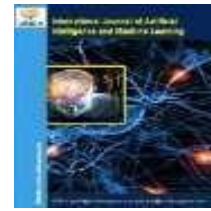




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HHO-Optimized Adaptive PI Control and Hybrid Smooth Torque Sharing Function For Ripple Torque Reduction in Switched Reluctance Motor

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ABSTRACT

Switched reluctance motors (SRMs) offer a simple and robust structure, but their doubly salient topology and sequential phase excitation result in significant electromagnetic ripple torque, particularly during phase commutation. This paper proposes a ripple torque reduction strategy for a four-phase 8/6 SRM drive based on the combination of an error- and error-rate-dependent smooth adaptive proportional-integral (EDSA-PI) controller and a hybrid smooth torque sharing function (TSF). The EDSA-PI controller dynamically adjusts its proportional gain according to the magnitude and rate of change of the speed error, while its integral gain is adapted according to the speed error. An anti-windup mechanism is also incorporated to handle controller-output saturation. At the torque-sharing level, the proposed hybrid TSF preserves the conventional rising-constant-falling structure while combining linear and minimum-jerk polynomial transitions to provide smoother phase-torque transfer during commutation. The six EDSA-PI parameters are optimized offline using the Harris Hawks Optimization (HHO) algorithm through closed-loop MATLAB/Simulink simulations. The optimized controller is evaluated at two operating points, namely 500 rpm with a load torque of 5 N·m and 1000 rpm with a load torque of 7 N·m. Using the same hybrid smooth TSF in both configurations, the proposed EDSA-PI configuration reduces the steady-state torque ripple from 56.92% to 20.12% at 500 rpm and from 47.15% to 12.80% at 1000 rpm, corresponding to reductions of 64.65% and 72.89%, respectively. The results demonstrate that the combination of HHO-optimized adaptive speed control and hybrid smooth torque sharing can substantially improve the electromagnetic torque quality of the investigated four-phase 8/6 SRM drive.

Index Terms: Switched reluctance motor, ripple torque reduction, torque sharing function, adaptive PI controller, Harris Hawks Optimization.

I. Introduction

Switched reluctance motors (SRMs) have attracted considerable attention in modern electric-drive applications due to their simple and rugged mechanical construction, absence of permanent magnets and rotor windings, high fault tolerance, wide constant-power speed range, and cost-effective manufacturing [1]. These intrinsic merits make SRMs highly promising candidates for traction drives in electric vehicles (EVs), industrial automation, aerospace actuation, and high-speed electromechanical conversion systems [2], [3]. Nevertheless, the doubly salient stator-rotor geometry and sequential phase-excitation paradigm inherently produce discontinuous phase inductance profiles and highly pulsating electromagnetic torque. Consequently, severe torque ripple, acoustic noise, and stator structural vibrations remain the primary impediments preventing SRMs from broad adoption in high-performance motion-control applications [4], [5].

The instantaneous electromagnetic torque in an SRM is a highly nonlinear function of rotor position, phase current, and local magnetic saturation. During steady-state continuous rotation, the total shaft torque is delivered through the overlapping conduction of energized phases. In the commutation region, the torque contribution of the outgoing phase decays while that of the incoming phase rises. To ensure ripple-free torque production, the sum of these instantaneous phase torques must precisely track the demanded reference torque. However, owing to magnetic saturation, limited DC-link voltage, back-electromotive force (back-EMF) at elevated speeds, and finite current rise and fall times (di/dt), practical phase current tracking deviates

substantially from the theoretical ideal [6], [7]. Consequently, uncoordinated phase-torque commutation results in noticeable torque dips, commutation current spikes, and increased copper losses [8], [9].

To address these commutation issues, torque sharing function (TSF)-based control has emerged as one of the most effective and widely adopted indirect torque-control strategies. In a TSF-based drive, the total reference torque generated by the speed controller is partitioned into individual phase torque references according to rotor position [10], [11]. These phase torque references are then mapped to target current profiles via multi-dimensional analytical models or inverted flux/torque look-up tables (LUTs) [12]. Compared with conventional current chopping control (CCC) or simple angle-position control (APC), TSF schemes offer enhanced flexibility in contouring the commutation trajectory of each active phase [13], [14].

Historically, analytical TSF profiles such as linear, cubic, sinusoidal/cosine, and exponential functions have been widely investigated. Seminal studies by Xue et al. demonstrated that the mathematical continuity of the sharing function directly dictates current derivative behavior, peak current magnitude, and maximum ripple-free operating speed, identifying cubic and higher-order functions as superior in terms of smoothness and low-ripple performance [6], [10]. Subsequent comparative investigations have consistently confirmed that smooth transition curves significantly reduce phase current tracking errors within inner hysteresis or sliding-mode current loops [14]. Nonetheless, fixed analytical profiles designed with constant turn-on and overlap angles cannot dynamically adapt across varying torque-speed operating points [7].

To overcome the stiffness of fixed mathematical functions, parameter optimization using metaheuristic algorithms has been widely studied. Xue et al. established genetic algorithm (GA) optimization to determine optimal turn-on and overlap angles for maximizing operating speed while minimizing copper loss [6]. Recently, Fetoui et al. implemented particle swarm optimization (PSO) across segmented commutation intervals to minimize negative torque and expand ripple-free drive boundaries [15]. Similar evolutionary tuning methodologies have utilized the flower pollination algorithm [16] and sailfish optimization [17]. In addition, Xu et al. proposed an adaptive exponential TSF that adjusts turn-on and overlap angles in real time to prevent severe peak currents and torque degradation under medium- and high-speed operation [7].

Another major line of research addresses the mismatch between mathematical TSF reference commands and the actual physical torque-producing capability of the machine phases. Due to rising back-EMF, the incoming phase frequently fails to establish excitation current rapidly enough, while the outgoing phase cannot demagnetize before entering the negative-inductance slope region [18]. To resolve this physical tracking bottleneck, hybrid and capability-weighted TSF strategies have been proposed. Gao et al. designed a hybrid TSF (HTSF) combined with online predictive compensation to suppress severe current spikes during phase handoff [8]. Costa et al. introduced a compensated torque sharing strategy (CTSS) combined with gain-scheduled proportional control to accommodate back-EMF variations in belt-driven starter-generator (BSG) systems [2]. Similarly, interval-segmented and dynamic region-division TSFs have been formulated by Hu et al. [19], Yao et al. [9], and Zhang et al. [20]. By analyzing the instantaneous torque-per-ampere ratio (TAR) of incoming and outgoing phases, these methods allocate torque references adaptively based on electromagnetic capacity rather than pre-assigned geometric trajectories, successfully reducing copper losses and commutation ripple [21], [22].

