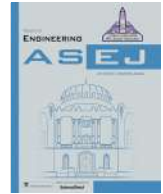




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An enhanced direct instantaneous torque control of switched reluctance motor drives using ant colony optimization

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ABSTRACT

The highly nonlinear characteristics of switched reluctance motors (SRMs) are the drawback that complicates their control and modeling. Hence, obtaining the best performance becomes a challenging task. Therefore, this paper presents an upgraded methodology of the ant colony optimization (ACO) technique. The proposed multistage ant colony optimization (MSACO) enhances the search capability of the classical ACO. Therefore, it helps to find the best switching angles without violating pre-specified constraints. The optimized angles are used to implement an improved high-performance direct instantaneous torque control (DITC) drive. This work focuses on reducing torque ripple, improving motor efficiency, and preventing generating a considerable amount of negative torque. Moreover, a current detector is used to provide information about negative torque production and thus helps to find optimal angles and avoid the set of solutions that give a considerable amount of negative torque. Furthermore, a new switching strategy is utilized to implement an efficient hysteresis torque controller, where the selection of the switching mode of the power converter is entirely determined based on the inductance profile of the SRM. The utilized switching strategy guarantees accurate torque tracking over the entire phase excitation period; thus, the machine's torque profile is improved further. The simulation results showed the superiority of the proposed control method over the traditional control method. In addition, the experimental measurements have been carried out to verify the simulation findings using a three-phase 750 W, 12/8 SRM prototype.

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1. Introduction

Even though the induction motors (IMs) and the permanent magnet motors (PMMs) provided fully mature technologies, the switched reluctance motors (SRMs) have several advantages compared to other motor topologies. The SRMs have a robust design,

low cost, fault tolerance, simple construction, and the ability to operate at high rotational speeds or temperatures. Moreover, SRMs are subjected to electrical phase isolation, which elevates SRMs over the other competing motors from a reliability point of view. Besides the phase's isolation, the absence of permanent magnets in their structure and the construction of their rotors without

Abbreviations: ACO, Ant Colony Optimization; AHBC, Asymmetric Half-Bridge Converter; ATC, Average Torque Control; CCC, Current Chopping Control; DITC, Direct Instantaneous Torque Control; FEM, Finite Element Method; GA, Genetic Algorithm; IITC, Indirect Instantaneous Torque Control; IMs, Induction Motors; LUT, Look-Up Tables; MPPT, Maximum Power Point Tracking; MSACO, Multistage Ant Colony Optimization; PMMs, Permanent Magnet Motors; PV, Photovoltaic; SRMs, Switched Reluctance Motors; TSF, Torque Sharing Function.

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windings are two additional features that set SRMs apart from other machines [1–3].

The stator and rotor in an SRM have salient poles. Due to the two-sided salience arrangement, the magnetic torque and flux linkage characteristics are extremely nonlinear functions of rotor position and current. Therefore, SRM modeling using general linear methods is challenging [4]. As a result, accurate modeling for these machines is commonly obtained either by experimental measurements or the finite element analysis method (FEM) [5]. By magnetizing any stator pole pair through a single current pulse, the nearest rotor pole pair will be attracted and aligned with the magnetizing stator pole pair. Hence, through sequentially energizing the stator winding, a magnetic torque in any direction of rotation will be generated. However, owing to the salient structure and the adopted energizing strategy, SRMs experience undesired ripple in the generated torque. As a result, vibration and acoustic noise issues will be produced accordingly.

Due to their advantages, growing interest in utilizing the SRMs in the industry has recently increased. And several issues related to its design, analysis, modeling, and control have been brought up. As a result, several studies have been carried out to address these issues, and the recent literature focused mainly on solving the torque ripple problem of the SRMs. Other objectives are also included in the recent literature, such as maximizing the output torque and power of these machines and improving their efficiency and the torque to current ratio. Some authors proposed maximizing the SRMs' performance by optimizing their geometrical dimensions and structures [6–9]. This strategy can enhance different aspects of SRMs performance and lead to torque ripple suppression, but it can do so only to a certain extent. On the other hand, other authors proposed advanced control schemes to maximize the benefits of SRMs and minimize their drawbacks [10–12]. The control schemes can provide significant torque ripple reduction and a remarkable improvement in other aspects of machine performance.

The most commonly applied control schemes in SRMs drives are current chopping control (CCC), average torque control (ATC), indirect instantaneous torque control (IITC), and direct instantaneous torque control (DITC) [11]. Each of these control schemes has its distinct benefits and drawbacks. In CCC, no torque controller or torque estimation unit is required. Thus, the drive's cost and complexity are reduced. However, this strategy suffers from a substantial amount of torque ripple as the applied current to each phase is regulated as a square pulse, and current profiling is not possible. Consequently, torque ripple suppression can only be attained partially by optimizing the excitation parameters (turn-on and turn-off angles) [13–16]. The ATC strategy can control the machine's output power in a wide speed range by controlling the average torque value. But this strategy requires an additional torque regulator. Like the CCC strategy, in the ATC method, no current profiling can be performed; thus, each phase's current is controlled in square waveforms. As a result, the ATC also suffers from considerable torque ripple [17,18].

On the other hand, The DITC and IITC can heavily reduce the torque ripple by controlling the instantaneous torque and generating an optimal current profile. Thus, the torque quality of the machine can be significantly improved, especially at low and medium speed ranges [11]. However, within these strategies, the phase current may reach very high peak values to make up for the poor torque generating capability near the aligned or un-aligned rotor positions.

Generally, further improvements can be made to maximize the benefits and minimize the drawbacks of either control scheme. For instance, in [12], a cascaded PID speed controller is implemented. The PID parameters of the cascaded controller are optimized using two approaches, including spotted hyena optimizer and local unimodal sampling. By this method, the speed of the machine is controlled effectively, and the torque ripple is partially reduced.

In [13], a new multilevel converter is implemented within a CCC system. The voltage excitation and demagnetization capabilities are improved; therefore, the phase current tracking capability is improved at high-speed ranges. However, multilevel converters require more power electronic devices, so the cost of SRM drive will be increased. In [14], a CCC scheme is proposed where the turn-off angle is off-line optimized according to a multi-objective function, while the turn-on angle is tuned online in order to force the incoming phase current to reach its reference value precisely at the turn-off moment of the previous phase. The torque ripple and the copper loss of the tested machine are reduced. However, this strategy can perform well only at low and medium speed ranges because using a delayed turn-off angle will generate significant negative torque. In [15], a low-cost CCC drive is implemented, and the switching angles are optimized to improve the SRM performance at extended speed ranges. The output torque is maximized, and torque ripple is minimized without considering other aspects such as machine efficiency or torque to current ratio. In [16], analytical expressions for both firing angles are utilized to implement an effective CCC strategy; these expressions allow the phase current to reach its commanded value and decay to zero at desired rotor positions to increase the machine efficiency. However, this method does not consider the torque ripple problem. In [17], a new ATC scheme is implemented by involving a flux controller, a current controller, and a microstepping process. By employing this method, the average torque can be controlled in a smaller angle interval, thus improving the torque quality of the SRM. However, this method complicates the control algorithm. In [18], a simplified ATC system is implemented by optimizing the firing angles. The work focused on two objectives: the torque ripple and the machine's efficiency. Additionally, proper constraints for both firing angles are included to attain further improvements.

In order to implement the IITC scheme for SRMs, a torque sharing function (TSF) is needed to distribute the reference torque between the machine phases. Each phase torque signal is then converted to a profiled reference current signal. And by controlling the actual current according to the reference current signal, the machine torque will be regulated indirectly. The IITC scheme is implemented in [19] by using the TSF strategy. The generated torque error is calculated via a torque model and fed back to the TSF to make additional torque error compensation; thus, the torque profile can be improved further. In [20], a new TSF is implemented using an effective strategy to generate the reference current. The current tracking error is minimized, and the torque quality of SRM is improved. Moreover, a secondary objective to reduce copper losses is also achieved. In [21], a novel hybrid TSF is presented. The hybrid TSF consists of two parts. The first part is built based on a non-linear mathematical expression. The second part is created during the real-time operation of the SRM to compensate for the torque tracking error during phase demagnetization. And hence, the torque ripple of the SRM is reduced further. The IITC scheme is also implemented in [22], where by employing a modulating factor, the currents that undergo overlapping are manipulated in real-time to provide further torque ripple suppression.

Unlike IITC, the DITC deals with the motor torque directly and does not require torque to current transformation; therefore, it can provide a better torque profile with a superior dynamic response. A detailed comparative analysis of three control schemes, including the DITC, IITC, and ATC schemes, is presented in [23]. Among the three-control methods, the DITC method provided the minimal torque ripple and best torque profile. Moreover, the DITC gave the highest machine efficiency and the best torque to current ratio at low and medium speed ranges. As a result, the DITC can be considered an effective torque control scheme for SRMs. High-performance DITC schemes are presented in [24,25]. By implementing real-time commutation strategies, both firing angles

are optimally adjusted during the machine operation to provide further torque ripple minimization and to avoid negative torque production. In [26], the PWM controller is included within the DITC scheme to attain further torque ripple reduction and thus improve the torque quality of the SRM.

