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A Novel Reduced-Ripple Average Torque Control Technique for Light Electric Vehicle Switched Reluctance Motors

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Abstract

The switched reluctance motors (SRMs) are an attractive solution for electric vehicles (EVs) and hybrid electric vehicles (HEVs). However, the main drawbacks of SRMs are their highly nonlinear magnetic characteristics, complicated control algorithms, and the inherent torque ripples. This paper presents a simple structure average torque control (ATC) technique with a better ability to reduce torque ripples. Based on the detailed analysis of an inductance profile, this paper introduces a novel current compensation mechanism (CCM) that has the ability to profile the phase current and, hence, reduce the torque ripple. The proposed CCM is meant for the minimum inductance zone (MIZ) to profile the current of the ongoing phase. Over the MIZ, the inductance is independent of the phase current that helps to simplify the deduced mathematical formulations and provides a simple structure ATC with a lower computational burden, making it a feasible solution for real-time implementations and future developments. A series of experimental results are achieved to show the feasibility and effectiveness of the proposed ATC technique. The results show the superior performance of the proposed ATC, providing better torque profiles and reducing the torque ripples with an average value of 30% compared to conventional ATC.

Keywords: switched reluctance motor; average torque control; torque ripple reduction; current compensation mechanism; inductance profile; electric vehicle



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1. Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are among the most sustainable and environmentally friendly alternatives to address global warming, decreasing petroleum reserves, deteriorated air quality, and the increased demand for a cleaner and healthier environment [1,2]. The switched reluctance motor (SRM) has recently garnered attention as a strong candidate for utilization in EVs and HEVs. SRMs are of great importance if compared with other existing motor technologies for EVs and HEVs, as depicted by the detailed comparison in Table 1, involving permanent magnet synchronous motors (PMSMs), induction motors (IMs), and SRMs. SRMs show superiority in their simple structure, lower manufacturing costs, wide speed operations, thermal capability, fault tolerance and reliability, sustainability, cooling requirement, and maintenance [1–5]. However, despite their features, SRMs exhibit a major notable drawback of high torque ripples

that are the main reason for the production of acoustic noise and vibrations. These issues adversely affect the performance of electric vehicles (EVs) and weaken the competitiveness of SRM-based propulsion systems relative to traditional motor technologies [4,5].

Table 1. Comprehensive comparison of EV traction motors.

Criterion	PMSMs	IMs	SRMs
Stator structure (windings)	Distributed	Distributed	Concentrated
Rare-earth materials	Required	None	None
Efficiency	Very High	High	High
Thermal robustness	Limited (magnets)	Good	Excellent
Demagnetization risk	High (magnets)	None	None
Fault tolerance	Low	Medium	Very high
Operation under phase loss	Usually not	Limited	Possible
Torque ripple	Low	Low	High
High-speed capability	Limited	Good	Excellent
Field-weakening range	Limited	Wide	Very wide
Over-speed capability	Limited	High	Very high
Starting torque	High	Moderate	High
Motor manufacturing cost	High (magnets)	Moderate	Low
Supply chain risk	High (rare earths)	Low	Very low
Sustainability	Poor	Good	Excellent
Cooling requirement	High	Moderate	Moderate
Maintenance	Low	Low	Very low
Reliability in harsh environments	Moderate	Good	Excellent
Cost stability (long term)	Volatile	Stable	High

To address these challenges, researchers have primarily focused on mitigating torque ripple in SRMs; the machine structural optimization and the advanced control strategies are the two main established approaches for that purpose [6–9]. The structural optimization can reduce the torque ripple but only with limited ranges [10]. On the other side, the advanced control strategies, compared to machine design and structural optimization, can effectively mitigate torque ripple and improve machine performance through a wide range of speeds, including current chopping control (CCC), average torque control (ATC), instantaneous torque control (ITC), and model predictive control (MPC) [11–15]. First, the CCC is a simple and robust approach that does not incorporate a torque controller, thereby eliminating the need for a torque estimation unit [11]. However, CCC inherently generates substantial torque ripple because it regulates the phase current in square waveforms, making accurate current profiling impossible. Second, ITC methods can be broadly classified into direct and indirect approaches. The direct ITC method regulates the motor's instantaneous torque directly without any current loop or torque-to-current conversion [8], whereas the indirect ITC achieves torque regulation through the utilization of a torque sharing function (TSF) and a current loop controller [16,17]. Both schemes enable notable torque ripple reduction

by regulating the output torque at each rotor position, thereby generating an optimal current profile and a smooth torque profile. However, the ITC schemes are meant for low-speed operation, and they lose their effectiveness at high speeds due to the difficult current control because of limited dc-link voltage and high back-emf. As a result, accurately tracking a shaped reference current within such a shortened excitation interval at high speeds becomes increasingly challenging [18]. Third, the model predictive control (MPC) offers an excellent dynamic response through utilizing a predictive machine model to estimate future system behavior and determine the corresponding control action [19,20]. However, its performance is strongly impacted by the accuracy of the predictive model. Due to the highly nonlinear magnetic characteristics of SRMs, acquiring an accurate predictive model is challenging and often requires simplifying assumptions, which can adversely affect the system's performance [21,22]. Finally, the ATC has the full ability to provide the requirements of an EV; it can provide fast torque-response, extended speed range, high efficiency, and reduced torque ripples [23,24]. In addition, the ATC offers many features if compared to the ITC and/or MPC; the ATC has a much simpler control structure, a higher torque/ampere ratio, and can be applicable over the entire range of speed control. However, the ATC has relatively high torque ripples compared to the ITC; it is very essential to reduce the torque ripples, especially at low speeds to avoid speed fluctuations. The vehicle inertia can filter the torque ripples at high speeds. To sum up, the ATC is a highly appropriate choice for EV [23–25].

Several studies have suggested enhancing the effectiveness of ATC approaches, including optimization-based methods for commutation angle tuning or setting the reference current [23,26–32], hybrid CCC–ATC [24] and flux–current locus control methods [33]. These contributions have demonstrated the ability of ATC to substantially minimize the torque ripple and improve the overall performance of the SRM drive system, thereby achieving the requirements of EV systems. In [23], a simplified scheme ATC approach was proposed for SRM, which encompasses the requirements of EVs, including low torque ripple over a wide speed range, high dynamic performance, and reduced copper losses. The torque ripple reduction had been achieved by providing the optimum solution of switching angles based on a multi-objective optimization function to minimize both torque ripple and copper losses. In [26], a direct ATC approach of SRM for a light EV is introduced. The proposed ATC algorithm was implemented to adjust the reference current and switching angles, thereby providing the desired average torque over a wide speed range with improved efficiency. In [27], the direct ATC was introduced to estimate the average torque and energy ratio online. The proposed method employed closed-loop torque control to adjust the reference torque by modifying the reference current and switching angles, thereby maintaining a constant and precise average torque at the reference torque value. In [28], an analytical and simple approach to adjusting the switching angles for the ATC strategy was proposed to enhance the efficiency of the SRM drive system over a wide range of operating conditions. In [29] a current-peak regulation scheme to control the average torque in single-pulse and commutation models of operation was presented. The proposed current-peak control approach adjusted the turn-on angles, allowing for a smooth transition between the two modes. In [30], a speed controller with an average torque control strategy for a wide-speed-range operation for SRM was achieved. The control parameters of the proposed approach are optimized based on a multi-objective function to minimize the torque ripple, maximize the average torque, and enhance system efficiency. In [31], an ATC strategy was introduced for an electric scooter application utilizing an 8/6 SRM. The proposed approach used a search algorithm based on a multi-objective function to determine the optimal switching angles, thereby enhancing the overall performance of the SRM drive over a wide speed range. In [32], a simplified ATC approach for EVs was

presented, based on a numerical estimation method for the optimum control parameters for SRM. The method employed a search algorithm to optimize the switched angles based on a multi-objective approach, achieving all vehicle requirements while reducing both complexity and overall implementation cost. In [24], an online ATC for the SRM drive system of EVs was proposed to reduce the influence of battery voltage variation on operating performances and improve dynamic performance. In addition, a hybrid crossover control was investigated to widen the adjustable speed range and improve the smoothness of the SRM, considering both acceleration and deceleration. In [33], a novel ATC approach based on a flux–current locus controller for SRMs is proposed to maximize the average torque with greater precision within a single stroke. The proposed ATC consists of a hybrid flux controller and current controller, as well as involving the micro-step process.

However, with the previously mentioned intensive research interest, the presented conventional ATC strategies demonstrate a limited adaptability in the presence of nonlinear magnetic saturation and varying load conditions, both of which are frequently encountered in EV applications. In addition, the optimization of switching angles and/or current levels can reduce the torque ripples to a limited range, hence, the ripples are still considered relatively high. For these reasons, the contributions of this paper are listed as follows:

- (1) It provides a novel ATC technique that has the ability to further reduce the torque ripples by an additional current profiling scheme to meet the requirements of an EV.
- (2) It introduces a novel current compensation mechanism (CCM) that has the ability to profile the phase current and, hence, reduce the torque ripple.
- (3) The simplicity of the control algorithm is considered, and the proposed CCM is meant only over the MIZ, hence, providing a simple mathematical formulation and fast control algorithm.