Concurrently, closed-loop torque tracking has increasingly progressed from inner-loop current tracking toward direct instantaneous torque control (DITC) and model predictive control (MPC). Direct instantaneous torque control regulates the instantaneous motor torque directly within a defined hysteresis band, offering fast dynamic response without requiring offline inverse torque-current-position look-up tables [23]. Sun et al. demonstrated that integrating TSF profiles into a DITC framework combines the direct torque regulation capability of DITC with the smooth reference allocation of TSF [23]. Abdelmalek et al. recently validated a dual-mode control architecture employing a TSF-based scheme below base speed and transitioning to fixed-frequency PWM-DITC at elevated speeds, bounding the switching frequency while maintaining low torque ripple across wide operating envelopes [24]. Chakma et al. further integrated linear active disturbance rejection control (LADRC) and repetitive control into DITC, achieving sharp attenuation of periodic torque pulsations and robust load-disturbance rejection [25]. Similarly, predictive torque control (PTC) and model predictive torque and force control (MPT&FC) have been extensively explored to simultaneously track TSF profiles, optimize candidate voltage vectors, and mitigate mechanical vibration [3], [5], [26]–[28].

Despite these notable advances, critical research gaps remain in current SRM drive architectures:

- 1) While model predictive control and advanced disturbance-observer architectures (e.g., LADRC, neural-network-assisted estimators [29]) exhibit high dynamic performance, their real-time execution imposes heavy computational burdens on embedded microcontrollers and requires highly accurate machine magnetic characterization [27], [28].
- 2) The vast majority of published literature approaches speed-loop regulation and torque-sharing profile optimization in complete isolation. Studies proposing advanced nonlinear outer speed regulators (e.g., terminal-sliding-mode control [30] or gain-scheduled regulators [2]) typically adopt conventional fixed or heuristic TSFs in the inner loop. Conversely, works focused on sophisticated TSF geometry optimization or

dynamic region division [9], [15] universally rely on standard, non-optimized linear proportional-integral (PI) outer-loop controllers.

- 3) Conventional linear, cubic, and piecewise segmented TSF profiles still contain discontinuities in their higher-order derivatives (such as acceleration and jerk) at the transition boundaries. Under rapid speed changes or variable load conditions, these derivative jumps excite high-frequency chattering in DITC hysteresis regulators, degrading instantaneous torque tracking.
- 4) Speed control and phase commutation are deeply coupled dynamic processes: the outer speed regulator dictates the dynamic total torque demand, whereas the inner TSF determines the instantaneous spatial gradient of the phase torque references. Optimizing either loop independently inevitably yields sub-optimal global performance during transient acceleration and load disturbances.

To bridge these gaps, this paper proposes an offline Harris Hawks Optimization (HHO)-tuned, co-designed control strategy for a four-phase 8/6 SRM operating under Direct Instantaneous Torque Control (DITC). The proposed architecture integrates an error- and error-rate-dependent smooth adaptive PI (EDSA-PI) speed controller with a newly formulated hybrid smooth TSF.

The EDSA-PI controller continuously adapts its proportional gain according to both the instantaneous speed error and its rate of change, while adapting its integral gain based on the error magnitude, augmented by an anti-windup mechanism to handle saturation during large transients. At the torque-distribution level, the proposed hybrid smooth TSF retains the practical rising-constant-falling structure while synthesizing a blend of linear characteristics with a fifth-order minimum-jerk polynomial. This mathematical design guarantees smooth continuity of torque derivatives at transition boundaries, dampening current chattering and torque spikes during commutation.

Rather than tuning the outer-loop gains and inner-loop commutation parameters separately, a unified offline optimization framework using the Harris Hawks Optimization (HHO) algorithm is established. The joint optimization vector incorporates six EDSA-PI parameters $[K_{p0}, K_{i0}, K_a, E_s, K_d, E_{ds}]$ and six hybrid smooth TSF parameters $[T_{on}, T_{off}, a, b, c, d]$. The optimization is executed using closed-loop dynamic simulations under a multi-objective cost function that penalizes speed-tracking error, acceleration overshoot, and instantaneous torque ripple simultaneously.

The performance and disturbance rejection of the proposed strategy are validated on a four-phase 8/6 SRM drive at two distinct operating regimes (500 rpm at 5 N·m and 1000 rpm at 7 N·m). To ensure a rigorous and transparent evaluation, the proposed EDSA-PI configuration is benchmarked directly against a standard PI controller sharing the identical HHO-optimized hybrid smooth TSF, thereby isolating and quantifying the exact performance contributions of the adaptive speed controller and the smooth TSF profile.

The principal contributions of this work are summarized as follows:

- 1) **Development of an EDSA-PI Speed Controller:** A smooth adaptive PI speed controller is designed for SRM drives where the proportional gain is dynamically reshaped by both speed-error magnitude and its derivative, and the integral gain is modulated by the speed error, improving transient tracking speed and disturbance recovery while mitigating integrator windup.
- 2) **Formulation of a Minimum-Jerk Hybrid Smooth TSF:** A novel torque sharing function is formulated by blending linear commutation transitions with fifth-order minimum-jerk polynomial curves, ensuring smooth torque derivatives across commutation boundaries without abandoning the practical rising-constant-falling operational structure.
- 3) **Joint Multi-Loop Optimization via HHO:** A unified offline optimization scheme based on the Harris Hawks Optimization algorithm is established to simultaneously co-tune the six parameters of the EDSA-PI speed controller and the six angular/geometry parameters of the hybrid smooth TSF, systematically capturing the dynamic cross-coupling between the outer speed loop and the inner torque-distribution mechanism.
- 4) **Controlled Comparative Validation Framework:** The proposed drive system is benchmarked against a conventional PI controller utilizing the identical HHO-optimized hybrid smooth TSF, providing an unequivocal evaluation of the speed-loop adaptive mechanism under identical inner-loop torque conditions.
- 5) **Comprehensive Quantitative Evaluation across Speed-Load Envelopes:** The closed-loop drive is evaluated under low-speed (500 rpm, 5 N·m) and medium-speed (1000 rpm, 7 N·m) conditions, demonstrating simultaneous suppression of steady-state torque ripple, reduction of commutation current spikes, and superior dynamic recovery under sudden load variations.

The remainder of this paper is organized as follows. Section II presents the mathematical model of the four-phase 8/6 SRM and the fundamental DITC operational principles. Section III details the mathematical formulation of the proposed EDSA-PI controller and the hybrid smooth TSF. Section IV describes the HHO-based joint optimization procedure, parameter bounds, and multi-objective fitness formulation. Section V

presents and discusses the simulation results, transient load-step responses, and comparative torque-ripple metrics. Finally, Section VI concludes the paper.

II. SRM Drive Model

A. SRM Configuration

The investigated drive employs a four-phase 8/6 switched reluctance motor (SRM), consisting of eight stator poles and six rotor poles. Each stator phase is independently energized through the power converter, while the rotor contains neither windings nor permanent magnets. The doubly salient structure of the machine results in a strongly position-dependent inductance and electromagnetic torque.