In [27], the ant colony optimization (ACO) is used to obtain optimal proportional-integral (PI) parameters to improve the performance of the speed controller for the SRMs. Moreover, a comparative analysis between the proposed ACO and Genetic Algorithm (GA) is also presented. The proposed ACO showed a greater superiority in tuning PI parameters over the GA approach. In [28], A photovoltaic (PV) system with maximum power point tracking (MPPT) is involved to power the SRM efficiently. The PI parameters of the proposed controller are optimized using the BAT search algorithm; therefore, the tracking response of MPPT for PV systems is increased.

The novelty of this article is the development of an optimized DITC scheme to enhance both the torque quality and the efficiency of SRMs. A promoted ant colony optimization (ACO) methodology is utilized for this purpose. The proposed multistage ant colony optimization (MSACO) provides enhanced search capability that is compatible with the nonlinearities of SRMs. Besides, it can find the optimal firing angles under different operating conditions without violating pre-specified constraints. Moreover, a current detector is used to provide information about the negative torque production and thus helps MSACO to avoid the set of solutions that give a considerable amount of negative torque. Hence, further efficiency improvement is achieved. Furthermore, a new switching strategy is adopted to implement an efficient hysteresis torque controller. Where the selection of the switching mode of an asymmetric half-bridge converter is entirely determined based on the rate of change of the inductance characteristics. The proposed switching strategy guarantees accurate torque tracking over the entire phase excitation period; thus, the machine's torque profile can be improved further. Finally, the experimental verification is achieved along with the simulation results.

The rest of this paper is organized as follows: Section II briefly describes two common control schemes of the SRM, and a brief illustration of the effect of the firing angles on SRM performance is also presented. Section III demonstrates the proposed DITC scheme. Section IV shows the simulation results. The experimental work is presented in Section V. Section VI is the conclusions.

2. Control and analysis of switching strategy for SRM drives

The current chopping control (CCC) strategy is widely utilized in SRMs because it can offer a simple, less costly, and efficient controller. Fig. 1 depicts the block diagram of the CCC scheme. In this control method, a proportional-integral (PI) speed controller is used to regulate the motor speed (ω). The output of the speed controller is set as a constant reference current (i^*), and the phase

current (i_{ph}) is measured using a current sensor. The error between the reference and the phase currents (Δi) and the firing angles (θ_{on} and θ_{off}) are fed to a hysteresis current controller to generate the appropriate switching signal for the power IGBT converter to rotate the machine. A position encoder is utilized to compute the rotor position (θ), and the rotation speed (ω) is estimated by differentiating the position of the rotor.

Fig. 2 depicts the SRM drive using the DITC method. The output of the PI speed regulator is the commanded reference torque (T^*), and the real-time motor torque (T_e) is estimated based on the instantaneous rotor position and the phase current using the look-up tables method. The instantaneous torque error (ΔT) between the commanded torque T^* and the instantaneous torque of the machine is fed directly to a switching unit or torque controller to generate a suitable switching signal for the IGBT power converter. The DITC deals directly with machine torque, resulting in improved dynamic response and lower torque ripple. Moreover, in the DITC, no torque to current conversion nor current controller is required.

The power converter in SRM drives is often an asymmetric half-bridge converter (AHBC). This circuit can apply three voltage levels to the SRM winding: $+V_{dc}$, 0, and $-V_{dc}$, as shown in Fig. 3.

To control the current in the SRM winding, soft and hard switching modes can be adopted as the switching rule of the torque controller. The circuit connection in Fig. 3a energizes the machine windings in both modes. However, to de-energize the windings, the connection in Fig. 3b is used to supply 0 V in the soft-switching mode, while the connection in Fig. 3c is utilized in the case of hard switching mode.

The commutation controller provides the commutation or firing angles to the DITC drive to determine an appropriate conduction range for each phase. These angles significantly impact the SRM performance indices, such as the average torque, torque ripple, and the efficiency of the SRM, as will be illustrated next.

In SRM, the inductance, flux, and torque characteristics are highly nonlinear against the rotor position. And thus, accurate selection of firing angles is a challenging task. Fig. 4 depicts the current (i_{ph}) along with the inductance (L) profile for one phase of the SRM, where θ is the position of the rotor, θ_m and θ_z are the instant positions when the rotor and stator poles begin and end overlapping, respectively, θ_{on} and θ_{off} are the switch-on and switch-off angles.

To produce positive (motoring) torque, each phase must be energized within the positive slope region of the inductance ($dL/d\theta > 0$), see Equation (1) [5].

$$T_e = \frac{1}{2} i^2 \frac{dL(i, \theta)}{d\theta} \quad (1)$$

Otherwise, if the phases are energized within the negative slope region ($dL/d\theta < 0$), then a negative (braking) torque will be generated. Moreover, if the phases are energized near the completely aligned or unaligned positions of the rotor ($dL/d\theta \approx 0$), then a

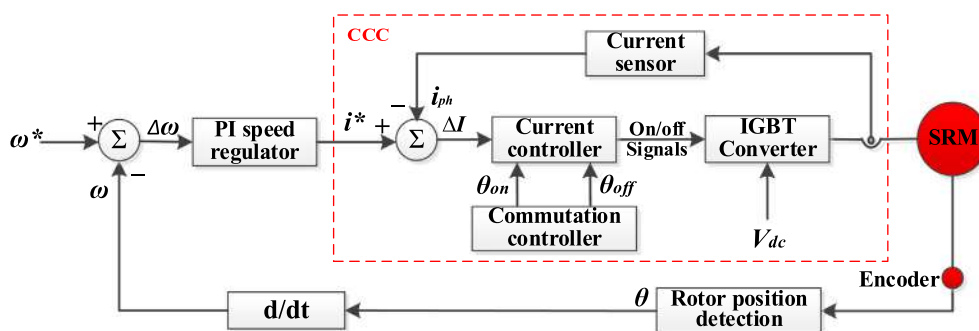


Fig. 1. SRM drive based on CCC strategy.

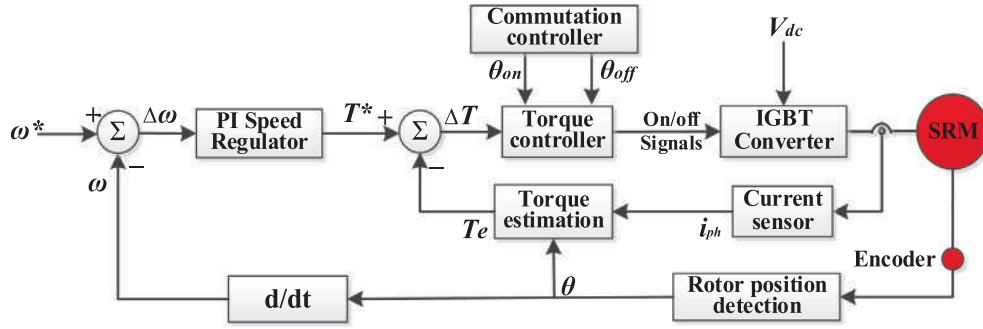


Fig. 2. SRM drive based on DITC strategy.

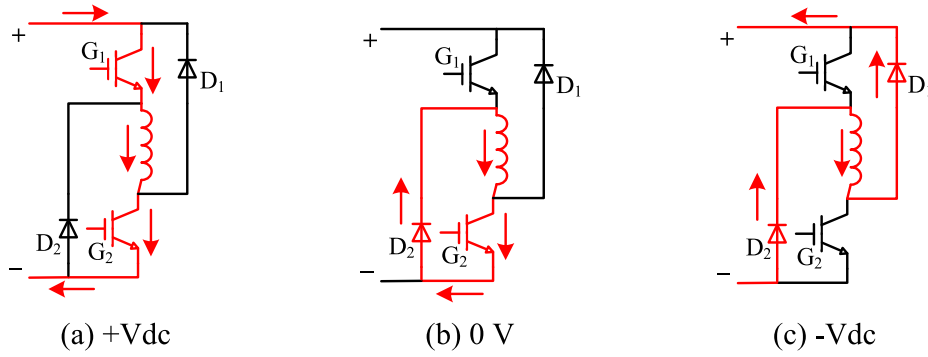


Fig. 3. An asymmetric half-bridge converter in different connections.