The paper is organized as follows: Section 2 presents the machine modeling. Section 3 discusses the conventional ATC approach for SRMs. Section 4 explains the proposed ATC scheme and its current compensation mechanism. Section 5 involves the experimental results and their discussions. Section 6 is a comparative summary. Section 7 is the conclusion.

2. Machine Modeling

This paper considers a three-phase 12/8 SRM prototype; the motor parameters are listed in Table 2.

Table 2. Parameters of SRM.

Parameter	SRM	Parameter	SRM
Stator/Rotor poles	12/8	Stator outer diameter	141 mm
Rated speed	800 rpm	Rotor outer diameter	82 mm
Rated torque	4 Nm	Stator pole width	10 mm
Max phase current	9 A	Rotor pole width	12 mm
Phase resistance	1.73 Ω	Stack length	71 mm

The motor is modeled based on the following set of Equations (1)–(3) [11]. Due to the double salient structure of SRMs, the flux-linkage $\lambda(i, \theta)$, inductance $L(i, \theta)$, and torque $T(i, \theta)$ are highly nonlinear functions of both the current level (i) and the rotor position (θ).

$$v_k = Ri_k + \frac{\partial \lambda_k(i_k, \theta)}{\partial t} = Ri_k + L_k(i_k, \theta) \frac{\partial i_k}{\partial t} + e; \quad e = \frac{\partial L_k(i_k, \theta)}{\partial \theta} i_k \omega_m \quad (1)$$

$$T_k = \frac{1}{2} i_k^2 \frac{\partial L_k(i_k, \theta)}{\partial \theta}; \quad T_e = \sum_{k=1}^q T_k \quad (2)$$

$$T_e - T_L = B\omega_m + J \frac{d\omega_m}{dt} \quad (3)$$

where v_k , i_k , λ_k , L_k , and T_k are the voltage, current, flux linkage, inductance, and torque for k th phase. R depicts the phase resistance; T_e is the total generated torque; q is the number of motor phases; T_L is the load torque; B and J are the friction and inertia coefficients, respectively. ω_m is the motor speed.

The equivalent circuit of an SRM is shown in Figure 1; it helps to explain the relationship between different motor parameters. The back-emf (e) in Equation (1) depends on motor speed; as the motor speed (ω_m) increases, the back-emf also increases. The back-emf works against the applied voltage (v_k), hence, reducing the ability of current control. For low speeds, below the rated motor speed (800 r/min), the applied voltage is much greater than the back-emf (e) and, hence, the current can be controlled in a very good and efficient way. On the other side, for higher speeds, above the rated motor speed (800 r/min), the back-emf (e) becomes high enough to make the current control a difficult task or even impossible depending on the operating speed range. In conclusion, as the motor speed increases, the back-emf (e) also increases, and the ability of current control decreases; the current control also means the ability of current profiling.

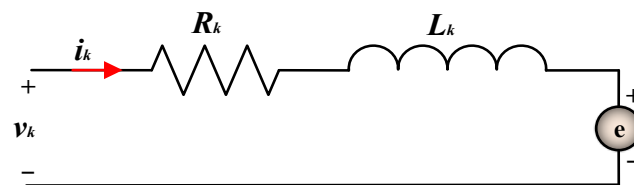


Figure 1. Equivalent circuit of SRM.

The indices for evaluating motor performance are listed in Equations (4)–(6) involving the torque ripple (T_{rip}), average torque (T_{av}), efficiency (η), average supply current (I_{av}), RMS phase current (I_{RMS}), and copper losses (P_{cu}) [11].

$$T_{rip} = \frac{T_{max} - T_{min}}{T_{av}}; \quad T_{av} = \frac{1}{\tau} \int_0^{\tau} T_e(t) dt \quad (4)$$

$$\eta = \frac{\omega_m T_{av}}{V_{dc} I_{av}}; \quad I_{av} = \frac{1}{\tau} \int_0^{\tau} i_s(t) dt \quad (5)$$

$$I_{RMS} = \sqrt{\frac{1}{\tau} \int_0^{\tau} i_k^2(t) dt}; \quad P_{cu} = q \cdot I_{RMS}^2 R \quad (6)$$

where T_{max} and T_{min} are the maximum and minimum instantaneous values of motor torque. V_{dc} is the DC bus voltage. i_s and i_k are the instantaneous values of the supply current and phase current, respectively. τ is the time of one electric cycle, over it the indices are calculated.

3. The Conventional Average Torque Control Technique for SRMs

Figure 2 shows the block diagram of the conventional ATC technique for SRMs. The outer loop speed controller (PI controller) outputs the reference commanded torque (T_{ref}) by handling the speed error ($\Delta\omega$). The phases' torques (T_a , T_b , T_c) are estimated based on current and rotor position data; their summation provides the instantaneous total electromagnetic motor torque (T_e); then, averaging based on Equation (4) is needed to provide the average torque (T_{av}) signal. T_{av} is compared to T_{ref} , then the torque error (ΔT) is processed by the torque controller (PI controller) to output the required reference current (i_{ref}). According to the phase sequence and the switching angles (θ_{on} , θ_{off}), the reference current (i_{ref}) is distributed among motor phases, and the reference phase currents (i_{a-ref} , i_{b-ref} , i_{c-ref}) are defined. The hysteresis current controller (HCC) regulates the current error for each phase (Δi_a , Δi_b , Δi_c) and defines the drive signals of the power converter.

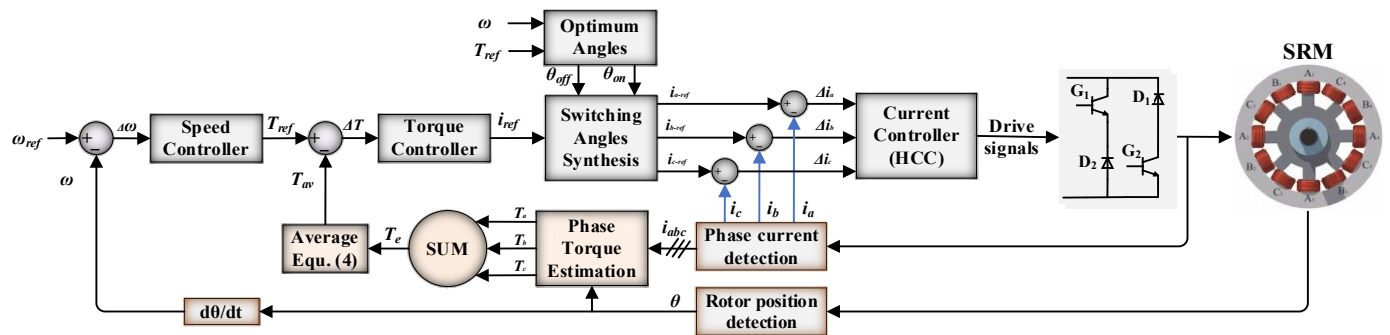


Figure 2. Block diagram of conventional average torque control technique for SRMs.

The problem of conventional ATC is that it has no control over the current profile, it controls only the current level, and adjusts its conduction period; hence, the torque ripples are high. The highest torque ripple appears in the overlapping region between any of the adjacent phases. The literature focused on improving the switching angles (θ_{on} , θ_{off}), aiming to provide a better torque distribution between the ongoing and outgoing phases. This, in turn, can improve the torque profile and reduce the torque ripples. However, the reduction in torque ripples is limited and the ATC still have significant levels of torque ripples.

4. The Proposed Average Torque Control Technique for SRMs

4.1. Description of Proposed ATC Technique

Figure 3 shows the block diagram of the proposed ATC technique for SRMs. The contribution is the proposed current compensation mechanism (yellow block). The reference current for each phase (i_{a-ref} , i_{b-ref} , i_{c-ref}) is compensated with additional current signals (δi_a , δi_b , δi_c); and, hence, the final compensated reference current signals for each motor phase are defined as ($i_{a-ref-comp}$, $i_{b-ref-comp}$, $i_{c-ref-comp}$). The inputs for the proposed current compensation mechanism involve four quantities; the three phases torques (T_a , T_b , T_c) and the instantaneous torque error ($\delta T = T_{ref} - T_e$). All these quantities already exist within the conventional ATC, and no additional effort is needed to estimate them. The only additional part involves the production of current signals (δi_a , δi_b , δi_c) which is achieved in a very simple way by utilizing a single mathematical formulation; hence, the additional computational burden for the proposed ATC scheme is minimal and can be ignored.