For phase k , the magnetic behavior is determined by the relationship between the phase current and rotor position. The phase flux linkage is therefore expressed as

$$\psi_k = \psi_k(i_k, \theta), \quad (1)$$

where ψ_k is the flux linkage of phase k , i_k is its phase current, and θ is the rotor position.

The nonlinear dependence of flux linkage on current and rotor position is particularly important for SRM torque production. During phase commutation, the torque contribution of the outgoing phase decreases while that of the incoming phase increases. Consequently, the current and torque profiles of consecutive phases must be appropriately controlled to obtain a smooth total electromagnetic torque.

B. Mathematical Model

The voltage equation of phase k can be expressed as

$$v_k = R_k i_k + \frac{d\psi_k(i_k, \theta)}{dt}, \quad (2)$$

where v_k and R_k represent the phase voltage and phase resistance, respectively.

The electromagnetic torque generated by each phase is obtained from the magnetic co-energy. For phase k , the torque is given by

$$T_{e,k} = \left. \frac{\partial W'_k(i_k, \theta)}{\partial \theta} \right|_{i_k}, \quad (3)$$

where W'_k denotes the magnetic co-energy of phase k .

Since the investigated machine has four independently controlled phases, the total electromagnetic torque is the sum of the individual phase torques:

$$T_e = \sum_{k=1}^4 T_{e,k}. \quad (4)$$

The mechanical dynamics of the drive are described by

$$J \frac{d\omega}{dt} = T_e - T_L - B\omega, \quad (5)$$

where J is the rotor inertia, ω is the mechanical angular speed, T_L is the applied load torque, and B is the viscous friction coefficient.

Equations (1)–(5) describe the fundamental electromagnetic and mechanical relationships governing the investigated SRM drive. The nonlinear magnetic characteristics of the motor determine the relationship between phase current, rotor position, and generated torque and are consequently reflected in the phase-torque response during commutation[34].

C. DITC-Based Drive Structure

The investigated SRM is operated using a direct instantaneous torque control (DITC)-based structure. In this control approach, the electromagnetic torque demand is generated by the outer speed-control loop and subsequently distributed among the individual phases according to the instantaneous rotor position.

For the four-phase SRM, the total electromagnetic torque can be written as

$$T_e = T_1 + T_2 + T_3 + T_4, \quad (6)$$

where T_j denotes the electromagnetic torque produced by phase j .

The torque-sharing function (TSF) determines the contribution assigned to each active phase. The reference torque of phase j is expressed as

$$T_j^* = F_j(\theta) T_e^*, \quad (7)$$

where T_e^* is the demanded electromagnetic torque and $F_j(\theta)$ is the normalized torque-sharing coefficient associated with phase j .

Ideally, the phase torque-sharing coefficients satisfy

$$\sum_{j=1}^4 F_j(\theta) = 1 \quad (8)$$

during the torque-production interval. This condition allows the total torque demand to be distributed among the active phases while the torque contribution is transferred from the outgoing phase to the incoming phase during commutation.

The generated phase torque references are subsequently converted into corresponding phase-current references using the torque-current-position characteristics of the SRM. The DITC switching system then regulates the phase currents according to the instantaneous torque and rotor-position conditions.

The overall control sequence can therefore be represented as

$$\omega^* \rightarrow \text{Speed Controller} \rightarrow T_e^* \xrightarrow{e} \text{TSF} \rightarrow T_j^* \xrightarrow{j} i_j^* \rightarrow \text{DITC Converter} \rightarrow \text{SRM}. \quad (9)$$

In the proposed configuration, the conventional speed controller in this structure is subsequently replaced by the error- and error-rate-dependent smooth adaptive PI (EDSA-PI) controller described in Section III. The torque-sharing stage is implemented using the proposed hybrid smooth TSF, whose formulation and transition characteristics are also presented in Section III.

III. Proposed Adaptive Control Strategy

The proposed control strategy combines an error- and error-rate-dependent smooth adaptive proportional-integral controller (EDSA-PI) with a hybrid smooth torque sharing function (TSF) within the DITC-based four-phase 8/6 SRM drive. The objective is to improve the electromagnetic torque quality by addressing the control action at the speed-control level and the torque-reference distribution during phase commutation.

The proposed control structure consists of two main components. First, the EDSA-PI controller generates the required electromagnetic torque demand from the speed error and dynamically modifies its control gains according to the instantaneous error conditions. Second, the hybrid smooth TSF distributes the demanded torque among the active phases using smooth rising and falling transition profiles. The parameters of the EDSA-PI controller are optimized offline using the HHO algorithm, as described in Section IV, whereas the parameters of the hybrid smooth TSF are kept fixed during the optimization and validation stages.

A. Overall Control Structure

The overall control structure is illustrated in Fig. 1. The reference speed ω^* is compared with the measured motor speed ω to obtain the speed error. This error is processed by the EDSA-PI controller to generate the demanded electromagnetic torque T_e^* . The demanded torque is then distributed among the four SRM phases by the hybrid smooth TSF according to the instantaneous rotor position.

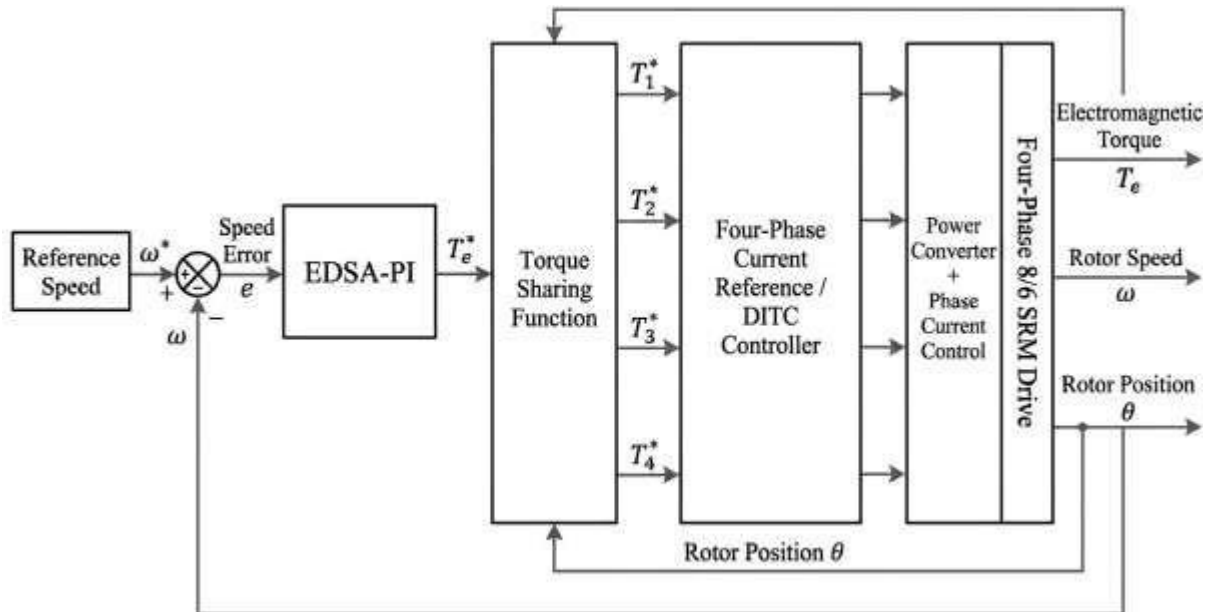


Fig. 1. Overall control structure of the proposed HHO-optimized EDSA-PI and proposed TSF based SRM drive.