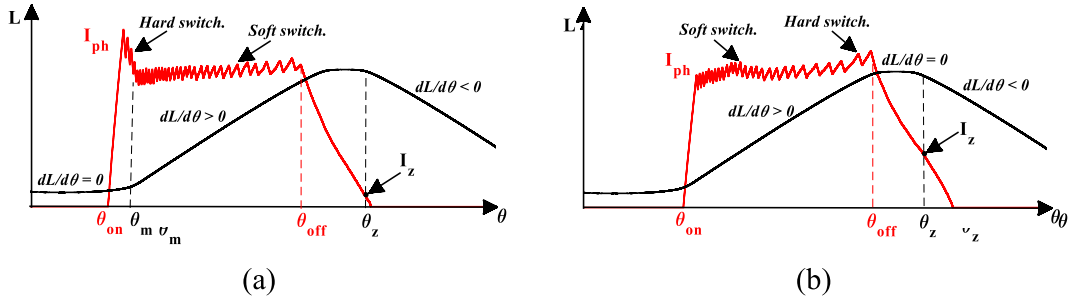


Fig. 4. Current and inductance profiles of one phase of the SRM.

higher current will be required to produce the commanded torque. For example, in the case of Fig. 4a, the SRM windings are switched-on early before θ_m , and since the rate of change of the inductance between θ_{on} and θ_m is very low, then higher current will be generated, leading to less motor efficiency. Alternately, if the SRM windings are switched-on at or after θ_m (see Fig. 4b), then, in this case, the inductance part before θ_m will not be utilized. Therefore, the torque-producing capability of the machine will be reduced. Regarding the switch-off angle, if the SRM windings are switched off early before the fully aligned position (see Fig. 4a), then the phase current will have sufficient time to completely demagnetize before the negative slope part of the inductance (θ_z). Thus, in this case, the detected current I_z at θ_z will be small or zero, and therefore, no serious negative torque will be generated. However, in this case, the positive slope part of the inductance after θ_{off} will not be utilized. In contrast, if the SRM windings are switched off near the inductance's fully aligned position, the phase current will not have enough time to decay to a small value before θ_z (especially at high-speed operation). Therefore, the high current I_z seen in

Fig. 4b will lead to a significant braking torque. Consequently, the firing angle should be selected based on an accurate optimization strategy for optimum machine performance.

3. The proposed DITC strategy

In this work, two modifications have been proposed to implement an improved DITC of SRM drives. First, an optimal commutation strategy has been developed, where the firing angles are optimized off-line using a promoted ant colony optimization (ACO) methodology. The second modification is based on the switching rule of torque controller, where the soft and hard switching modes are utilized depending on the instantaneous rotor position and the pre-selected optimal firing angles.

3.1. Proposed commutation strategy

The aim is to develop a commutation controller that can continuously provide the best firing angles for DITC drive to improve SRM

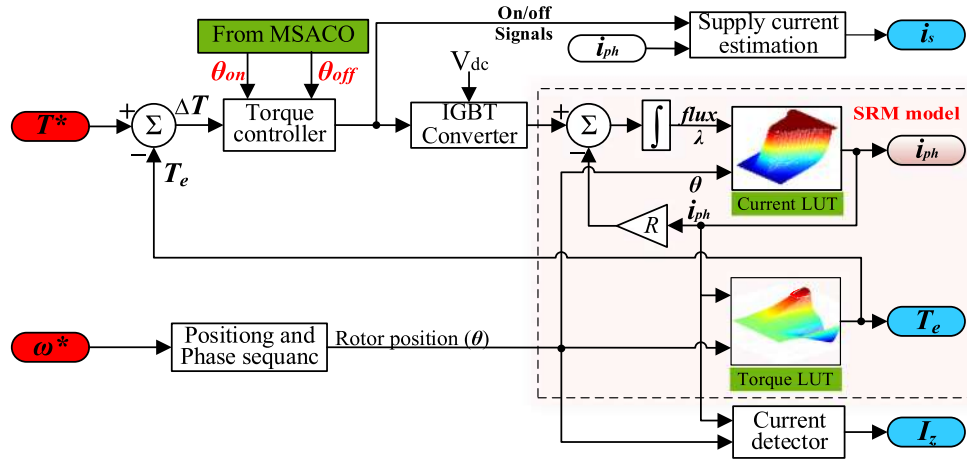


Fig. 5. Steady-state Simulink model for the SRM drive using the DITC method.

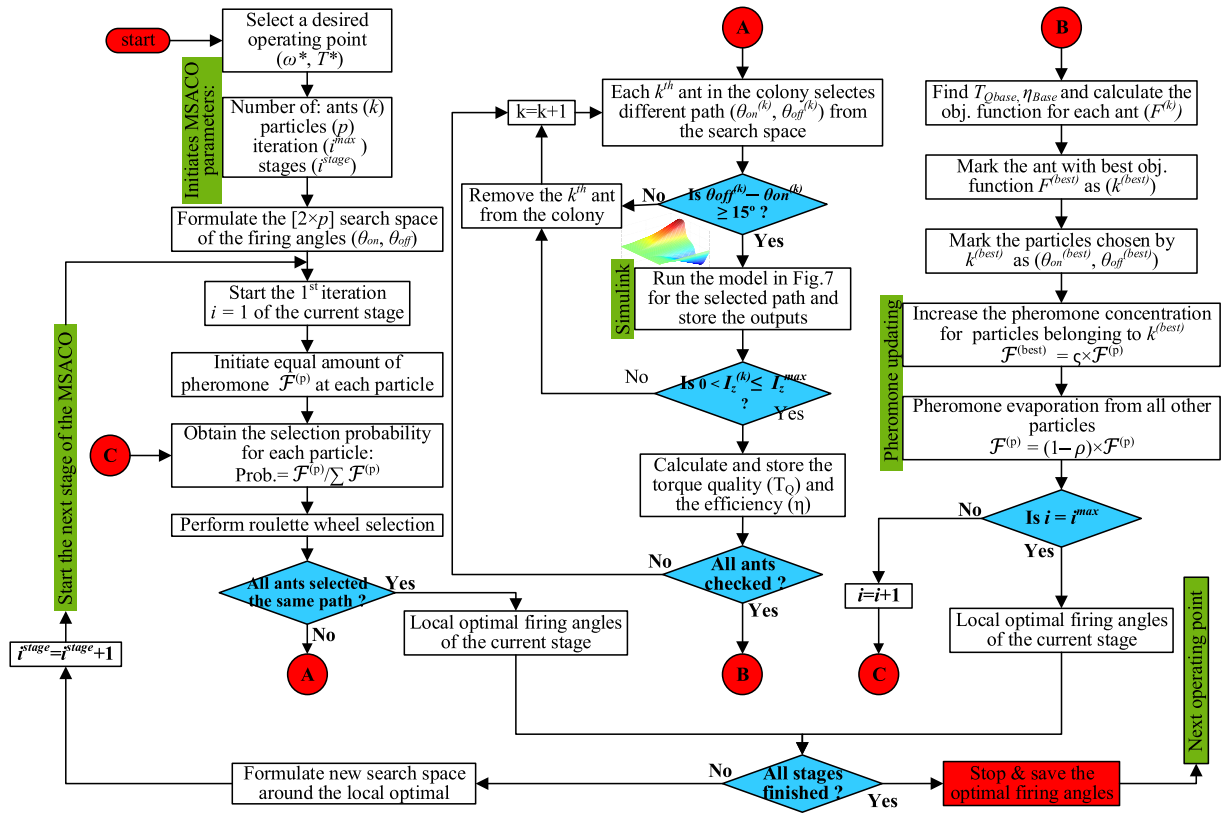


Fig. 6. Detailed flowchart of the optimization process for firing angles.

performance under different speeds and torque conditions. These angles can be determined using efficient optimization techniques. The proposed MSACO is utilized since it has many advantages, such as fast allocation of reasonable solutions, short computational time, and guaranteed convergence. However, to formulate the optimization problem, a steady-state DITC Simulink model is built and utilized, as seen in Fig. 5.

The model has four inputs: speed (ω^*), torque reference (T^*), and the firing angles (θ_{on} and θ_{off}). The outputs are motor torque waveform (T_e), supply current waveform (I_s), and the sampled cur-

Table 1
MSACO parameters.

MSACO Parameters	Range
Number of ants	30
Number of particles/stage	13
Number of stages	3
Allowed iterations/ stage	25
Pheromone scaling factor (ζ)	1.5
Pheromone evaporation rate (ρ)	0.2

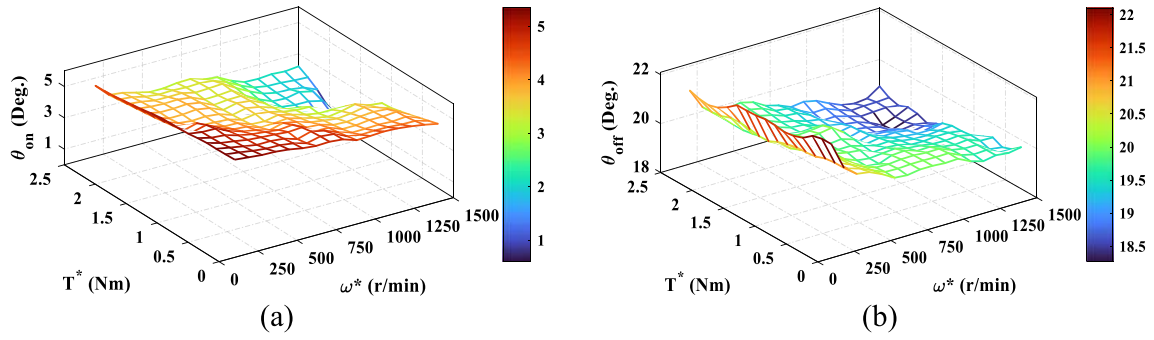


Fig. 7. The results of the optimization problem (a) Switch-on angle (b) Switch-off angle.

Table 2

Proposed sub-regions of the positive slope part of the SRM inductance.