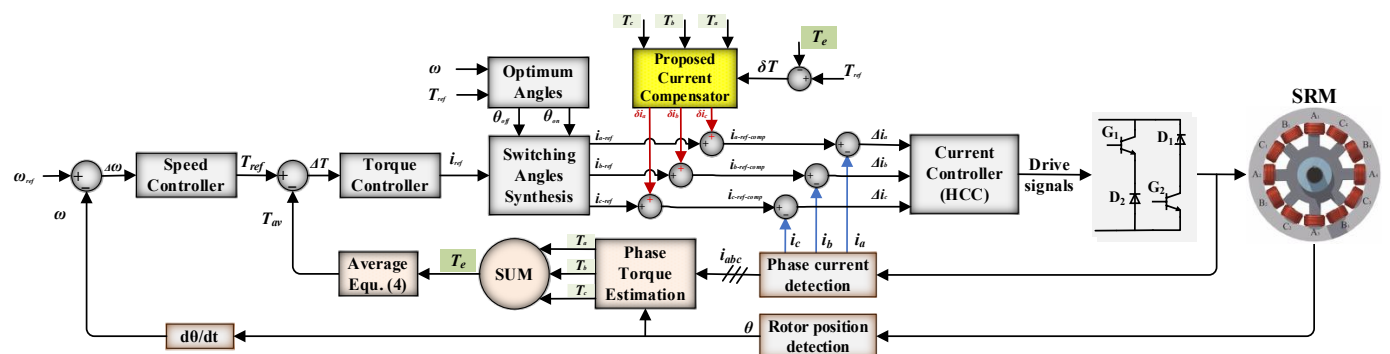


Figure 3. Block diagram of proposed average torque control technique for SRMs.

The proposed ATC technique features the following:

- (1) The proposed current compensator allows us to profile the phase current and, hence, provide a better torque ripple reduction capability.
- (2) The compensation mechanism is simple and does not complicate the overall control algorithm.

- (3) The compensation mechanism is very flexible; it can be activated or deactivated any time while maintaining the conventional ATC scheme.
- (4) No additional hardware is required.
- (5) The proposed method is totally compatible with any SRM even with different configurations or a different structure, as the proposed control method is applied for each phase due to the independent phase control of SRMs.
- (6) The proposed method has no limitations in terms of control accuracy. The only limitation is the speed range, especially the high speeds. As the proposed method profiles the phase current, it will show superior performance for low- and medium-speed operations while the phase current control is still effective. However, under high-speed operation, the current control becomes difficult, limiting the functionality of the proposed control method for effective current profiling.

4.2. The Main Idea for Proposed Current Compensation Mechanism

The torque equation for each phase of SRMs is given in Equation (2) [11]. The torque is a function of the square of the current level (i_k^2) and the derivative of phase inductance $\partial L_k(i_k, \theta)/\partial \theta$. What complicates the problem is that the phase inductance $L_k(i_k, \theta)$ is the function of both the current level (i_k) and rotor position (θ). Hence, the torque control is a hard task. However, the analysis of the inductance profile reveals a possible solution for that problem.

Figure 4a shows the inductance profile of the tested 12/8 SRM prototype. The minimum inductance zone (MIZ) starts from the unaligned rotor position ($\theta = 0^\circ$) to the angle θ_m at which the rotor and stator poles begin overlapping. θ_m depends on motor design, and in this paper θ_m is set as 7° . Over the MIZ, the inductance is independent of the current level, it depends only on rotor position. By other means the current does not affect the inductance profile, and the inductance profile is the same for the current of 4A, 6A, and even 15 and 20A; noting that the machine is in deep magnetic saturation for the case of high current levels (15 and 20A), and even the magnetic saturation has no effect on the inductance profile over the MIZ. The effect of magnetic saturation is clearly obvious after angle θ_m , which means outside MIZ. These make the inductance a function of the current level. As the current changes, the inductance also changes in a highly nonlinear relationship with the current and also with the rotor position. Developing control techniques in this region is a difficult task; this is the main reason this paper is considering only the MIZ to simplify the analysis and the developed control technique. Based on that fact, Equation (7) is used to develop the proposed current compensation mechanism as follows:

For a given rotor position θ , the derivative $\partial L_k(i_k, \theta)/\partial \theta$ will be constant whatever the current level changes. If the motor current is changed from i_1 to i_2 , the developed phase torque will also change from T_1 to T_2 ; the relationship between the phase torque and phase current can be written as follows, noting that this relationship is considered only over the MIZ.

$$\frac{T_1(\theta)}{T_2(\theta)} = \left(\frac{i_1}{i_2}\right)^2 \quad (7)$$

This equation is the backbone for developing a current compensator-based torque ripple reduction for SRMs. Considering the motor is running on the developing torque of T_1 while consuming current i_1 , now the torque has to be compensated to reach level T_2 in order to reduce the torque error, then the required current i_2 can be estimated as follows:

$$i_2 = i_1 \left(\frac{T_2(\theta)}{T_1(\theta)}\right)^{0.5} \quad (8)$$

Figure 4 discusses, in detail, the concept of the proposed control. First, in Figure 4b, the motor current is 4A; the phases' torques (T_a , T_b , T_c) are summed to produce the total motor torque (T_e). Unfortunately, the torque profile is showing a large amount of torque ripple; there is a big torque dip in the overlap regions. In Figure 4c, if the current for phase A is increased to 5A, its torque profile will be the solid black line, higher than the dashed black line at 4A. Now, only over the minimum inductance zone for phase A, its current will be compensated to reach 5A instead of 4A, so its torque will increase, and the current compensation can be achieved using Equation (8). The final compensated torque profile is shown in Figure 4d, the solid green line, and it shows a better torque profile with a significant reduction in torque ripple compared to the original non-compensated torque profile. Hence, the proposed control is an efficient method to suppress the torque ripples for SRMs.

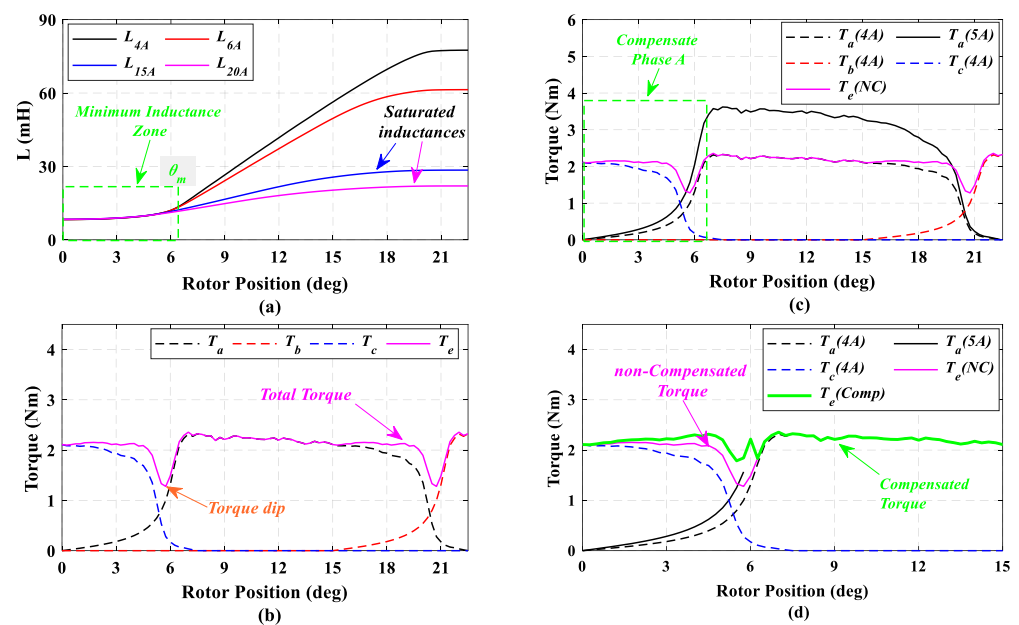


Figure 4. The inductance profile for an SRM (a) inductance profile, (b) torque at 4A, (c) torque at 4A and 5A, (d) compensated torque profile.

4.3. Real-Time Implementation of Proposed Control for SRMs

For the real-time implementation of the proposed control, the torque error is estimated online, as given by Equation (9). Then, the compensated phase current, expressing for phase A (i_{a-comp}), can be deduced, as shown in Equation (10). Finally, the compensation current (δi_a) is given by Equation (10).

$$\delta T(\theta) = T_{ref} - T_e \quad (9)$$

$$i_{a-comp} = i_a \left(\frac{T_a(\theta) + \delta T(\theta)}{T_a(\theta)} \right)^{0.5}; \quad \delta i_a = i_{a-comp} - i_a \quad (10)$$

The implementation steps for the proposed control scheme are as follows:

- (1) Measure the phases' currents (i_a , i_b , i_c) and the rotor position (θ).
- (2) Estimate the torque component for each phase (T_a , T_b , T_c).
- (3) Calculate the total instantaneous motor torque (T_e) using Equation (2).
- (4) Calculate the torque error (δT) using Equation (9).
- (5) Calculate the required current compensation (δi_a) using Equation (10).
- (6) Update the final compensated reference current for each phase ($i_{a-ref-comp}$, $i_{b-ref-comp}$, $i_{c-ref-comp}$).

Noting that points 1, 2, and 3 are already involved by the conventional ATC. The proposed ATC adds a low computational burden, involving additional points 4, 5, and 6. To evaluate the computational efficiency, the conventional and proposed ATC techniques are performed 10 million times, and the running simulation time is recorded for each case. The average running times for the conventional and the proposed techniques are 10.6623097999 and 11.3819934399 microseconds, respectively. The proposed method adds only 6.75% more computational burden.