For phase j , the corresponding torque reference is defined as

$$T_j^* = F_j(\theta) T_e^*, \quad j = 1, 2, 3, 4, \quad (10)$$

where $F_j(\theta)$ is the torque-sharing coefficient of phase j and θ is the rotor position.

The resulting phase torque references are converted into corresponding current references using the torque-current-position characteristics of the SRM. These current references are subsequently tracked by the DITC-based converter through the appropriate switching signals.

The complete control sequence can therefore be expressed as

$$\omega^* \rightarrow \text{EDSA-PI} \rightarrow T_e^* \rightarrow \text{Hybrid TSF} \rightarrow T_j^* \rightarrow i_j^* \rightarrow \text{DITC} \rightarrow \text{SRM}. \quad (11)$$

The use of the same hybrid smooth TSF with both the reference PI controller and the proposed EDSA-PI controller is maintained throughout the comparative simulations. Consequently, the effect of the proposed adaptive speed controller can be evaluated without simultaneously changing the torque-sharing function.

B. Error- and Error-Rate-Dependent Smooth Adaptive PI Controller

The conventional PI controller uses fixed proportional and integral gains. Such fixed gains may provide satisfactory performance around a particular operating point but may not provide the same control action when the magnitude or dynamics of the speed error change. To introduce a variable control response, the proposed EDSA-PI controller modifies its gains according to the instantaneous speed error and its rate of change.

The speed error is defined as

$$e(k) = \omega^*(k) - \omega(k), \quad (12)$$

where ω^* is the reference speed and ω is the measured motor speed.

The discrete error rate is calculated as

$$\dot{e}(k) = \frac{e(k) - e(k-1)}{T_s}, \quad (13)$$

where T_s denotes the controller sampling period.

To provide smooth gain adaptation, an error-dependent activation function is defined as

$$A_e = 1 - \exp \left[- \left(\frac{|e|}{E_s} \right)^2 \right], \quad (14)$$

where E_s is the error-scaling parameter.

Similarly, the error-rate-dependent activation function is expressed as

$$A_{\dot{e}} = 1 - \exp \left[- \left(\frac{|\dot{e}|}{E_{ds}} \right)^2 \right], \quad (15)$$

where E_{ds} is the error-rate scaling parameter.

Using these activation functions, the proportional gain is dynamically adjusted according to

$$K_p = K_{p0} + K_a A_e + K_d A_{\dot{e}}, \quad (16)$$

where K_{p0} is the nominal proportional gain, K_a determines the contribution of the speed-error magnitude, and K_d determines the contribution associated with the error rate.

Equation (16) allows the proportional action to increase smoothly when the speed error becomes significant or when the error changes rapidly. In contrast to a fixed-gain PI controller, the proportional response therefore varies according to the instantaneous dynamic state of the drive.

The integral adaptation is introduced through the following error-dependent function:

$$A_i = \exp \left[- \left(\frac{|e|}{E_i} \right)^2 \right], \quad (17)$$

where E_i is the integral adaptation scaling parameter.

The adaptive integral gain is then defined as

$$K_i = K_{i0} (1 + \Gamma A_i), \quad (18)$$

where K_{i0} is the nominal integral gain and Γ determines the magnitude of the integral adaptation.

The controller output before saturation is given by

$$u_{\text{unsat}} = K_p e + I, \quad (19)$$

where I denotes the integral state.

Because the controller output is subject to physical limits, the final control signal is constrained according to

$$u = \begin{cases} U_{\text{max}}, & u_{\text{unsat}} > U_{\text{max}}, \\ u_{\text{unsat}}, & U_{\text{min}} \leq u_{\text{unsat}} \leq U_{\text{max}}, \\ U_{\text{min}}, & u_{\text{unsat}} < U_{\text{min}}. \end{cases} \quad (20)$$

An anti-windup correction is incorporated into the integral state to reduce excessive accumulation when the controller output reaches its limits. The discrete integral update is expressed as

$$I(k+1) = I(k) + T_s [K_i e + K_{aw} (u - u_{\text{unsat}})], \quad (21)$$

where K_{aw} is the anti-windup gain.

The implemented EDSA-PI controller therefore contains three adaptation mechanisms: error-dependent proportional adaptation, error-rate-dependent proportional adaptation, and error-dependent integral adaptation. The proportional gain depends on both $|e|$ and $|\dot{e}|$, whereas the integral gain depends on $|e|$.

C. Hybrid Smooth Torque Sharing Function

The torque-sharing function determines the desired torque contribution of each active phase during the commutation process. The conventional TSF generally employs linear rising and falling transitions between consecutive phase torque contributions. Although this structure is simple, abrupt changes in the slope of the torque reference can contribute to undesirable torque variations when combined with the nonlinear magnetic characteristics and finite current dynamics of the SRM.

To obtain smoother transition profiles while preserving the basic TSF structure, a hybrid smooth TSF is employed. The proposed function retains the conventional rising-constant-falling sequence and combines a linear transition with a fifth-order minimum-jerk polynomial.

Let θ_1 , θ_2 , θ_3 , and θ_4 denote the angular boundaries of the torque-sharing regions. For the rising transition, a normalized position variable is defined as

$$x = \frac{\theta - \theta_1}{\theta_2 - \theta_1}, \quad \theta_1 \leq \theta < \theta_2. \quad (22)$$

The minimum-jerk polynomial is defined as

$$S(x) = 10x^3 - 15x^4 + 6x^5. \quad (23)$$

This function satisfies

$$S(0) = 0, \quad S(1) = 1, \quad (24)$$

and

$$S'(0) = 0, \quad S'(1) = 0. \quad (25)$$

The hybrid rising transition is obtained by combining the linear and polynomial profiles:

$$F_{rise}(x) = (1 - \lambda)x + \lambda S(x), \quad (26)$$

where λ is the fixed blending coefficient.