Region	Start	End	Switching mode
I	θ_{on}	θ_m	Hard
II	θ_m	$\theta_m + 15^\circ$	Soft
III	$\theta_m + 15^\circ$	θ_{off}	Hard

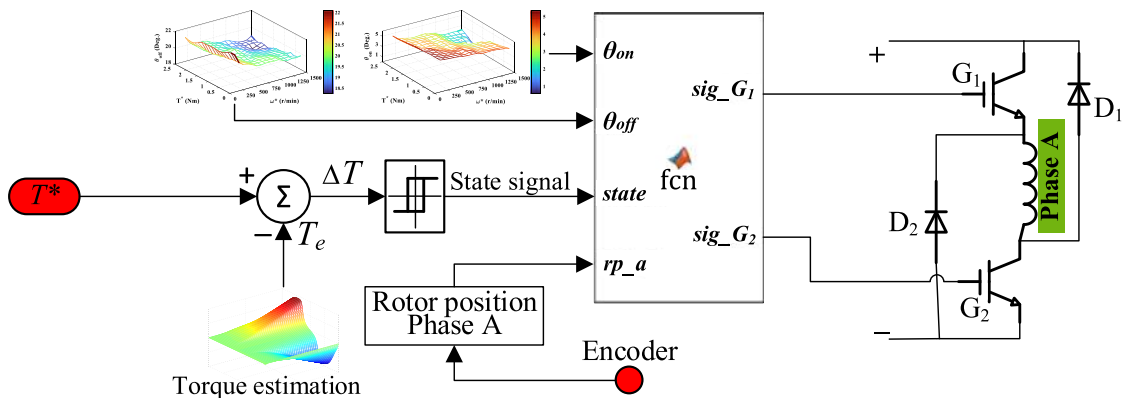


Fig. 8. Proposed switching strategy for the DITC drive.

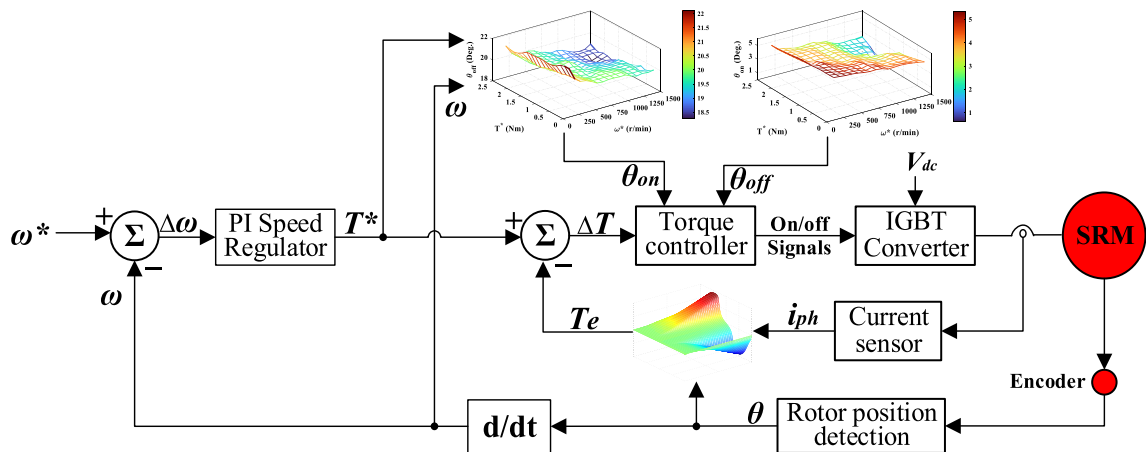


Fig. 9. Proposed DITC drive.

Table 3

Data of the chosen SRM prototype.

Parameter	Value	Parameter	Value
Phases	3	Stator outer/ inner diameter	138/ 82 mm
Poles (stator/ rotor)	12/8	Rotor outer/ inner diameter	81.5/ 62.4 mm
Power	750 W	Air-gap /stack lengths	0.25 / 70 mm
Rated speed	1500 r/min	Pole arcs (stator/ rotor)	15°/ 18°
Resistance/ phase	0.16 Ω	No. of turns/ pole	24

rent I_z . The machine model is achieved using the look-up tables that contain the torque and flux data. The torque and flux data of SRM can be measured experimentally or calculated using the finite element method (FEM).

For each combination of speed and torque, the MSACO simulates the steady-state model, gets its outputs, determines the value of the objective function, and checks the constraints. The MSACO continuously changes the firing angles (θ_{on} and θ_{off}) until it finds the optimal firing angle that gives the best SRM performance or reaches the maximum allowable iterations.

The average torque (T_{ave}), net torque ripple (T_{ripple}), and the efficiency (η) of the SRM are all mixed in a multi-objective function (F) and optimized as shown in Equations (2) to (6).

$$T_{ave} = \frac{1}{\tau} \int_0^{\tau} T_e(t) dt \quad (2)$$

$$T_{ripple} = T_{max} - T_{min} \quad (3)$$

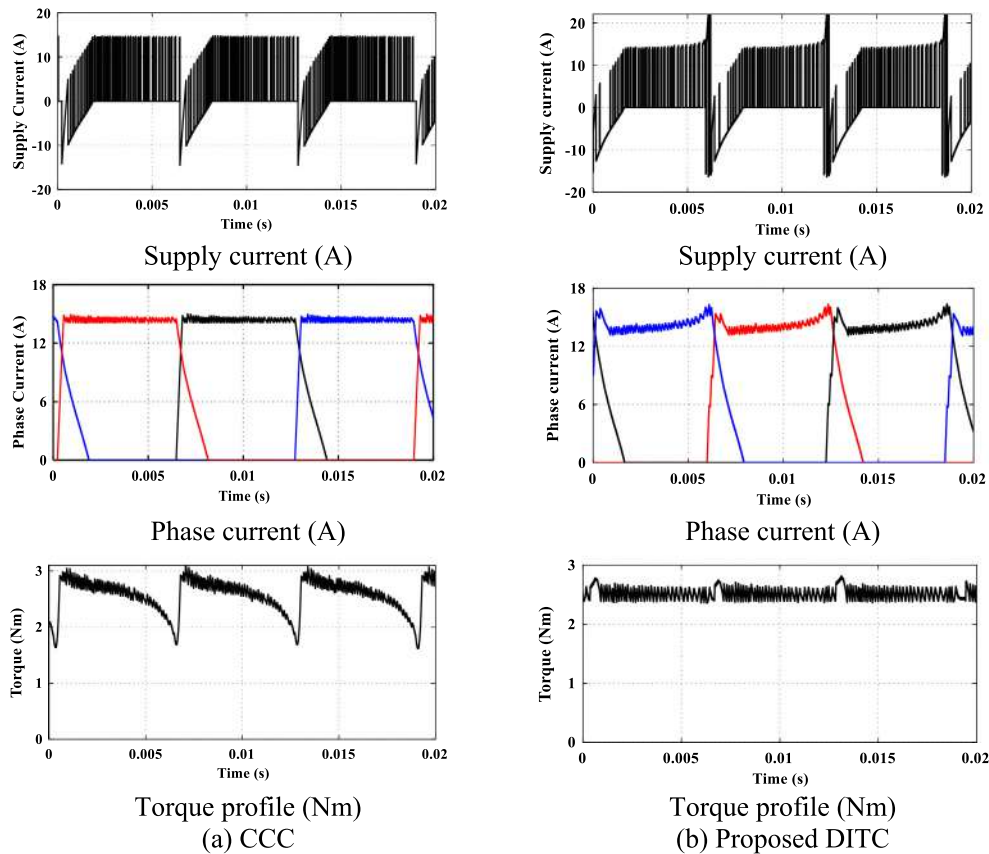
$$T_Q = (T_{ave} - w_r(T_{max} - T_{min})) \quad (4)$$

$$\eta = \frac{\omega T_{ave}}{V_{dc} I_{ave}} \quad (5)$$

$$F = w_q \frac{T_Q}{T_{Qbase}} + w_e \frac{\eta}{\eta_{base}} \quad (6)$$

where T_{max} and T_{min} are the highest and lowest values of the torque waveform (T_e) over one electric cycle (τ), T_Q is the torque quality factor, ω is the motor speed in rad/sec, V_{dc} is the applied voltage to the AHBC, I_{ave} is the mean value of the supply current, T_{Qbase} and η_{base} are the base values of T_Q and η , respectively. w_r , w_q , and w_e are weighting factors. In (6), greater attention is given to the torque quality, and thus w_q is selected higher than w_e .