5. Experimental Validations

The experimental results are achieved with a three-phase 12/8 SRM prototype; the motor parameters are listed in Table 1. The experimental testbed is shown in Figure 5, it involves the SRM, torque transducer, hysteresis brake, 3600 PPR incremental encoder, DC power supply, SCALEXIO dSPACE control unit, current and voltage sensors, and six-phase inverter (PELAB-6PH) that is configured to provide a symmetrical bridge converter for motor drive. The real-time data are monitored and saved using the dSPACE ControlDesk, then they are plotted using MATLAB R2022b.

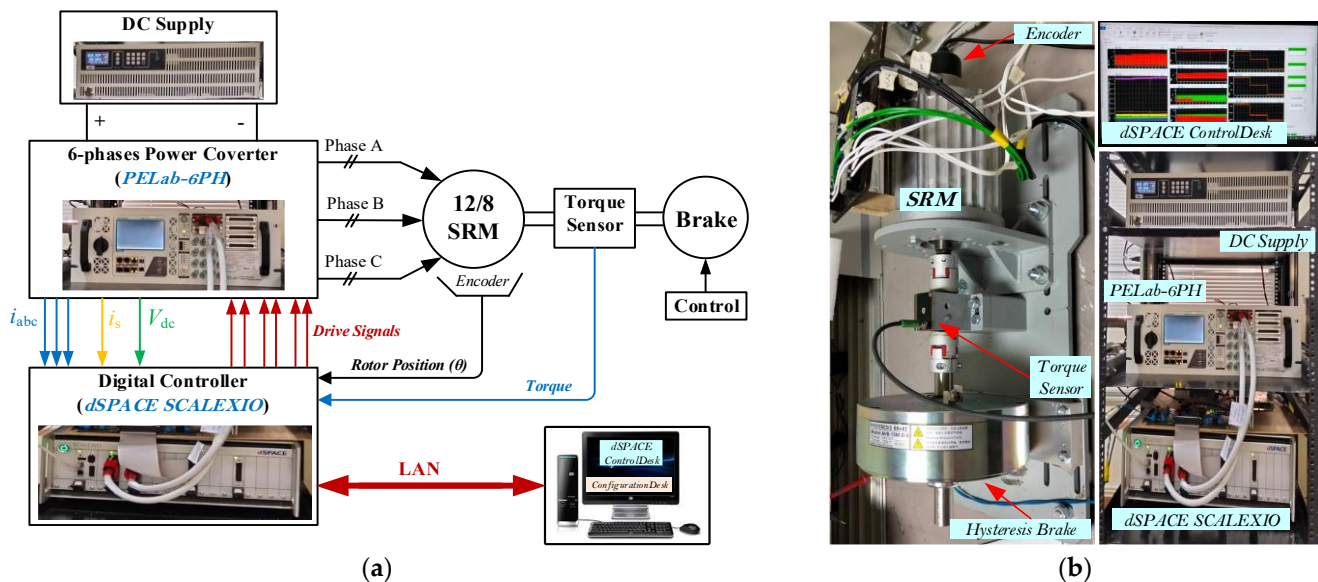


Figure 5. The experimental testbed: (a) its schematic diagram, (b) its practical implementation.

The experimental results involve the following cases:

- (1) **Case 1:** Detailed performance analysis for proposed ATC technique.
- (2) **Cases 2:** Comparison between the proposed and conventional ATC techniques, considering open loop torque control.
- (3) **Cases 3:** Comparison between the proposed and conventional ATC techniques, considering closed loop control.
- (4) **Cases 4:** Comparison between the proposed and conventional ATC techniques under speed change
- (5) **Cases 5:** Comparison between the proposed and conventional ATC techniques under sudden change in loading torque.

Noting that the experimental results are achieved in such a way to ensure the exact same operating point when comparing the proposed and conventional ATC techniques, the two control algorithms (proposed and conventional) are experimentally implemented in a parallel coding platform. Then, a selection switch is added to switch between them

in the real-time running motor conditions; the experimental results show the two control techniques side by side for better visualization and analysis.

5.1. Case 1: Detailed Performance Analysis for Proposed ATC Technique

Figure 6 explains the detailed performance of the proposed ATC (Prop-ATC) compared to the conventional ATC (Conv-ATC). First, the left column shows the performance of Conv-ATC; the phase current is controlled in a flat profile, as shown in Figure 6a; this in turn provides less torque controllability and, hence, generates huge torque ripples in the torque profile, as depicted by Figure 6b; the torque ripple is high, and it is about 52.62%. The torque error is also high, as seen in Figure 6c.

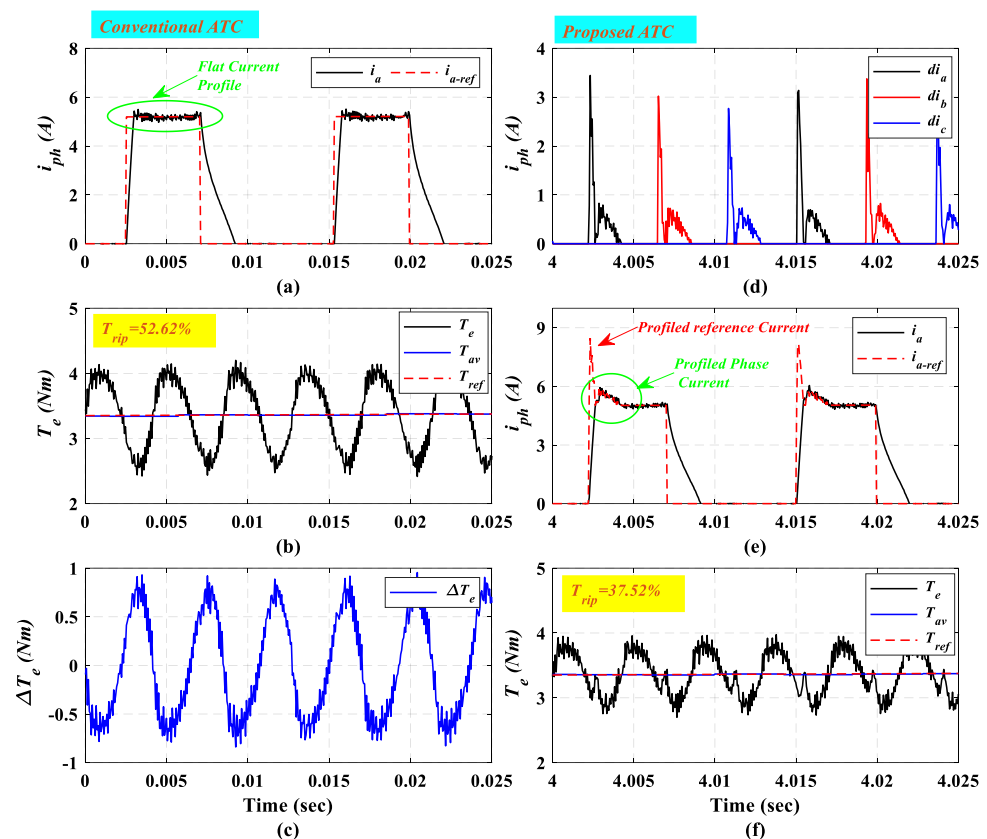


Figure 6. The experimental results for detailed performance of Prop-ATC at speed of 600 r/min and 3.45 Nm, (a) phase current profile for Conv-ATC, (b) torque profile for Conv-ATC, (c) torque error for Conv-ATC, (d) compensation currents for Prop-ATC, (e) phase current profile for Prop-ATC, (f) torque profile for Prop-ATC.

On the contrary, the right column shows the performance of Prop-ATC. First, the torque error is used to generate the compensation currents (di_a , di_b , di_c) for the three phases, see Figure 6d, based on the proposed mathematical formulation in Equation (10). Second, the reference phase current is adapted accordingly with torque error, as shown in Figure 6e, and, hence, the actual phase current is profiled, leading to a better torque profile with reduced torque ripples, as given in Figure 6f. The torque ripples are reduced to 37.52% compared to 52.62% for Conv-ATC; the reduction ratio of torque ripple is 28.69%.

5.2. Case 2: Open Loop Torque Control

In this section, the motor is operated under open loop torque control, the outer loop speed controller in Figures 2 and 3 is deactivated, hence, the reference torque (T_{ref}) is the direct control input; the load torque is controlled to adjust the motor speed as required. The

open loop torque control has a constant pure line reference torque signal, hence, providing a better reflection of torque ripples.

Figure 7 shows the experimental results at a low speed of 550 r/min and a loading torque of 3 Nm. The motor is running first under a Conv-ATC till time of 2.7 s, then the Prop-ATC is activated. The motor speed is almost constant, see Figure 7a, and the small change is due to the open loop control. In Figure 7b, the Prop-ATC is showing a significant improvement in torque profile, while maintaining a higher current, as seen in Figure 7c, due to the compensated current component. The torque ripple of Conv-ATC is 54.52%, see Figure 7d, compared to 37.73% for Prop-ATC, see Figure 7g; the reduction ratio of the torque ripples is 30.79%. The Conv-ATC has a flat current profile, as shown in Figure 7e, while the Prop-ATC is profiling the phase current, see Figure 7h, to compensate for the torque errors and, hence, reduce torque ripples. The switching angles are optimized to provide zero negative torque (ZNT) generation, and, hence, provide a better drive performance and improved system efficiency. The ZNT generation is very clear in Figure 7f,i.

