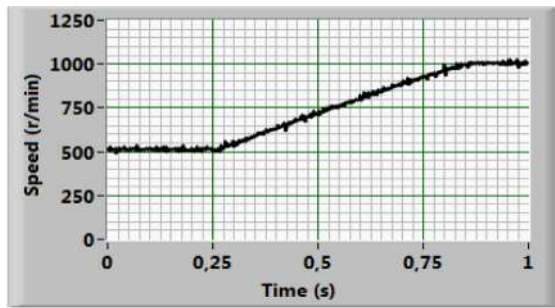
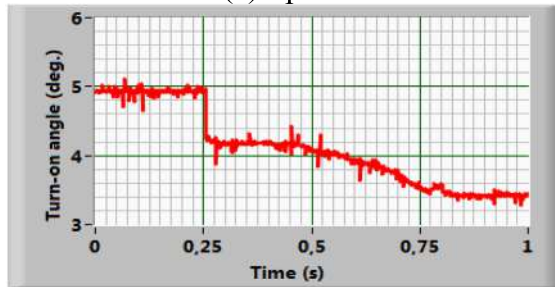


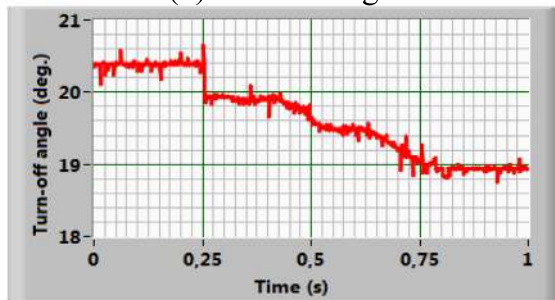
Fig. 21 Experimental results at a speed of 1500 r/min and 1 Nm torque.



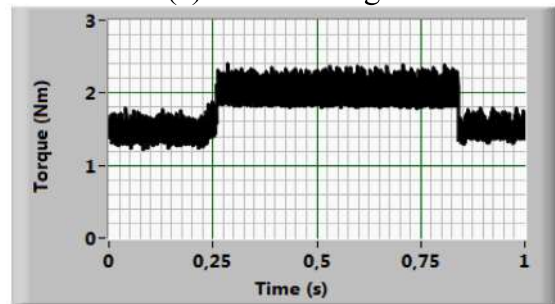
(a) Speed



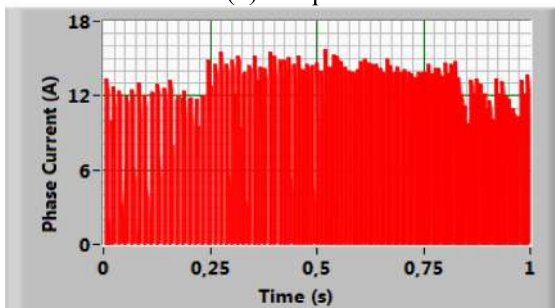
(b) Turn-on angle



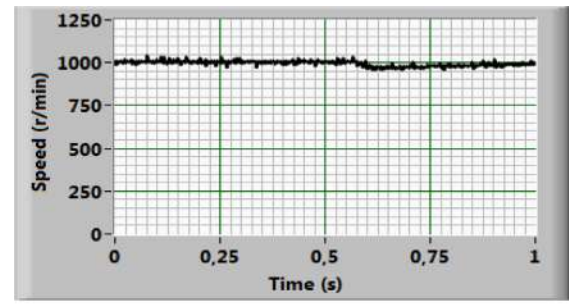
(c) Turn-off angle



(d) Torque



(e) One phase current



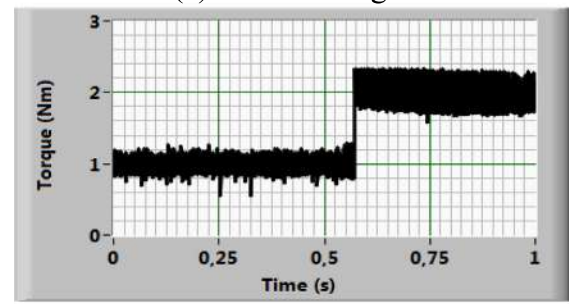
(a) Speed



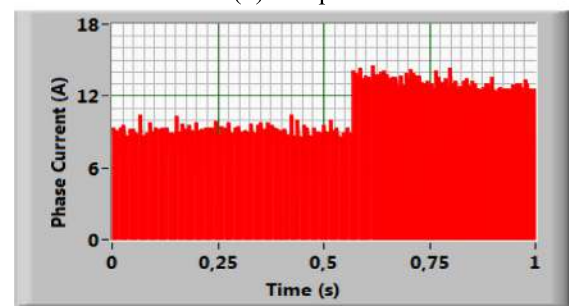
(b) Turn-on angle



(c) Turn-off angle



(d) Torque



(e) One phase current

Fig. 22 Dynamic response with speed changes.

Fig. 23 Dynamic response with load change.

7. Conclusion

An enhanced DITC based adaptive commutation strategy is proposed. It aims to improve the torque profile and efficiency of SRM. According to the operating speed and loading torque of SRM, initial values for switching angles are selected to fully utilize the torque generation capability of SRM. A torque error compensator and current detector are used to modify the initially obtained angles in real-time operation. The main concept behind the turn-on angle adjustment is to reduce the error between real-time average torque and its commanded reference torque. Thus, it minimizes torque ripple. Moreover, the turn-off angle is adjusted to prevent an affective negative torque generation. Thus, it improves motor efficiency. Both findings in simulations and experimental measurements confirm the feasibility and effectiveness of the proposed strategy to reduce torque ripple and improve motor efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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