In this optimization problem, the selection of the firing angles is subjected under two constraints: firstly, the minimum conduction angle (θ_{cnd}) for three-phase 12/8 SRM should be at least 15°, as shown in Equation (7). Moreover, to obtain further efficiency improvement, the switch-off angle is selected to realize the maximum possible employment of the positive slop part of the inductance without serious negative torque generation. Whereby using a current detector, the sampled current I_z at θ_z can be obtained at

**Fig. 10.** Simulation outcomes when running the SRM at 400 r/min speed and 2.5 Nm torque.

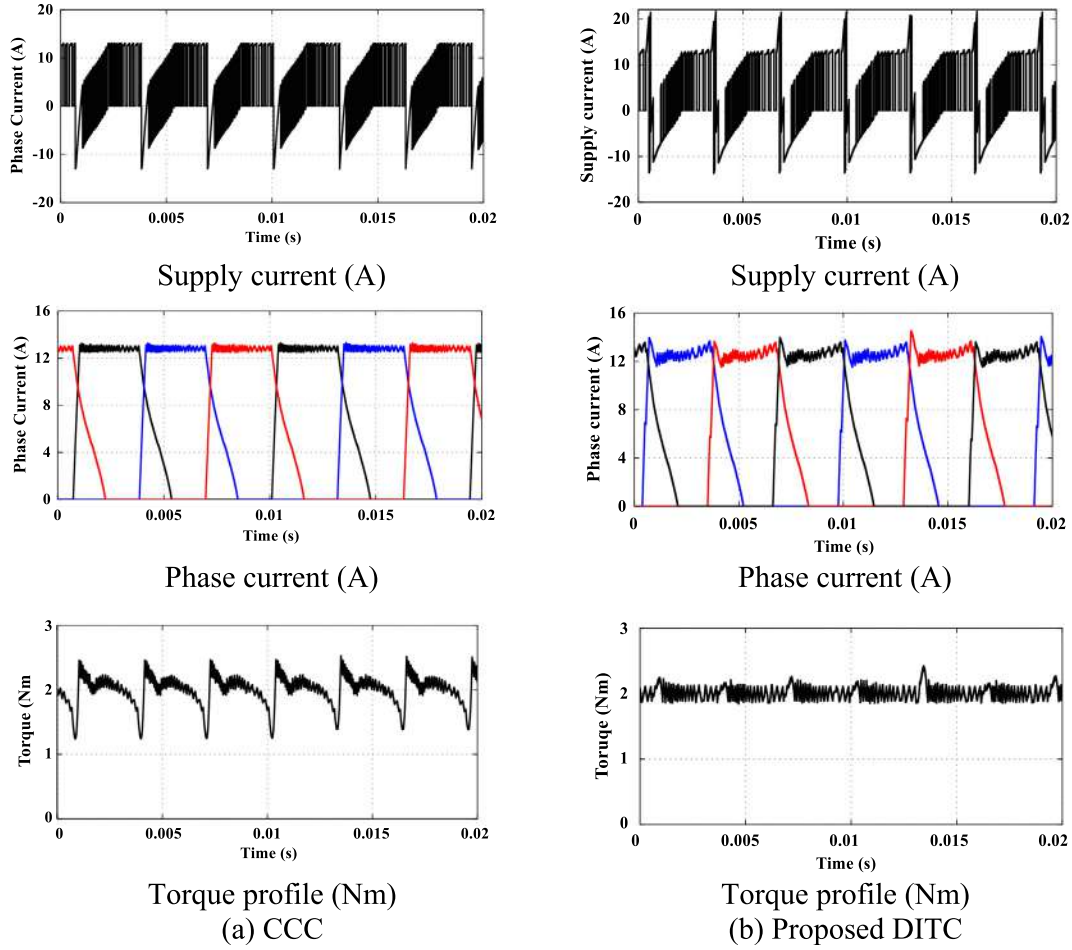


Fig. 11. Simulation outcomes when running the SRM at 800 r/min speed and 2 Nm torque.

each iteration. If the detected I_z is zero, this indicates that the outgoing phase is switched-off too early. Thus, the positive slop part of the inductance after θ_{off} will not be utilized for torque production, or if a high value of I_z is detected (see Fig. 4b), then a considerable amount of braking torque will be generated. Therefore, for optimum performance, I_z must be constrained as shown in (8), and thus the set of solutions that give zero I_z or a value higher than the pre-selected tolerance (I_z^{max}) will be avoided by the MSACO.

$$\theta_{cnd} = \theta_{off} - \theta_{on} \geq 15^\circ \quad (7)$$

$$0 < I_z \leq I_z^{max} \quad (8)$$

I_z^{max} is selected between 0.5 and 1 A. For more clarification, the optimization process of the firing angles is depicted in the following detailed flowchart (Fig. 6). The adopted MSACO parameters are given in Table 1.

The MSACO is utilized in our previous work in [29] to solve a 6-variables optimization problem. The MSACO results outperformed the results obtained by Genetic Algorithms (GA). And thus, the effectiveness of the MSACO is already validated.

The optimization problem results are the optimum firing angles θ_{on} and θ_{off} and are stored in look-up tables (LUT), as depicted in Fig. 7.

3.2. The proposed switching strategy

In this work, the instantaneous torque of SRM is controlled via a hysteresis controller. The output state signal of the hysteresis controller is not applied directly to the power converter but is processed through a proposed switching unit. The switching unit provides both soft and hard switching modes. Suppose the rotor poles undergo positions where the rate of change of the inductance is very low. In that case, hard switching is employed to provide faster damping to the peak current in these regions. Alternatively, the soft-switching mode is used at rotor positions where the rate of change of the inductance is high. As in this case, the generated current is lower. For this purpose, the positive slope region of the inductance is divided into three sub-regions, as shown in Table 2.

However, depending on the optimized firing angles that MSACO obtains, regions I and III may be omitted. If θ_{on} is selected equal to or higher than θ_m , then region I will be omitted. Or, if the winding is switched-off early ($\theta_{off} \leq \theta_m + 15^\circ$), region III will be omitted. The proposed switching rule for one phase of the SRM is depicted in Fig. 8. The complete dynamic DITC drive is depicted in Fig. 9.

4. Simulation results

In order to validate the feasibility and effectiveness of the proposed DITC strategy, both simulations and experimental measure-

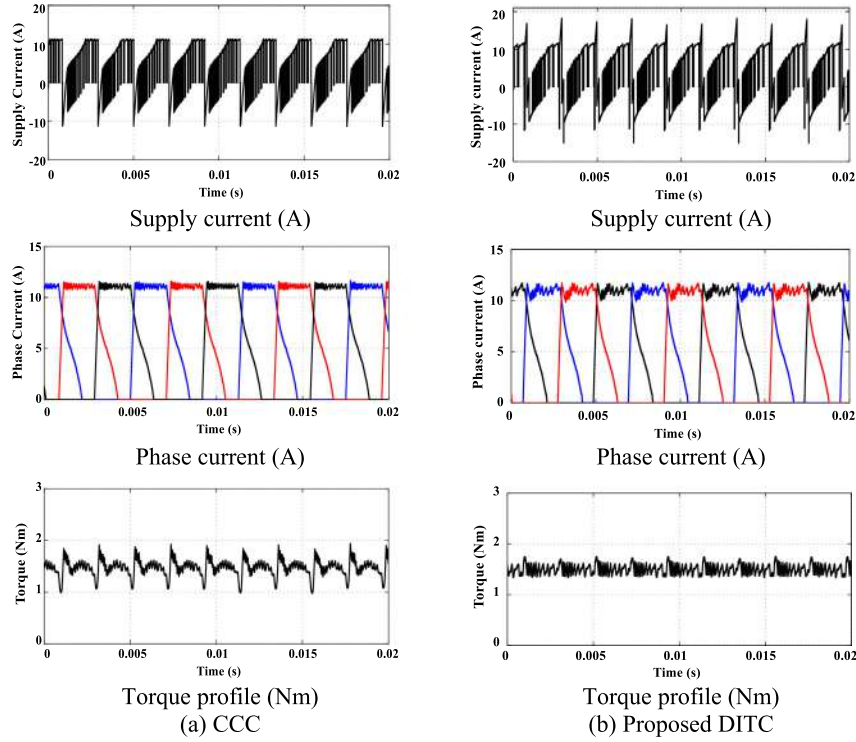


Fig. 12. Simulation outcomes when running the SRM at 1200 r/min speed and 1.5 Nm torque.

ments are subjected to comparative analysis. For this purpose, the CCC in Fig. 1 is adopted since it is commonly used in literature. The simulations are carried out by utilizing a three-phase 750 W, 12/8 SRM. The parameters of the adopted machine prototype are given in Table 3.

Fig. 10a, Fig. 11a, and Fig. 12a depict the obtained currents and torque waveforms when applying the CCC strategy and running the machine at 400 r/min, 800 r/min, and 1200 r/min, respectively. Whilst Fig. 10b, Fig. 11b, and Fig. 12b present the corresponding outcomes after adopting the proposed DITC. Within the CCC strategy, the analytical approach in (9) is used to obtain the switch-on angle since it can maximize the efficiency of SRM [30]. Additionally, the switch-off angle is selected to provide the minimum conduction angle as in (10).

$$\theta_{on} = \theta_m - \frac{\omega L_u}{R + K_b \omega} \ln \left[1 - I^* \left(\frac{R + K_b \omega}{V_{dc}} \right) \right] \quad (9)$$

$$\theta_{off} = \theta_{on} + 15^\circ \quad (10)$$

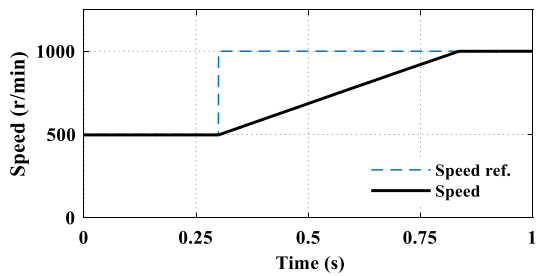
where the inductance of SRM at the unaligned region (L_u) is a non-linear function of rotor position (θ) only, K_b is nothing but its derivative, R is the resistance/phase, and I^* is the commanded current to the CCC. The DITC continuously supplies the optimal firing angles already obtained by the MSACO given in Fig. 7.