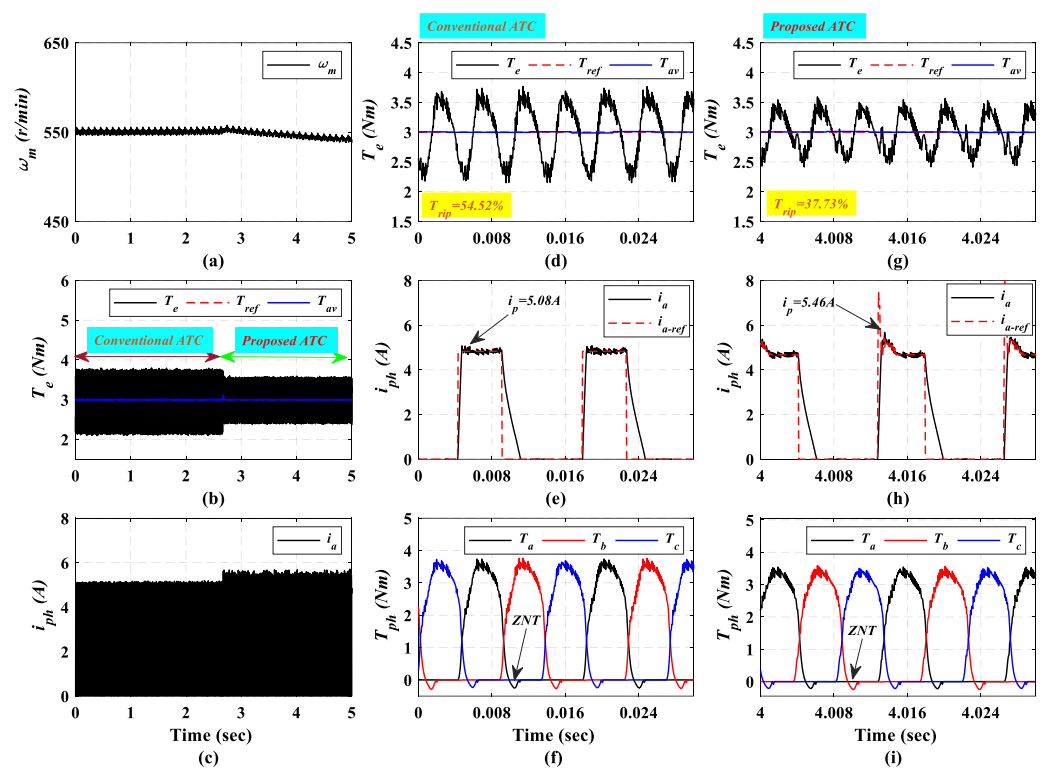


Figure 7. The experimental results under open loop torque control at speed of 550 r/min and 3 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

Figure 8 shows the experimental results at a high speed of 900 r/min and a loading torque of 2 Nm. The Prop-ATC still shows a significant improvement in the torque profile, as depicted by Figure 8b. The torque ripples for Prop-ATC are 37.96% compared to 53.23% for Conv-ATC. The reduction ratio of the torque ripples is 28.71%, due to the profiled current profile for Prop-ATC, as seen in Figure 8h. The ZNT generation is guaranteed, reflecting the optimum operation and improved performance, see Figure 8f,i.

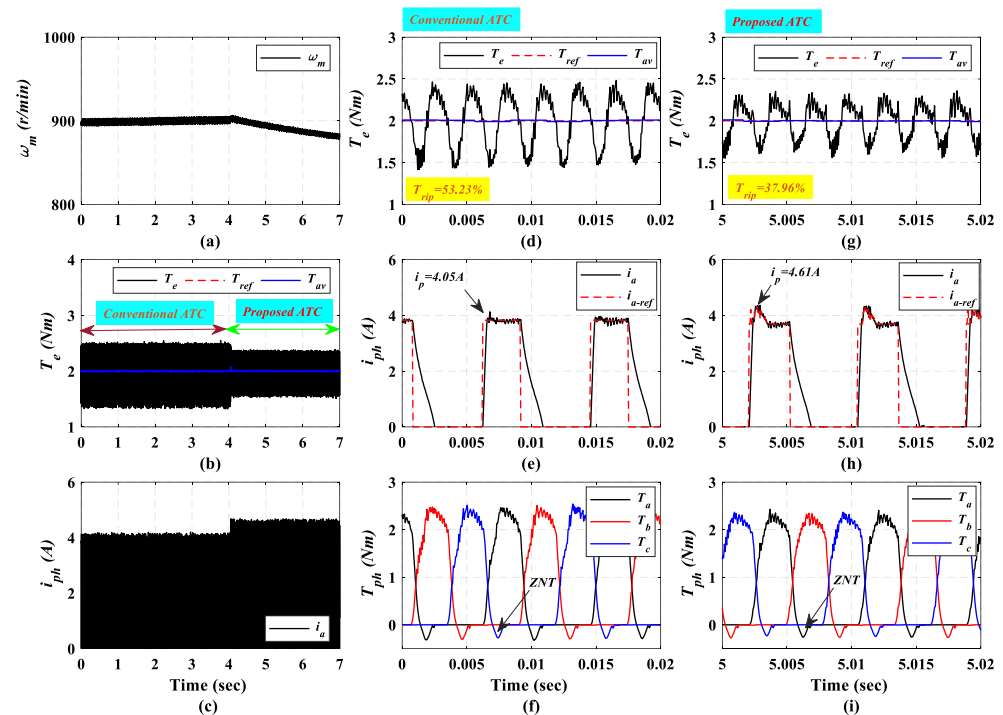


Figure 8. The experimental results under open loop torque control at speed of 900 r/min and 2 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

As a conclusion, the numerical analysis under open loop torque control is summarized in Table 3; the Prop-ATC produces the best torque profile with the minimum torque ripples, and it has a reduction ratio of 30.79% and 28.71% compared to Conv-ATC. However, it shows higher peak phase currents due to the proposed current profiling mechanism. In addition, the RMS current is given as a direct measure for the copper losses, as illustrated by Equation (6), that also reflects the heating conditions; the increase in the RMS current is relatively small so it raises no heating issues. In addition, the increased current has a slight effect on the drive efficiency. However, a trade-off has to be performed between the efficiency and torque ripple.

Table 3. Comparison of Conv-ATC and Prop-ATC under open loop torque control.

	550 r/min and 3 Nm		900 r/min and 2 Nm	
	Conv-ATC	Prop-ATC	Conv-ATC	Prop-ATC
T_{rip} (%)	54.52%	37.73%	53.23%	37.96%
Reduction ratio of T_{rip} (%)	-----	30.79% ↓	-----	28.71% ↓
Peak current i_p (A)	5.08	5.46	4.05	4.61
RMS current I_{RMS} (A)	2.9305	2.9841	2.3492	2.4309
Efficiency η (%)	69.693	68.930	80.397	79.874

5.3. Case 3: Closed Loop Control

In this section, the motor is operated under closed loop control, and the outer loop speed controller is activated, hence, reflecting the real-time actual operating conditions. The results are obtained for different speeds from a low speed of 400 r/min reaching a very high speed of 1800 r/min, and also considering different loading levels of heavy loads of 4 Nm and light loads of 2 Nm.

Figure 9 shows the experimental results at a low speed of 400 r/min, see Figure 9a, and a heavy loading torque of 4 Nm. The Prop-ATC has the ability to provide a better torque profile compared to Conv-ATC, as shown in Figure 9b. The torque ripples are reduced significantly. The torque profile for Conv-ATC is seen in Figure 9d with a ripple ratio of 56.14%, while the torque profile for Prop-ATC has a ripple ratio of 38.38%, as depicted in Figure 9g; the reduction ratio of the torque ripples is 31.63%. The torque profiles for each phase in Figure 9f,i ensure ZNT production, and it is approved for the improved system performance.