For the constant torque-sharing region,

$$F_{const} = 1, \quad \theta_2 \leq \theta < \theta_3. \quad (27)$$

For the falling transition, the normalized variable is defined as

$$x = \frac{\theta - \theta_3}{\theta_4 - \theta_3}, \quad \theta_3 \leq \theta \leq \theta_4. \quad (28)$$

The corresponding hybrid falling profile is

$$F_{fall}(x) = (1 - \lambda)(1 - x) + \lambda[1 - S(x)]. \quad (29)$$

The complete torque-sharing function can therefore be written as

$$F(\theta) = \begin{cases} 0, & \theta < \theta_1, \\ (1 - \lambda)x + \lambda S(x), & \theta_1 \leq \theta < \theta_2, \\ 1, & \theta_2 \leq \theta < \theta_3, \\ (1 - \lambda)(1 - x) + \lambda[1 - S(x)], & \theta_3 \leq \theta \leq \theta_4, \\ 0, & \theta > \theta_4. \end{cases} \quad (30)$$

The complementary form of the rising and falling functions preserves the required transfer between consecutive phase torque contributions. In particular, when the outgoing and incoming phases are represented by complementary transition functions, their ideal normalized torque-sharing contributions satisfy

$$F_{out}(\theta) + F_{in}(\theta) = 1. \quad (31)$$

This property allows the demanded electromagnetic torque to be transferred progressively from one phase to the next rather than being abruptly reassigned.

The proposed TSF is designed to modify the transition shape rather than replace the complete conventional torque-sharing structure. The linear component preserves the basic behavior of the conventional TSF, while the minimum-jerk component introduces a smoother transition profile. The blending coefficient λ determines the relative contribution of the two components.

In the present study, λ is maintained at its selected fixed value and is not included in the HHO optimization vector. Thus, the TSF remains unchanged between the reference PI-Hybrid Smooth TSF configuration and the proposed EDSA-PI-Hybrid Smooth TSF configuration.

D. Integration of the EDSA-PI and Hybrid Smooth TSF

The EDSA-PI controller and hybrid smooth TSF operate at different levels of the SRM control structure. The EDSA-PI controller determines the total electromagnetic torque demand based on the speed-control error, whereas the hybrid smooth TSF distributes this demand among the active phases according to rotor position. The interaction between the two stages can be expressed as

$$T_e^* = f_{EDSA-PI}(\omega^* - \omega), \quad (32)$$

followed by

$$T_j^* = F_j(\theta) T_e^*. \quad (33)$$

The resulting phase torque references are then used to determine the corresponding current references for the DITC stage.

The proposed strategy therefore does not require an online optimization process. HHO is used only during the offline parameter-tuning stage. During real-time operation, the controller executes the EDSA-PI gain adaptation and the hybrid smooth TSF using the measured speed, speed error, error rate, and rotor-position information.

For the comparative simulations, two configurations are considered:

- 1) PI-Hybrid Smooth TSF: conventional fixed-gain PI controller combined with the hybrid smooth TSF.
- 2) EDSA-PI-Hybrid Smooth TSF: HHO-optimized EDSA-PI controller combined with the same hybrid smooth TSF.

Maintaining the same TSF in both configurations provides a consistent basis for evaluating the effect of the proposed adaptive PI controller on the electromagnetic torque response. The HHO optimization procedure used to determine the EDSA-PI parameters is described in the following section.

IV. Harris Hawks Optimization of the Proposed Controller

The Harris Hawks Optimization (HHO) algorithm is employed to optimize the parameters of the proposed SRM control strategy. The optimization considers both the error- and error-rate-dependent smooth adaptive PI (EDSA-PI) controller and the hybrid smooth torque sharing function (TSF). Therefore, the HHO search simultaneously determines the parameters governing the speed-control action and the angular characteristics of the torque-sharing process.

The optimization is performed offline using the MATLAB/Simulink model of the four-phase 8/6 SRM drive. For each candidate solution, the corresponding controller and TSF parameters are introduced into the simulation model and the resulting speed and electromagnetic torque responses are evaluated using the predefined objective function. After completion of the optimization, the best parameter vector is retained and used in the subsequent validation simulations.

Unlike online optimization approaches, HHO is not executed during the real-time operation of the SRM drive. Its role is restricted to the offline determination of suitable controller and TSF parameters. The resulting parameters are then fixed during the real-time simulation, while the adaptive equations of the EDSA-PI controller remain active.

A. Harris Hawks Optimization Algorithm

Harris Hawks Optimization is a population-based metaheuristic inspired by the cooperative hunting behavior of Harris' hawks. In the optimization process, each hawk represents a candidate solution, whereas the best solution found during the search represents the prey, commonly referred to as the rabbit.

The HHO algorithm alternates between exploration and exploitation according to the escaping energy of the prey. The escaping energy is expressed as

$$E = 2E_1E_0, \quad (34)$$

where

$$E_1 = 2 \left(1 - \frac{t}{T_{max}}\right) \quad (35)$$

and

$$E_0 = 2r - 1, \quad r \in [0,1]. \quad (36)$$

Here, t denotes the current iteration and T_{max} is the maximum number of iterations. The parameter E determines the transition between the exploration and exploitation phases.

When

$$|E| \geq 1, \quad (37)$$

the hawks perform exploration by searching different regions of the solution space. Depending on a random probability, a candidate solution can be generated with respect to a randomly selected hawk or the mean position of the population.

When

$$|E| < 1, \quad (38)$$

the algorithm enters the exploitation stage. The hawks progressively move toward the current best solution. Depending on the escaping energy and a random probability, different besiege strategies are employed, including soft besiege, hard besiege, and rapid-diving mechanisms.

For the rapid-diving mechanism, Levy-flight perturbations are introduced to generate alternative candidate solutions around the current search position. The candidate solutions are evaluated using the SRM simulation, and the solution providing the lower fitness value is retained.

The HHO procedure used in this work can therefore be summarized by the following steps:

- 1) Initialize a population of candidate controller and TSF parameter vectors within the prescribed lower and upper bounds.
- 2) Evaluate the fitness of each candidate using the MATLAB/Simulink SRM model.
- 3) Identify the candidate with the minimum fitness as the current best solution.
- 4) Calculate the escaping energy of the prey.
- 5) Perform exploration or exploitation according to the magnitude of the escaping energy.
- 6) Generate new candidate solutions using the corresponding HHO position-update mechanism.
- 7) Apply the prescribed parameter bounds to the updated solutions.
- 8) Evaluate the new candidates using the SRM simulation.
- 9) Apply greedy selection to retain improved solutions.
- 10) Update the global best solution and its fitness value.
- 11) Repeat the procedure until the maximum number of iterations is reached.

The complete implementation used to optimize the proposed SRM controller is presented in Algorithm 1.