Table 4 gives a detailed quantitative comparison between the obtained performance indices, including the average torque, percent torque ripple, and efficiency. As noted from the figures and the tables, the optimized DITC strategy showed a significant torque ripple reduction, improved efficiency, and comparable average torque against the CCC method.

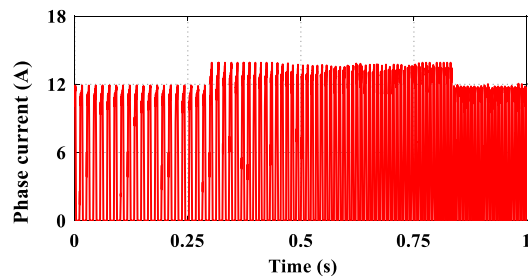
To demonstrate the dynamic behavior of the proposed DITC, Fig. 13 presents the response of SRM under-speed change from 500 to 1000 r/min. Fig. 14 depicts the results when the machine is subjected to a sudden load change from 1 to 2 Nm. Both cases

Table 4
Comparative analysis for the simulation results.

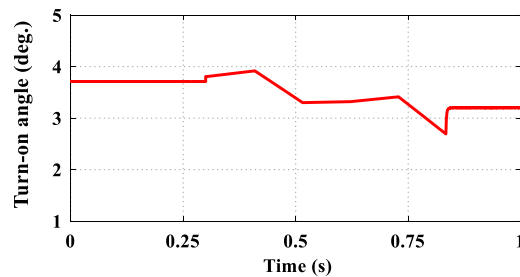
Operating point	400 r/min speed and 2.5 Nm		800 r/min speed and 2.0 Nm		1200 r/min speed and 1.5 Nm	
	CCC	DITC	CCC	DITC	CCC	DITC
θ_{on}	5.03°	3.8°	4.84°	3.32°	4.55°	3.2°
θ_{off}	20.03°	19.5°	19.84°	19.32°	19.55°	19.29°
T_{ave} (Nm)	2.57	2.51	2	2.01	1.47	1.5
T_{ripple} (%)	56	19	63	20	58	27
η (%)	73.2	74.1	81.9	83.6	85.5	87.4



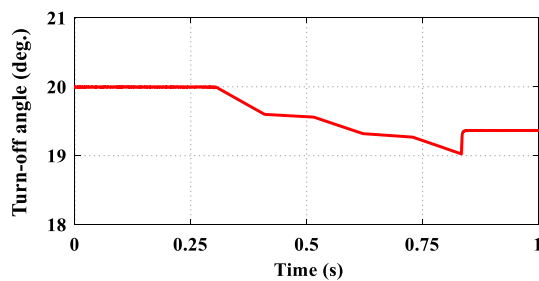
(a) Speed (r/min)



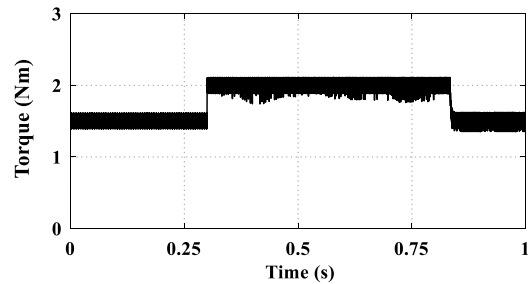
(b) One phase current (A)



(c) Switch-on angle (Deg.)

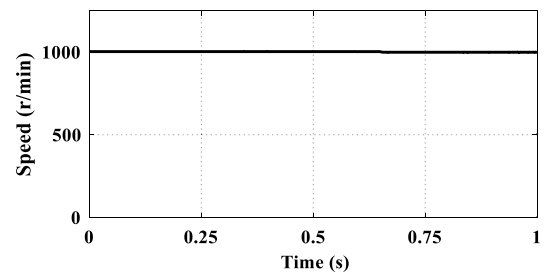


(d) Switch-off angle (Deg.)

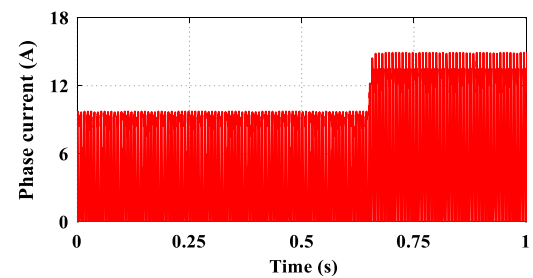


(e) Motor torque (Nm)

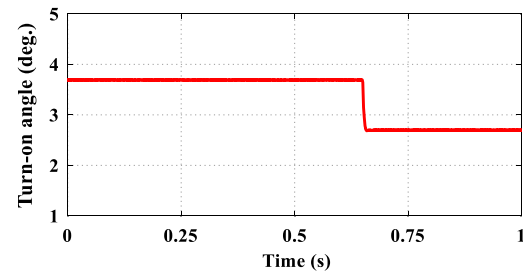
Fig. 13. DITC response under speed change from 500 to 1000 r/m.



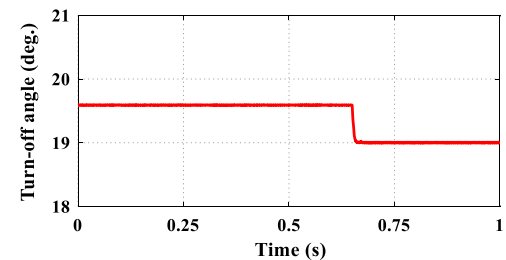
(a) Speed (r/min)



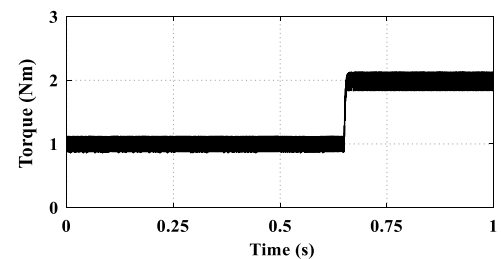
(b) One phase current (A)



(c) Switch-on angle (Deg.)



(d) Switch-off angle (Deg.)



(e) Motor torque (Nm)

Fig. 14. DITC response under step load change from 1 to 2 Nm.

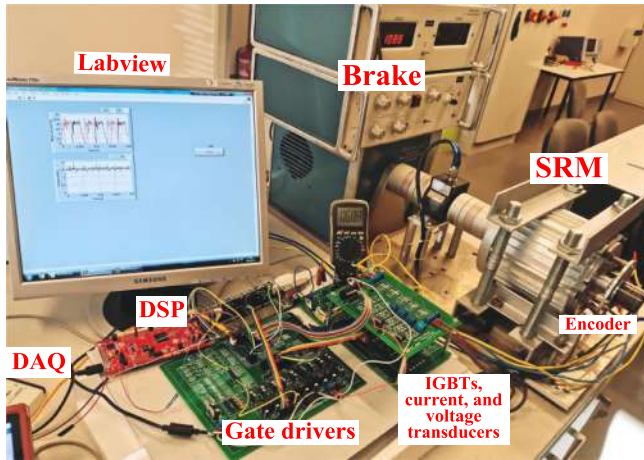


Fig. 15. Experimental platform.

show that the firing angles continuously change to the optimal values, resulting in an improved machine performance with an excellent torque profile.

5. Experimental verifications

Simulation findings of the previous section are confirmed experimentally to further validate the effectiveness of the proposed DITC. The platform in Fig. 15 includes the testbed and the DITC drive system. The 12/8 SRM is fixed to MAGTORL model electromagnetic brake and OMRON incremental type encoder. The drive system mainly consists of an XPT IGBT module as a power converter, LTSR 15-NP module as a current sensor, MCP6001 operational amplifier-based circuit for measuring the phases voltage, and an optocoupler-based circuit as IGBT Gate Driver. Implementation of the control algorithm is carried out using TMS320F28335 digital signal processor from Texas Instruments. The results are presented by means of data acquisition board unit type DAQ NI USB-6009 and LabVIEW.