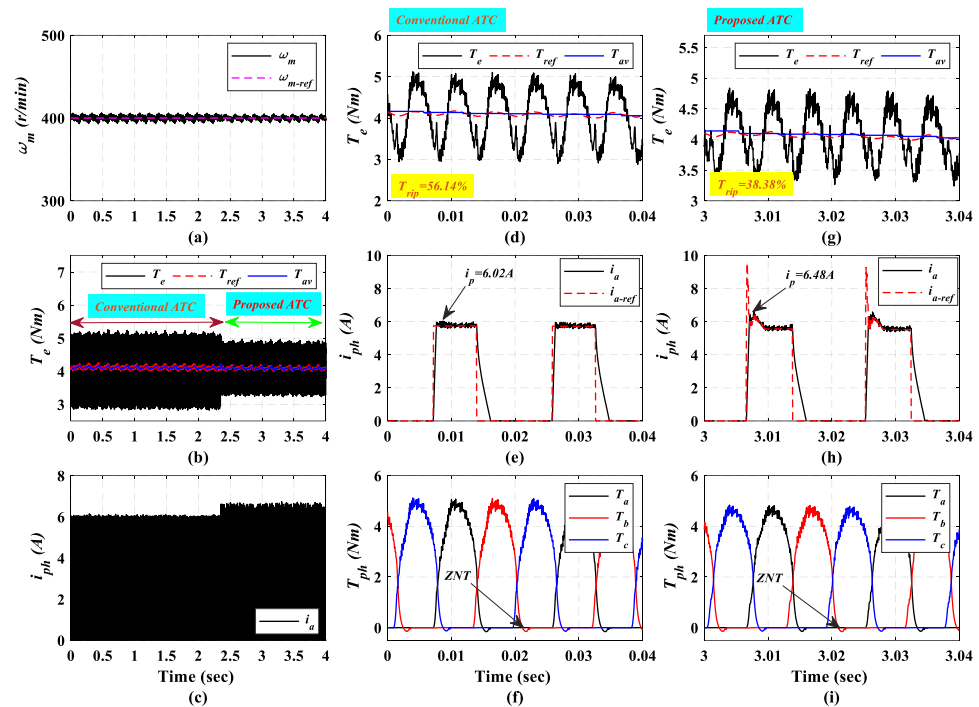


Figure 9. The experimental results under closed loop control at speed of 400 r/min and 4 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

Figure 10 shows the experimental results at a rated-speed of 800 r/min and a heavy loading torque of 4 Nm. The Prop-ATC still shows a better torque profile with reduced torque ripples; the torque ripples are reduced from 37.64% for Conv-ATC to 31.93% for Prop-ATC; the reduction ratio of the torque ripples is 15.17%. A small negative torque (NT) appears in Figure 10f,i due to the higher speed and the heavy load; however, it is still not significant, as reducing it will affect the average torque. By other means, the best motor operation is achieved by maximizing the total torque generation, but it comes with a small NT generation; the negative torque appears under heavy loads and under high speed.

Figure 11 shows the experimental results at a high speed of 1200 r/min and a heavy loading torque of 4 Nm. At high speeds, the current control of the SRM becomes difficult due to the high back-emf. As a result, the torque profiles for Conv-ATC and Prop-ATC schemes, shown in Figure 11b, are very close. The actual current profiles, in Figure 11e,h, are almost the same; the current profiling at high speed is ineffective due to the limited dc-link voltage and the high back-emf. However, the torque ripple is reduced from 45.23% for Conv-ATC to 40.36% for Prop-ATC; the reduction ratio of the torque ripples is 10.76%. The NT appears in Figure 11f,i due to high speed and heavy loads; they are not significant.

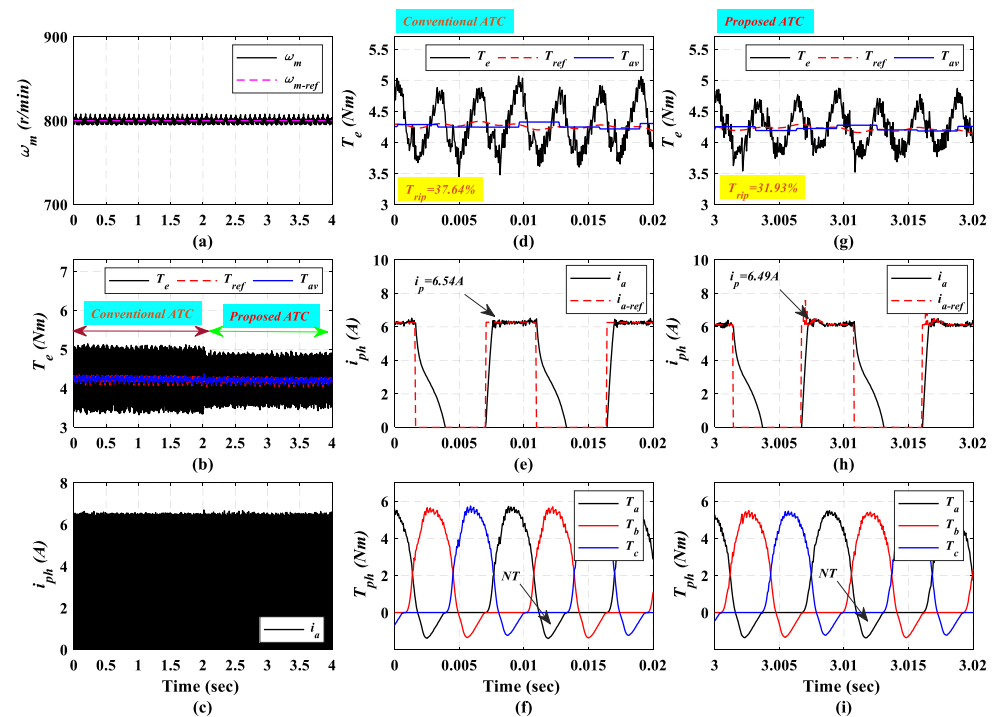


Figure 10. The experimental results under closed loop control at speed of 800 r/min and 4 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

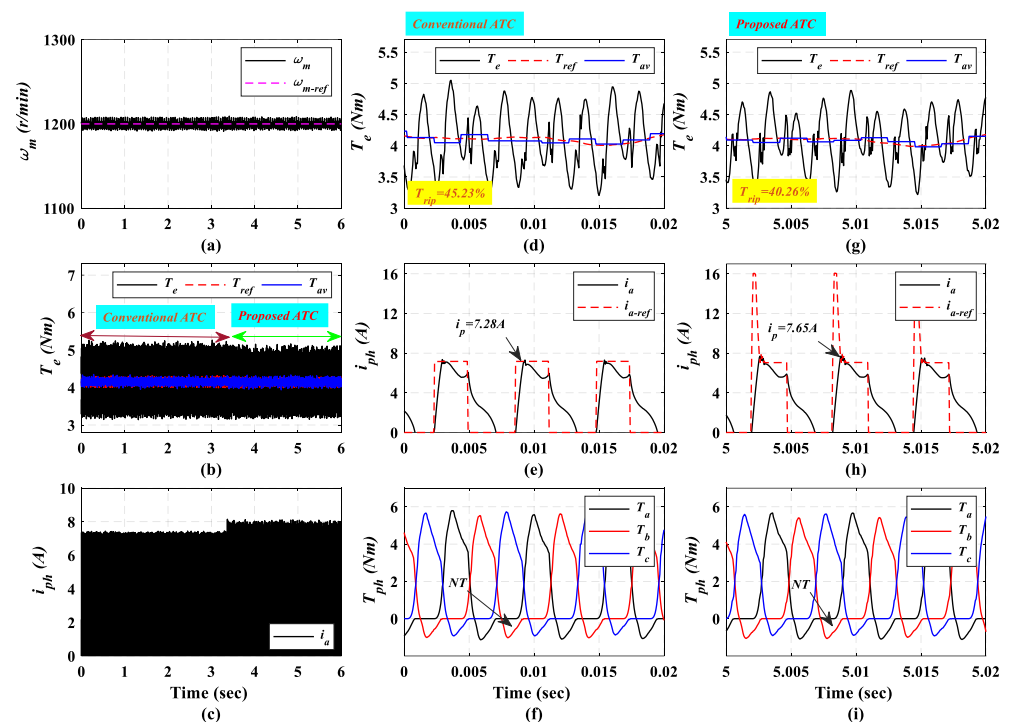


Figure 11. The experimental results under closed loop control at speed of 1200 r/min and 4 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

Figure 12 shows the experimental results at a very high-speed of 1800 r/min and a loading torque of 2 Nm. At this very high speed, the motor operates in a single pulse control (SPC) mode, the phase voltage is almost a single pulse without chopping, and there is almost no current control; the current level is defined accordingly by the loading torque and value of the back-emf. Due to the uncontrolled current at very high speeds, any current profiling will be completely ineffective. As a result, the torque profiles for the Conv-ATC and the Prop-ATC techniques will be almost the same, see Figure 12b. The torque ripple is 53.32% for Conv-ATC and 50.91% for Prop-ATC; the reduction ratio of the torque ripples is 4.38%. The NT appears in Figure 12f,i due to the very high speed.