B. Optimization Variables

The HHO decision vector contains twelve variables. The first six variables correspond to the EDSA-PI controller, while the remaining six variables define the angular parameters used by the hybrid smooth TSF. The complete optimization vector is given by

$$X = [K_{p0}, K_{i0}, K_a, E_s, K_d, E_{ds}, T_{on}, T_{off}, a, b, c, d]. \quad (39)$$

The EDSA-PI parameters are defined as follows:

- K_{p0} is the nominal proportional gain;
- K_{i0} is the nominal integral gain;
- K_a determines the contribution of the speed-error magnitude to the proportional gain;
- E_s is the scaling parameter associated with the speed error;
- K_d determines the contribution of the error rate to the proportional gain;
- E_{ds} is the scaling parameter associated with the error rate.

The remaining six variables determine the angular characteristics of the hybrid smooth TSF:

- T_{on} defines the phase turn-on angular condition;
- T_{off} defines the phase turn-off angular condition;
- a, b, c , and d define the corresponding angular transition characteristics used by the TSF.

The exact mapping between these parameters and the transition angles θ_1 – θ_4 follows the implementation of the proposed TSF described in Section III.

The parameters Γ , E_i , and K_{aw} of the EDSA-PI controller are maintained at fixed values during the optimization:

$$\Gamma = 0.5, \quad E_i = 150, \quad K_{aw} = 20. \quad (40)$$

Similarly, the blending coefficient λ of the hybrid smooth TSF is kept fixed at its selected value. Consequently, HHO optimizes the parameters that determine the adaptive PI behavior and the angular characteristics of the TSF, while the remaining adaptation and blending parameters are kept constant.

The lower bounds of the twelve decision variables are defined as

$$X_{min} = [0.05, 1.0, 0.05, 50, 0.001, 1000, 6.0, 21.0, -2.0, 3.5, 3.0, 18.0], \quad (41)$$

while the corresponding upper bounds are

$$X_{max} = [0.50, 15.0, 2.00, 800, 0.20, 15000, 10.0, 25.0, 1.0, 8.0, 6.0, 22.0]. \quad (42)$$

Thus, each candidate solution is constrained according to

$$X_{min} \leq X \leq X_{max}. \quad (43)$$

C. Objective Function

The objective function is formulated to evaluate both the speed-regulation behavior and the electromagnetic torque quality of the SRM drive. For each candidate solution, the twelve parameters are transferred to the MATLAB/Simulink model, and the resulting drive response is used to calculate the fitness value.

The speed-related component is based on the time-weighted absolute speed error:

$$J_{speed} = \int_0^{t_f} t |e(t)| dt, \quad (44)$$

where

$$e(t) = \omega^*(t) - \omega(t). \quad (45)$$

Here, ω^* and ω represent the reference and measured mechanical speeds, respectively.

To evaluate the torque response, the steady-state portion of the simulation is considered. The torque-tracking error is calculated as

$$J_{TL} = \frac{1}{N} \sum_{n=1}^N |T_e(n) - T_L(n)|, \quad (46)$$

where N is the number of samples in the selected steady-state interval.

A torque-ripple index is also introduced as

$$J_{TR} = \frac{T_{e,max} - T_{e,min}}{2 |T_{L,mean}|}, \quad (47)$$

where $T_{e,max}$ and $T_{e,min}$ denote the maximum and minimum electromagnetic torque values within the selected steady-state interval, respectively, and $T_{L,mean}$ is the mean absolute load torque.

The torque-related objective is then defined as

$$J_{torque} = 0.60 J_{TL} + 0.40 J_{TR}. \quad (48)$$

The complete fitness function is expressed as

$$J = 0.40 J_{speed} + 0.60 J_{torque}. \quad (49)$$

The resulting optimization problem can be formulated as

$$X^* = \underset{X_{min} \leq X \leq X_{max}}{\operatorname{argmin}} J(X). \quad (50)$$

The objective function gives greater importance to the torque-related performance while retaining speed-regulation behavior in the optimization. This weighting is selected because torque-ripple reduction represents the main objective of the proposed SRM control strategy.

D. HHO-Based Optimization Procedure

The complete HHO-based optimization procedure is summarized in Algorithm 1. Initially, a population of candidate solutions is generated randomly within the specified parameter bounds. Each candidate contains the six EDSA-PI parameters and six TSF parameters defined in (39).

For each candidate solution, the corresponding parameters are assigned to the MATLAB/Simulink SRM model. The drive is then simulated under the specified optimization operating condition. The resulting speed, electromagnetic torque, and load torque signals are processed to calculate the fitness value according to (49). The candidate providing the minimum fitness is selected as the initial best solution. During each HHO iteration, the escaping energy is updated and the corresponding exploration or exploitation strategy is applied. The generated solutions simultaneously modify the EDSA-PI and TSF parameters.

For rapid-diving operations, two candidate solutions can be generated using the standard HHO and Levy-flight mechanisms. Their fitness values are evaluated through the SRM simulation, and the candidate with the lower fitness is retained.

After generation of the updated population, all candidate parameters are restricted to the predefined search limits according to

$$X_{ij} = \min[\max(X_{ij}, X_{j,min}), X_{j,max}]. \quad (51)$$

The updated population is then evaluated, and greedy selection is applied by comparing the new fitness values with those of the previous population. The global best solution is updated whenever a lower fitness value is obtained.

The optimization terminates when the specified maximum number of iterations is reached. The resulting vector

$$X^* = [K_{p0}^*, K_{i0}^*, K_a^*, E_s^*, K_d^*, E_{ds}^*, T_{on}^*, T_{off}^*, a^*, b^*, c^*, d^*] \quad (52)$$

is retained as the final optimized parameter set.

Algorithm 1 HHO-Based Optimization of the Proposed SRM Controller

Require: Population size N , maximum number of iterations T_{max} , lower bound X_{min} , upper bound X_{max} , SRM simulation model

Ensure: Optimal parameter vector X^*

```

1: Define the twelve-dimensional decision vector  $X = [K_{p0}, K_{i0}, K_a, E_s, K_d, E_{ds}, T_{on}, T_{off}, a, b, c, d]$ 
2: Initialize the hawk population randomly within  $X_{min}$  and  $X_{max}$ 
3: Evaluate the fitness of each hawk using the SRM simulation
4: Identify the best solution:  $X^* = \operatorname{argmin}_X J(X_i)$ 
5: for  $t = 1$  to  $T_{max}$  do
6:   Calculate the prey escaping energy  $E$ 
7:   for  $i = 1$  to  $N$  do
8:     if  $|E| \geq 1$  then
9:       Update  $X_i$  using the HHO exploration strategy
10:    else
11:      Generate random probability  $q$ 
12:      if  $q \geq 0.5$  then
13:        Perform soft or hard besiege according to  $|E|$ 
14:      else
15:        Generate a rapid-diving candidate solution
16:        Generate a Levy-flight candidate solution
17:        Evaluate both candidate solutions
18:        Retain the candidate with the lower fitness
19:      end if
20:    end if
21:    Apply the lower and upper parameter bounds
22:  end for
23:  Evaluate the updated population using the SRM simulation
24:  Apply greedy selection between the old and new populations
25:  Update the global best solution  $X^*$ 
26:  Store the best fitness value for the convergence curve
27: end for
28: return  $X^*$ 

```

E. Optimization Configuration

The HHO optimization is performed using the MATLAB/Simulink model of the four-phase 8/6 SRM drive. The optimization operating condition is set to 500 rpm and 5 N·m load torque. This operating point is used for the fitness evaluation of the candidate solutions.