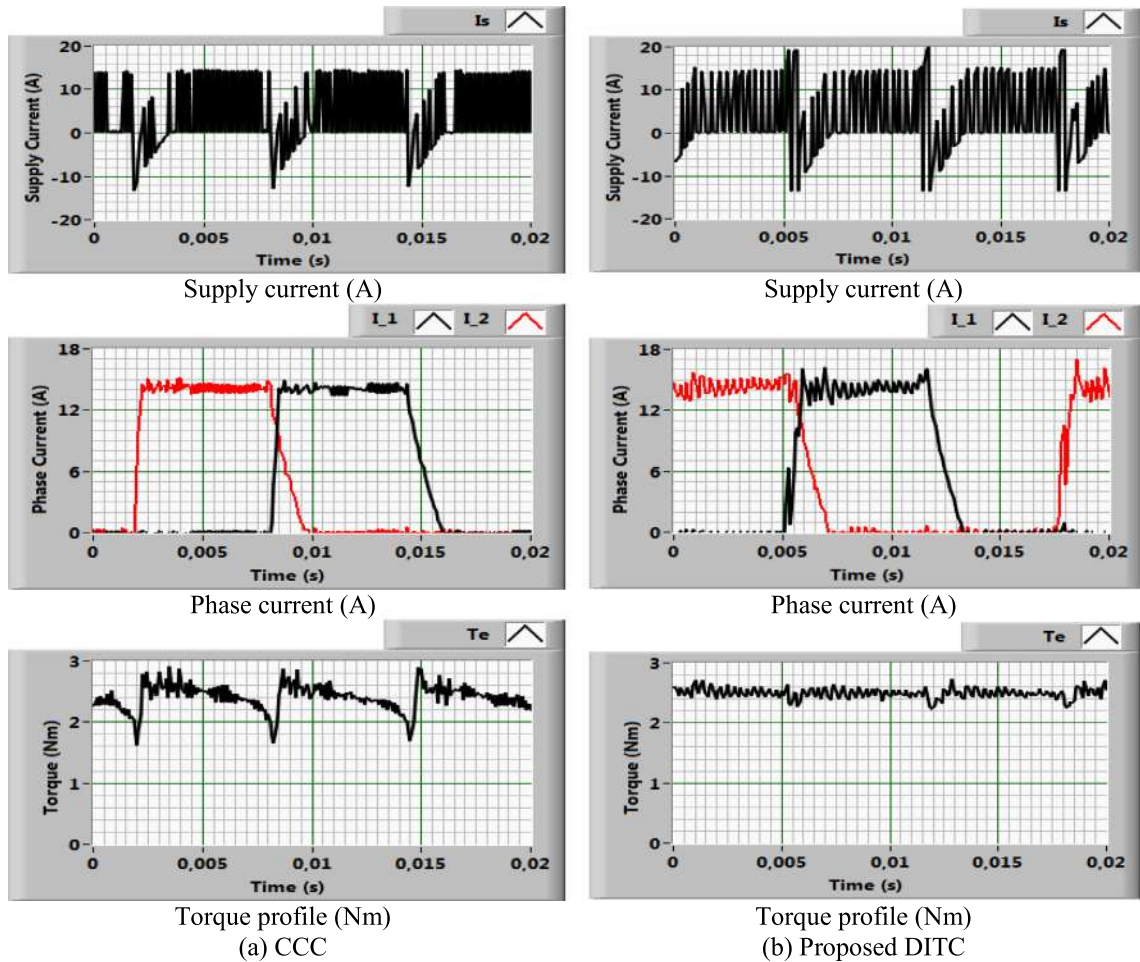


Fig. 16. Experimental outcomes at 400 r/min speed and 2.5 Nm torque.

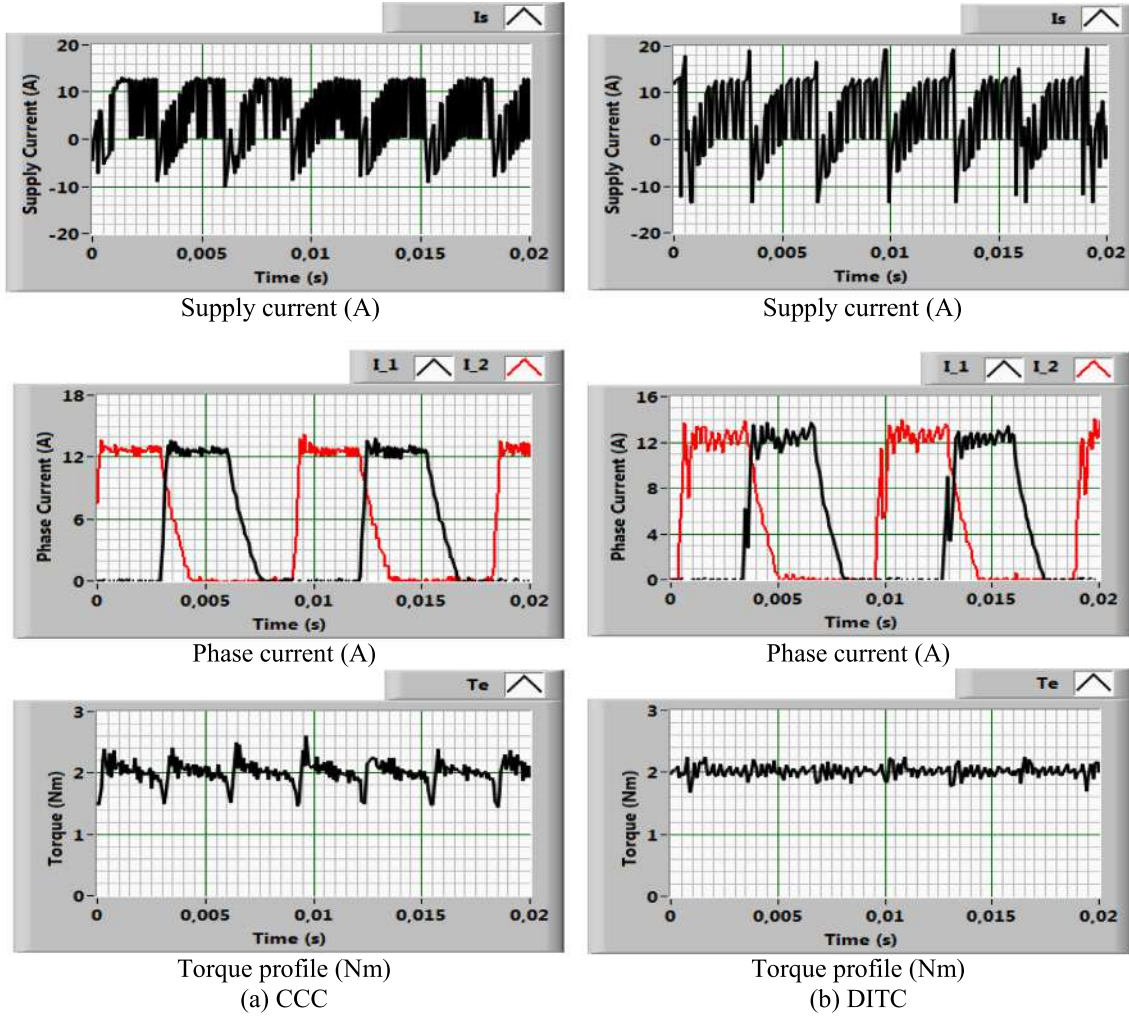


Fig. 17. Experimental outcomes at 800 r/min speed and 2 Nm torque.

Fig. 16a, Fig. 17a, and Fig. 18a show the measured currents and torque waveforms obtained by using the CCC strategy when running the machine at 400 r/min, 800 r/min, and 1200 r/min, respectively. The corresponding measurements of the proposed DITC can be seen in Fig. 16b, 17b, and 18b. The performance indices of experimentally obtained results are given in Table 5. As can be seen, the proposed method provides significant suppression for torque ripple of SRM with higher efficiency than the traditional CCC method. It's also worth pointing out that there is a slight difference between simulation-based and experimental-based obtained performance indices. This is due to different types of measurement noise and the minor errors in machine modeling.

Dynamic results, including speed change and load torque step-change, can be seen in Fig. 19 and Fig. 20, respectively. As noted from both tests, the proposed commutation controller continuously adjusts the firing angles to their optimal values during the transit conditions to improve SRM efficiency and maintain the best torque quality, as shown in Fig. 19d and Fig. 20d.

6. Conclusion

In this research article, an upgraded methodology of ant colony optimization (ACO) is adopted to attain a precise search for the optimal firing angles that maximizes the performance of SRMs. For this purpose, a constrained optimization problem is formulated, and a multi-objective function is created to maximize the torque quality and efficiency of the machine. Moreover, the negative torque generation is set as a constraint in the optimization problem. The generation of negative torque is to be avoided. Hence, the SRM performance is improved further. The optimal findings of this optimization problem are used to implement an enhanced direct instantaneous torque control (DITC) drive for the SRMs. Furthermore, a new switching strategy is utilized to implement an efficient hysteresis torque controller. The selection of the switching mode of an asymmetric half-bridge converter is entirely determined based on the inductance profile of the SRM. If the rate of change of the inductance is very low, then a hard-switching mode is employed. Alternatively, the soft-switching mode is employed whenever a high rate of inductance change exists. The