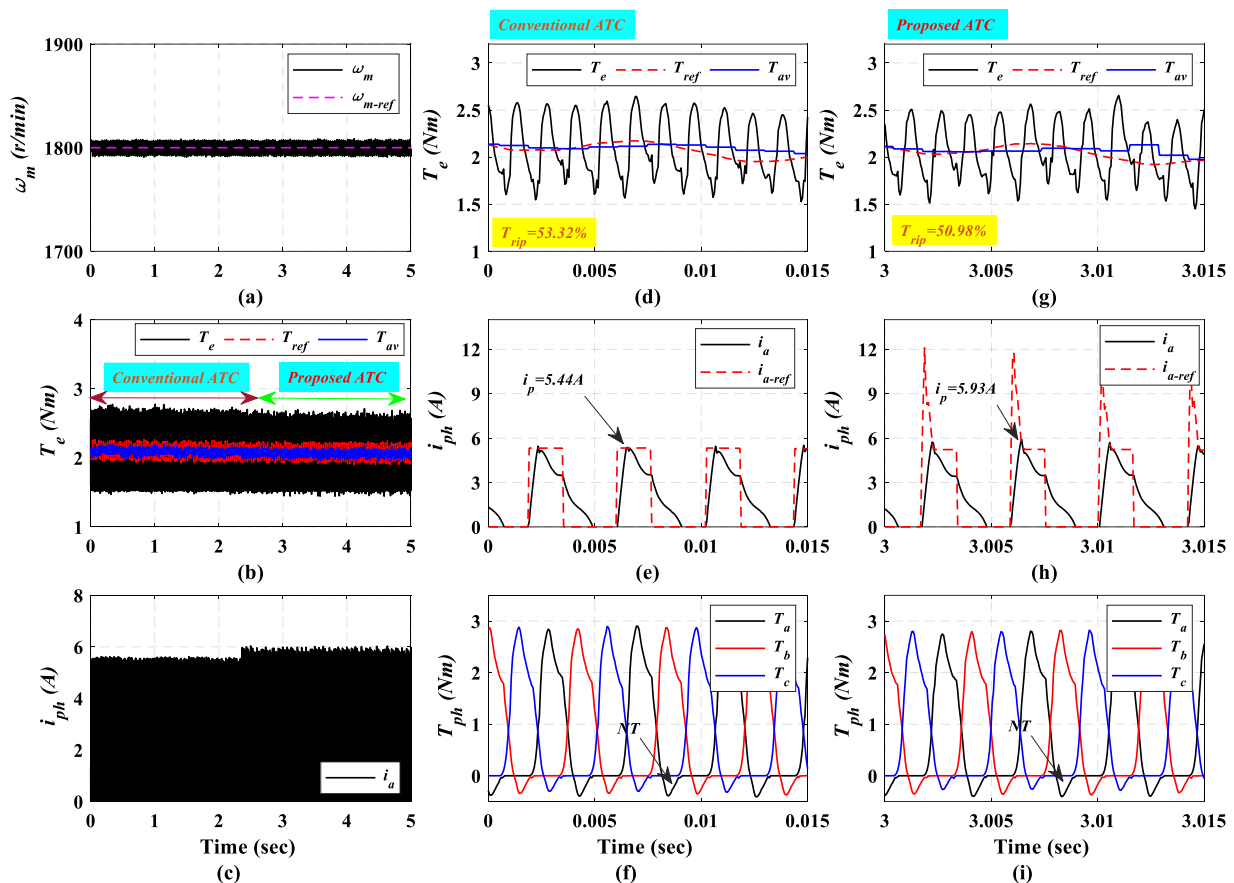


Figure 12. The experimental results under closed loop control at speed of 1800 r/min and 2 Nm, (a) speed, (b) torque, (c) current, (d) torque profile for Conv-ATC, (e) phase current profile for Conv-ATC, (f) phase torque profile for Conv-ATC, (g) torque profile for Prop-ATC, (h) phase current profile for Prop-ATC, (i) phase torque profile for Prop-ATC.

As a conclusion, the numerical analysis for the closed loop control is summarized in Table 4; the Prop-ATC shows a significant reduction in the torque ripples till rated speed. As the speed increases, the reduction ratio of the torque ripple decreases because the current control becomes difficult due to the limited dc-link voltage and the high back-emf. Higher peak phase currents are observed for the Prop-ATC due to the CCM. Moreover, the RMS current for the Prop-ATC and the Conv-ATC are very close, raising no heating issues after the proposed current compensation logic. Furthermore, the drive efficiency is shown to increase with speed; at 1800 r/min, both the Prop-ATC and the Conv-ATC provide the same efficiency. However, for lower speeds, the efficiency of Prop-ATC is a bit lower with the beneficial torque ripple reduction capability. Hence, it is a must to trade-off between the efficiency and torque ripple.

Table 4. Comparison of Conv-ATC and Prop-ATC under closed loop control.

		T_{rip} (%)	RR T_{rip} (%)	i_p (A)	I_{RMS} (A)	η (%)
400 r/min and 4 Nm	Conv-ATC	56.14%	-----	6.02	3.5164	63.080
	Prop-ATC	38.38%	31.63% ↓	6.48	3.6186	62.112
800 r/min and 4 Nm	Conv-ATC	37.64%	-----	6.54	4.1447	73.441
	Prop-ATC	31.93%	15.17% ↓	6.49	4.1765	72.837
1200 r/min and 4 Nm	Conv-ATC	45.23%	-----	7.28	4.1229	80.030
	Prop-ATC	40.36%	10.76% ↓	7.65	4.2773	79.684
1800 r/min and 2 Nm	Conv-ATC	53.32%	-----	5.44	2.7141	89.833
	Prop-ATC	50.91%	4.38% ↓	5.93	2.7138	89.863

5.4. Case 4: Closed Loop Control with Speed Change

Figure 13 shows the experimental results with step change in the reference speed with a constant loading torque of 2.8 Nm. The motor speed is suddenly changed to 600 r/min at a time of 0.25 s, see Figure 13a. The motor starts its operation from rest, as shown in Figure 13a,d for the Conv-ATC and Prop-ATC schemes, respectively. The fast response is observed by the torque profiles in Figure 12b,e; the average torque (T_{av}) is tracking its reference torque signal (T_{ref}) at a time of 0.37 s for the Conv-ATC, as shown in Figure 13b; the required time for tracking is $(0.37 - 0.25 = 0.12)$ s. For the Prop-ATC, in Figure 13e, T_{av} is tracking T_{ref} at a time of 0.36 s; the required tracking time is $(0.36 - 0.25 = 0.11)$ s. As a result, the Prop-ATC is 8.33% faster compared to the Conv-ATC. In addition, the Prop-ATC has a better torque profile with 40.33% torque ripples compared to 56.44% for the Conv-ATC.

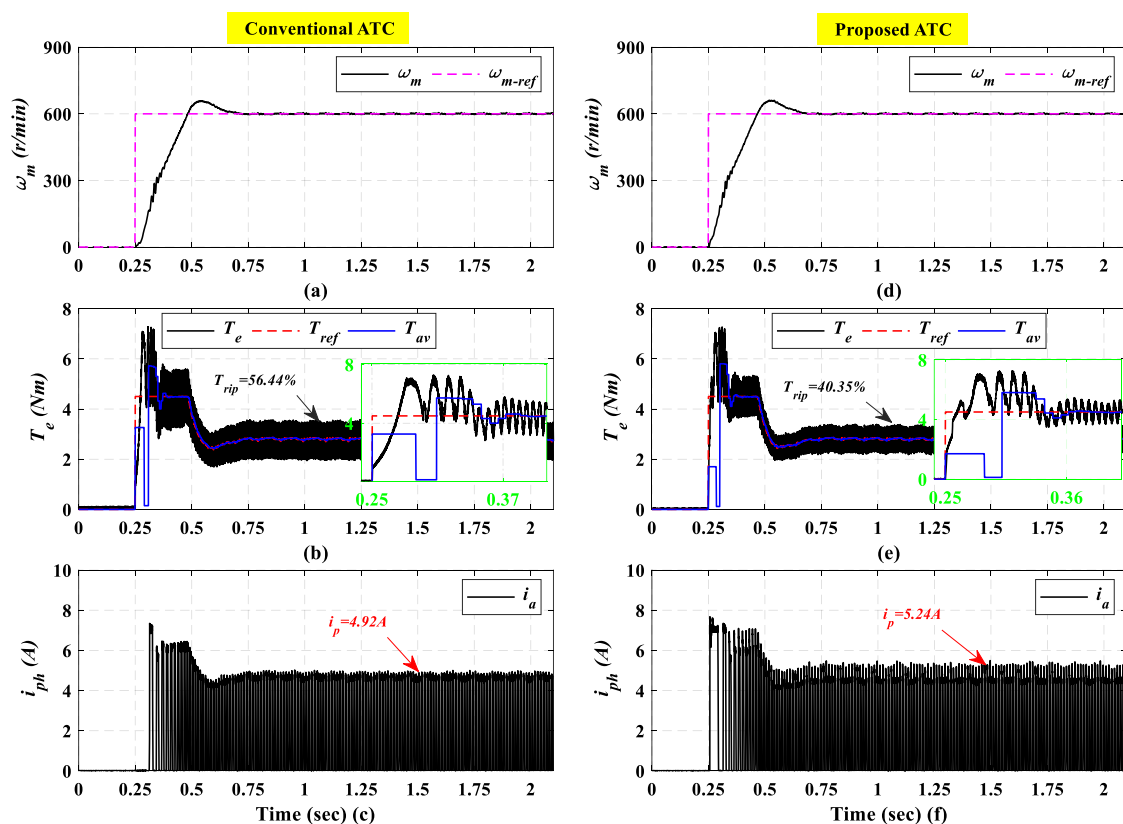


Figure 13. The experimental results with speed change at 2.8 Nm, (a) speed for Conv-ATC, (b) torque for Conv-ATC, (c) current for Conv-ATC, (d) speed for Prop-ATC, (e) torque for Prop-ATC, (f) current for Prop-ATC.

5.5. Case 5: Closed Loop Control with Sudden Change in Loading Torque

Figure 14 shows the experimental results under a sudden load change. The motor is running at a speed of 700 r/min, see Figure 14a, with a loading torque of 3 Nm, then the load torque is completely removed (load off), and the motor becomes unloaded (no load condition). Fast responses are observed over the torque profiles in Figure 14b,e for the Conv-ATC and Prop-ATC schemes, respectively. The Prop-ATC provides a better torque profile with 39.86% torque ripples compared to 52.98% for the Conv-ATC. The torque reduction ratio is 24.75%.