The main optimization parameters are summarized in Table I.

Because every candidate solution requires a complete SRM simulation, the population evaluations are performed in parallel using MATLAB parallel simulation facilities. The Simulink model is executed in accelerator mode to reduce the computational time associated with repeated simulations, while fast restart is used where applicable to reduce repeated model initialization.

The optimization is performed offline, and therefore the HHO search is not part of the real-time control loop. After the optimal parameter vector has been obtained, the resulting EDSA-PI and hybrid smooth TSF parameters are transferred to the SRM drive. During the subsequent simulations, these optimized parameters remain fixed, while the EDSA-PI controller continues to calculate its instantaneous adaptive gains according to the equations presented in Section III.

Table I. HHO Optimization Configuration.

Parameter	Value
Optimization algorithm	HHO
Population size	20
Number of decision variables	12
Optimization speed	500 rpm
Optimization load torque	5 N·m
Simulation duration	1 s
Γ	0.5
E_i	150

Parameter	Value
K_{aw}	20
λ	0.20

The convergence history of the HHO optimization and the resulting optimal parameter values are presented in Section V. The optimized parameters are then used for the evaluation of the proposed control strategy at the selected operating conditions.

V. Simulation Results and Discussion

The proposed control strategy was evaluated through MATLAB/Simulink simulations of the four-phase 8/6 switched reluctance motor (SRM) drive. The evaluation focuses on the electromagnetic torque behavior and torque ripple reduction obtained by combining the hybrid smooth torque sharing function (TSF) with the proposed error- and error-rate-dependent adaptive PI (EDSA-PI) controller.

To isolate the contribution of the proposed speed controller, the same hybrid smooth TSF was used in both configurations. The first configuration consists of a conventional PI controller combined with the hybrid smooth TSF, denoted as PI-Hybrid Smooth TSF. The second configuration employs the HHO-optimized EDSA-PI controller with the same hybrid smooth TSF and is denoted as EDSA-PI-Hybrid Smooth TSF. Therefore, the comparison does not involve a change in the TSF between the two configurations.

Two operating conditions were considered for the evaluation: 500 rpm with a load torque of 5 N·m and 1000 rpm with a load torque of 7 N·m. The torque ripple was calculated over the steady-state interval from 0.8 to 1.0 s using the peak-to-peak torque ripple definition

$$TR(\%) = \frac{T_{e,max} - T_{e,min}}{T_{e,avg}} \times 100, \quad (53)$$

where $T_{e,max}$, $T_{e,min}$, and $T_{e,avg}$ represent the maximum, minimum, and average electromagnetic torque over the selected steady-state interval, respectively.

The SRM drive was simulated using the developed MATLAB/Simulink model. The same motor, converter, current-control structure, sampling conditions, and hybrid smooth TSF were maintained for both control configurations. The conventional PI controller was used as the reference configuration, whereas the proposed configuration employed the EDSA-PI controller whose parameters were optimized offline using the Harris Hawks Optimization (HHO) algorithm.

The EDSA-PI controller contains six optimized parameters, namely K_{p0} , K_{i0} , K_a , E_s , K_d , and E_{ds} . The parameters Γ , E_i , and K_{aw} were maintained at their predefined values, while the hybrid smooth TSF blending factor was also kept fixed. Consequently, the HHO optimization was restricted to the six EDSA-PI parameters used by the implemented controller.

Before evaluating the dynamic performance of the proposed controller, the optimization process and the resulting torque-sharing function are examined. Fig. 2 presents the convergence characteristics of the HHO algorithm used to determine the EDSA-PI controller parameters.

The convergence curve illustrates the evolution of the best objective-function value during the optimization process. The optimization searches for controller parameters that provide an appropriate compromise between speed regulation and torque performance. The final parameter set obtained from HHO is then used in the proposed EDSA-PI controller for the subsequent simulations.

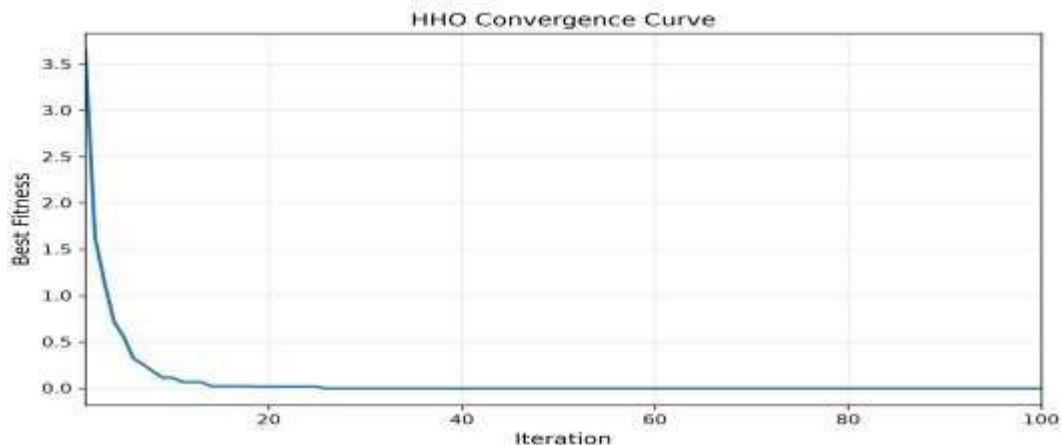


Fig. 2. Convergence characteristics of the HHO optimization process.

A. Performance at 500 rpm and 5 N·m

The corresponding electromagnetic torque responses are shown in Fig. 3.

The conventional PI-TSF configuration exhibits considerable oscillations in the electromagnetic torque around the required 5 N·m operating level. These oscillations become particularly visible in the magnified steady-state region. The repeated peaks and valleys are associated with the sequential excitation and commutation of the SRM phases.

In contrast, the proposed controller produces a considerably smoother electromagnetic torque waveform. The torque remains closer to the required load level, while the amplitude of the steady-state oscillations is reduced. This improvement results from the combined effect of the adaptive speed controller and the modified phase torque-sharing trajectory.