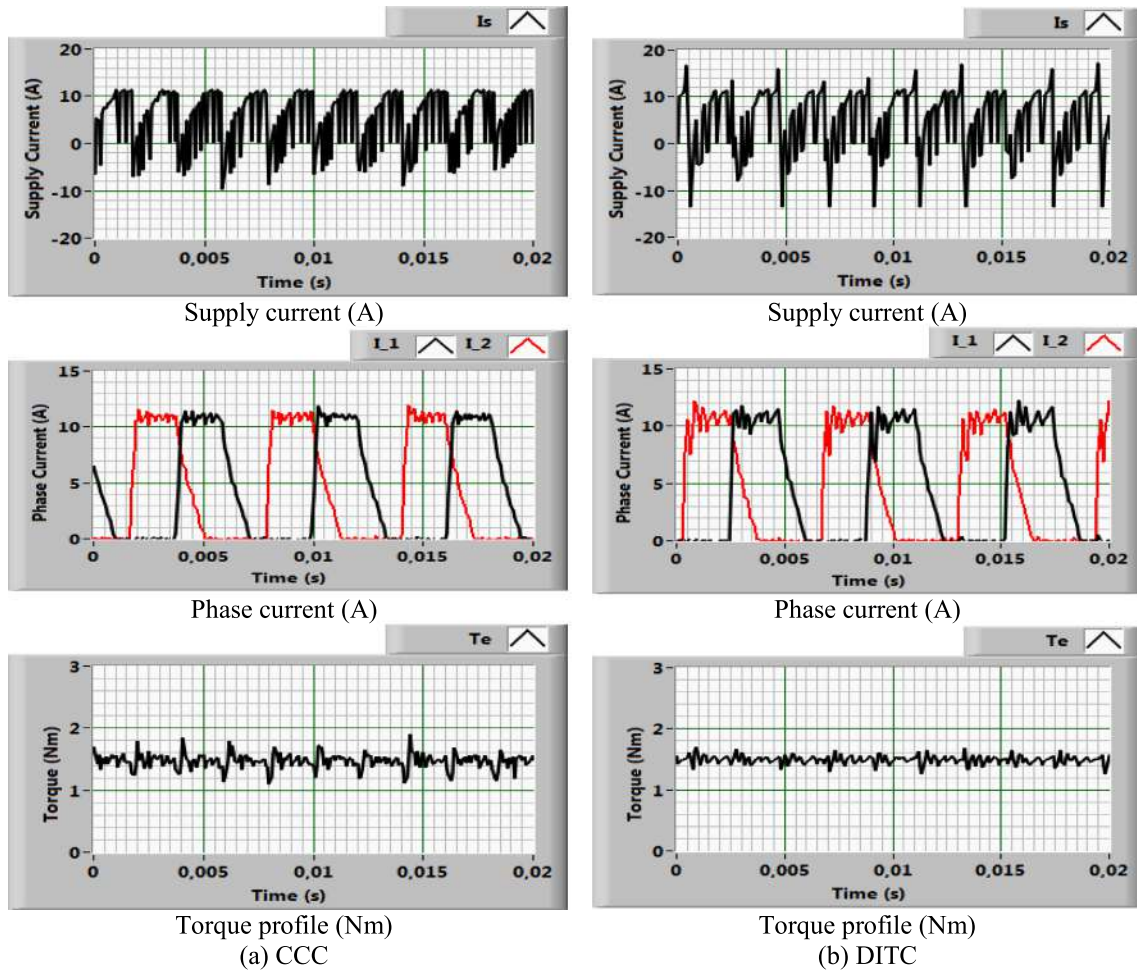


Fig. 18. Experimental outcomes at 1200 r/min speed and 1.5 Nm torque.

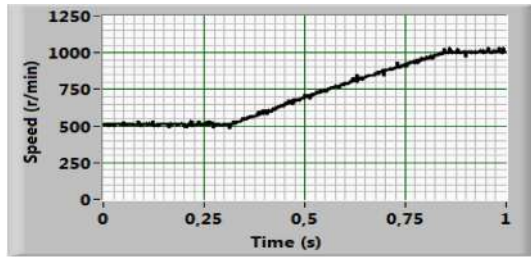
Table 5

Comparative analysis for the Experimental results.

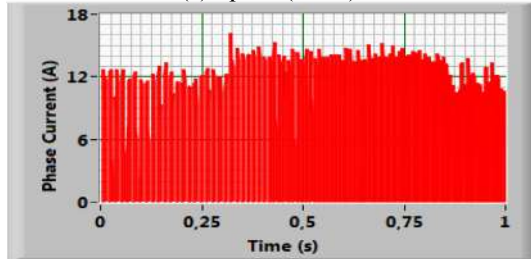
Operating point SRM Parameter	400 r/min speed and 2.5 Nm		800 r/min speed and 2.0 Nm		1200 r/min speed and 1.5 Nm	
	CCC	DITC	CCC	DITC	CCC	DITC
θ_{on}	5.03°	3.8°	4.84°	3.32°	4.55°	3.2°
θ_{off}	20.03°	19.5°	19.84°	19.32°	19.55°	19.29°
T_{ave} (Nm)	2.49	2.51	2.01	2	1.48	1.49
T_{ripple} (%)	49	18	51	21	56	26
η (%)	70.3	72.3	80.2	82.5	84	85.5

utilized switching strategy guarantees accurate torque tracking over the entire phase excitation period; thus, the machine's torque profile is improved further. Both simulations and experimental measurements confirmed the effectiveness of the proposed DITC in reducing the torque ripple and improving the machine's efficiency. However, the DITC performs best over low and medium

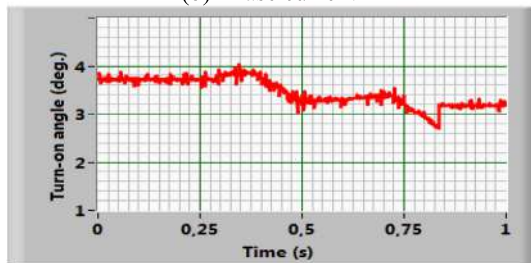
speed ranges. Its performance deteriorates under high-speed operation. Hence, future works could improve the DITC over high speeds or develop a universal control of SRM. The universal control could involve DITC for low and medium speed ranges as it gives the best performance and another torque control technique such as ATC for high speeds.



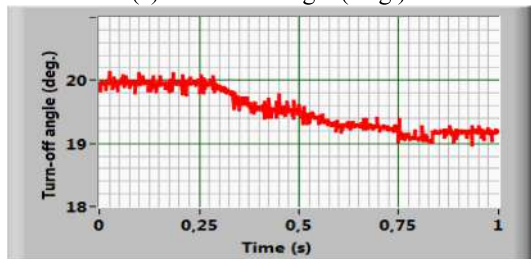
(a) Speed (r/min)



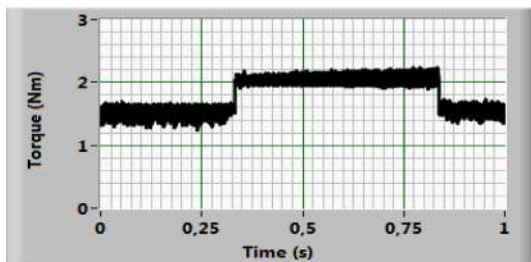
(b) Phase current



(c) Switch-on angle (Deg.)

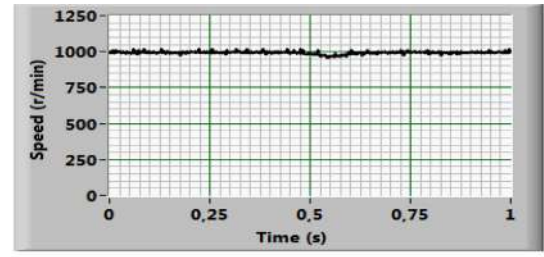


(d) Switch-off angle (Deg.)

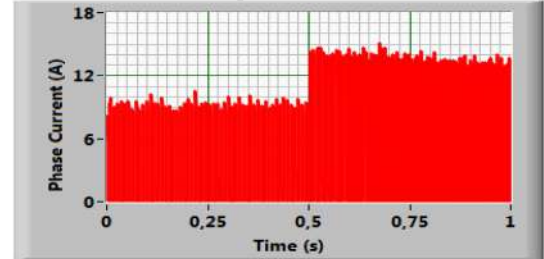


(e) Motor torque

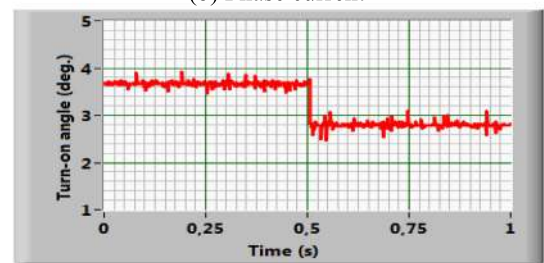
Fig. 19. DITC response under speed change from 500 to 1000 r/min.



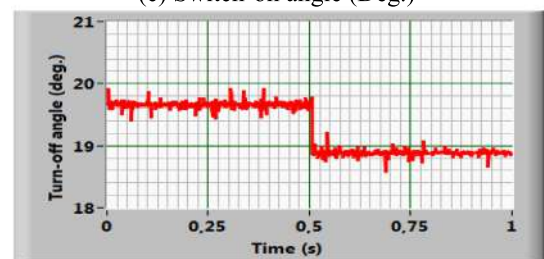
(a) Speed (r/min)



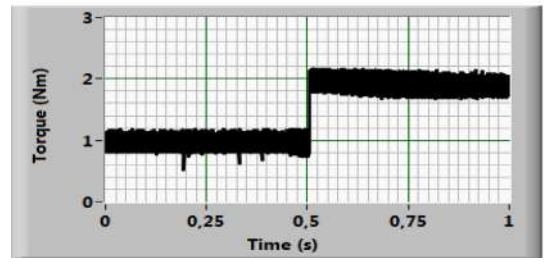
(b) Phase current



(c) Switch-on angle (Deg.)



(d) Switch-off angle (Deg.)



(e) Motor torque

Fig. 20. DITC response under step load change from 1 to 2 Nm.

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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