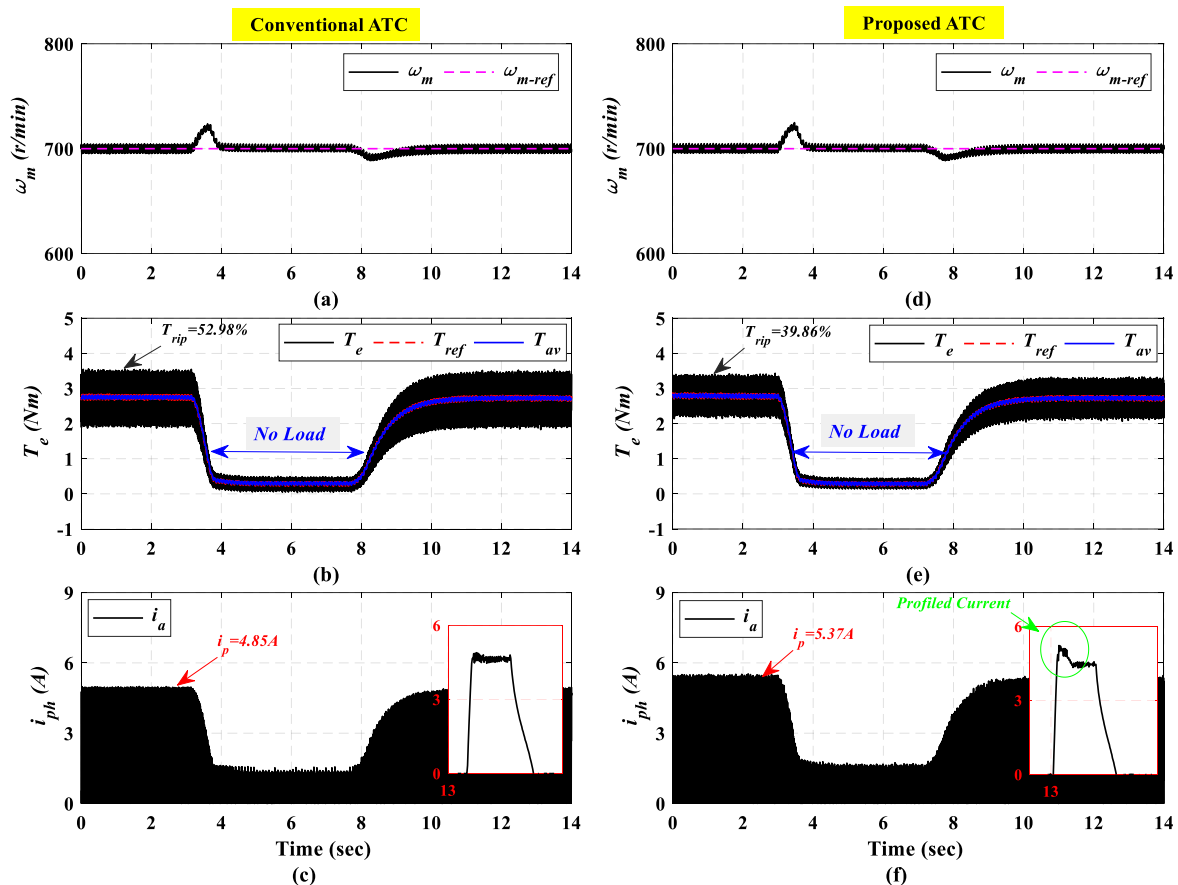


Figure 14. The experimental results with sudden change in loading torque from 3 Nm to 0.3 Nm at 700 r/min, (a) speed for Conv-ATC, (b) torque for Conv-ATC, (c) current for Conv-ATC, (d) speed for Prop-ATC, (e) torque for Prop-ATC, (f) current for Prop-ATC.

6. Comparative Summary

The superiority of Prop-ATC over the existing torque control techniques for SRMs is shown in Table 5. The ATC is the most significant solution regarding the complexity, fault tolerant operation, generalization for multi-phase SRMs, reliability under harsh conditions, development cost, and efficiency. However, the torque ripple can be reduced to an acceptable level using a proper control method as presented in this paper. The proposed control method based on the ATC scheme shows a significant torque ripple reduction capability of about 30%, especially at low speeds; achieving the superiority of ATC as listed in Table 5 while mitigating the torque ripples.

Table 5. Comparison of different torque control techniques of SRMs.

Criterion	IITC	DITC	MPC	Prop-ATC
Model dependency	Moderate	Low	Very high	Very low
Computational burden	Low	Moderate	Very high	Minimal
Implementation complexity	Low	Medium	Highest	Lowest
Fault tolerance compatibility	Good	Very good	Moderate	Excellent
Operation under phase failure	Limited	Possible	Complex	Highly possible
Scalability to multi-phase SRMs	Excellent	Moderate	Limited	Excellent
Development cost	Moderate	High	Very high	Low
Real-time feasibility	Excellent	Good	Challenging	Excellent
Reliability under harsh conditions	Good	Good	Questionable	Excellent
Sensitivity to parameter mismatch	Moderate	Low	High	Very low
Ease of calibration and tuning	Moderate	Difficult	Very difficult	Very easy
Robustness to noise and disturbances	Moderate	High	Moderate	Excellent
Torque ripple (system-level)	Lower	Lower	Lowest	<i>Acceptable</i>
Overall EV system efficiency	Similar	Similar	Marginal gain	Competitive

7. Conclusions

This paper presents a novel average torque control technique with a current profiling mechanism for better torque ripple reduction capability. First, a simple analytical torque ripple reduction technique is proposed based on the detailed analysis of the inductance profile; the torque error is processed to compensate for the reference phase current of the ongoing phase over its minimum inductance zone (MIZ); the consideration of MIZ helps to simplify the mathematical formulations and, hence, provides a simple ATC scheme for fast real-time implementations with lower computational effort. Second, the proposed control is achieved experimentally for the 12/8 SRM prototype; the experimental results show the superior performance of the proposed ATC (Prop-ATC) scheme compared to the conventional ATC; the Prop-ATC succeeds in profiling the phase current of the ongoing phase over extended speed ranges; it reduces the torque ripples significantly with an average reduction ratio of about 30% for low speeds; as the speed increases, the torque reduction ratio decreases due to the difficult current control/profiling. In addition, the Prop-ATC provides a faster torque response of about 8.33% compared to the conventional ATC. The Prop-ATC is a very powerful solution for electric vehicles as it reduces the low-speed torque ripples significantly, hence, providing comfortable driving; the high-speed torque ripples can be filtered by vehicle inertia.

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Abbreviations

ATC	Average torque control
CCC	Current chopping control
CCM	Current compensation mechanism
DC	Direct current
EVs	Electric vehicles
HEVs	Hybrid electric vehicles
ITC	Instantaneous torque control
MIZ	Minimum inductance zone
MPC	Model predictive control
PPR	Pulse per revolution
SRMs	Switched reluctance motors
TSF	Torque sharing function

Nomenclature

Symbol	Definition	Unit
B	The combined rotor and load viscous friction coefficient	$\text{Kg}\cdot\text{m}^2$
I_{av}	The average supply current	A
$i_{a-ref}, i_{b-ref}, i_{c-ref}$	The reference current of phases A, B, and C	A
$i_{a-ref-comp}, i_{b-ref-comp}, i_{c-ref-comp}$	The final compensated reference current signals for phases A, B, and C	A
i_k	The phase current of k th phase	A
i_{ref}	The reference current	A
i_s	The instantaneous supply current	A
i_p	The peak phase current	A
J	The combined rotor and load inertia coefficient	$\text{Kg}\cdot\text{m}^2\cdot\text{s}$
L_k	The inductance of k th phase	H
q	The number of motor phases	
R	The phase resistance	Ω
T_{av}	The average torque	$\text{N}\cdot\text{m}$
T_e	The total electromagnetic torque	$\text{N}\cdot\text{m}$
T_k	The torque of k th phase	$\text{N}\cdot\text{m}$
T_L	The load torque	$\text{N}\cdot\text{m}$
T_{max}	The maximum value of instantaneous motor torque	$\text{N}\cdot\text{m}$
T_{min}	The minimum value of instantaneous motor torque	$\text{N}\cdot\text{m}$
T_{rip}	The torque ripple	$\text{N}\cdot\text{m}$
T_{ref}	The reference torque	$\text{N}\cdot\text{m}$
V_{dc}	The DC supply voltage	V
v_k	The phase voltage of k th phase	V
θ	The rotor position	Deg.
θ_m	The angle where rotor and stator poles start to overlap	Deg.
θ_{on}	The turn-on angle	Deg.
θ_{off}	The turn-off angle	Deg.
η	The drive efficiency	

ω_m	The actual motor speed	Rad/min
ω_{ref}	The reference commanded speed	Rad/min
$\delta T, \Delta T$	The torque errors	N·m
$\delta i_a, \delta i_b, \delta i_c$	The compensated current signals for phases A, B, C	A
τ	The time of one electric cycle	s

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