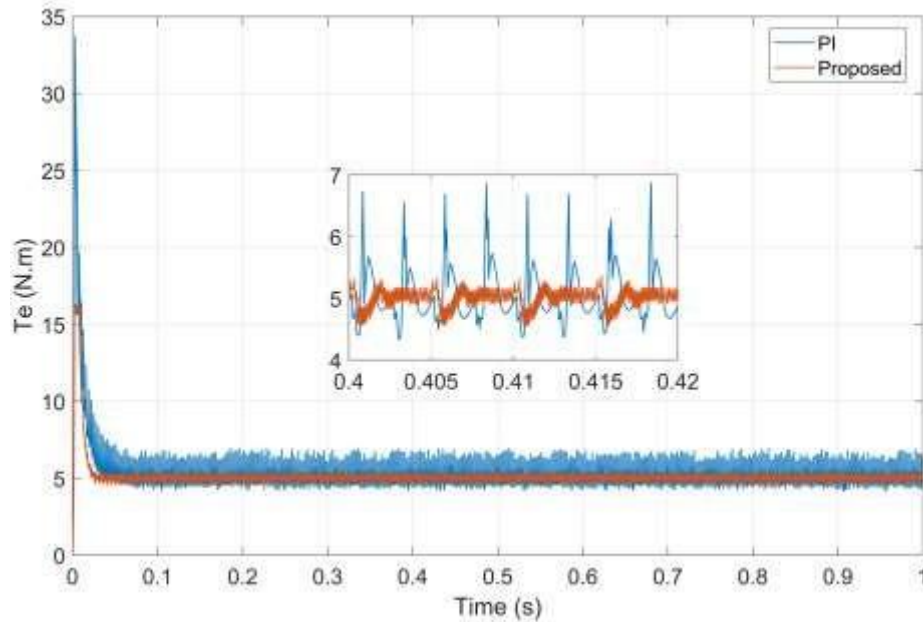


Fig. 3. Electromagnetic torque response at 500 rpm and 5 N·m: comparison between the conventional PI-TSF and the proposed HHO-EDSA-PI-hybrid-TSF.

The corresponding four-phase torque contributions without optimization are shown in Fig. 4.

The phase torque waveforms demonstrate the individual contribution of phases A–D to the total electromagnetic torque. Noticeable oscillations can be observed in the active torque intervals, particularly around the plateau regions. Since the total electromagnetic torque is the sum of the individual phase contributions, these phase-level oscillations directly influence the overall torque ripple.

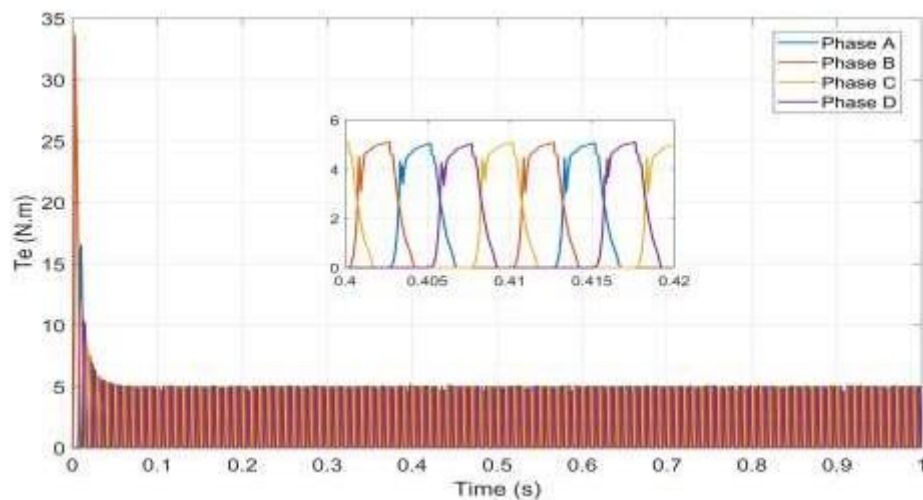


Fig. 4. Four-phase torque contributions at 500 rpm and 5 N·m using the conventional PI-TSF configuration.

For comparison, the optimized/proposed phase torque contributions are shown in Fig. 5.

The proposed phase torque waveforms exhibit smoother transitions between successive phases. The incoming phase progressively increases its torque contribution while the outgoing phase decreases its contribution. This produces a smoother overlap between consecutive phase torques and reduces the discontinuity in the resultant electromagnetic torque.

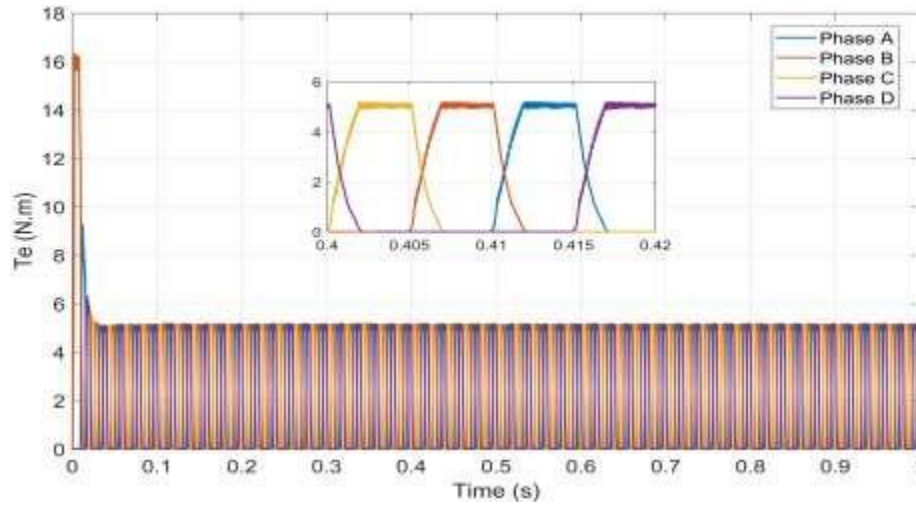


Fig. 5. Four-phase torque contributions at 500 rpm and 5 N·m using the proposed HHO-EDSA-PI-hybrid-TSF configuration.

The calculated torque-ripple factor for the conventional PI-TSF controller is 56.92%. After applying the proposed HHO-EDSA-PI and hybrid smooth TSF, the torque-ripple factor decreases to 20.12%. The relative reduction is therefore

$$R_{500} = \frac{56.92 - 20.12}{56.92} \times 100 = 64.65\%. \quad (54)$$

Thus, the proposed strategy reduces the torque-ripple factor by 64.65% at 500 rpm and 5 N·m.

B. Performance at 1000 rpm and 7 N·m

The corresponding electromagnetic torque responses are presented in Fig. 6.

The conventional controller produces pronounced torque oscillations around the required 7 N·m load torque. The magnified steady-state region clearly illustrates the periodic torque fluctuations caused by the commutation process. The proposed configuration considerably reduces these oscillations. The electromagnetic torque remains closer to the required load torque and exhibits a smoother steady-state waveform. The improvement becomes particularly important at this operating point because the motor operates at both a higher rotational speed and a higher torque demand.

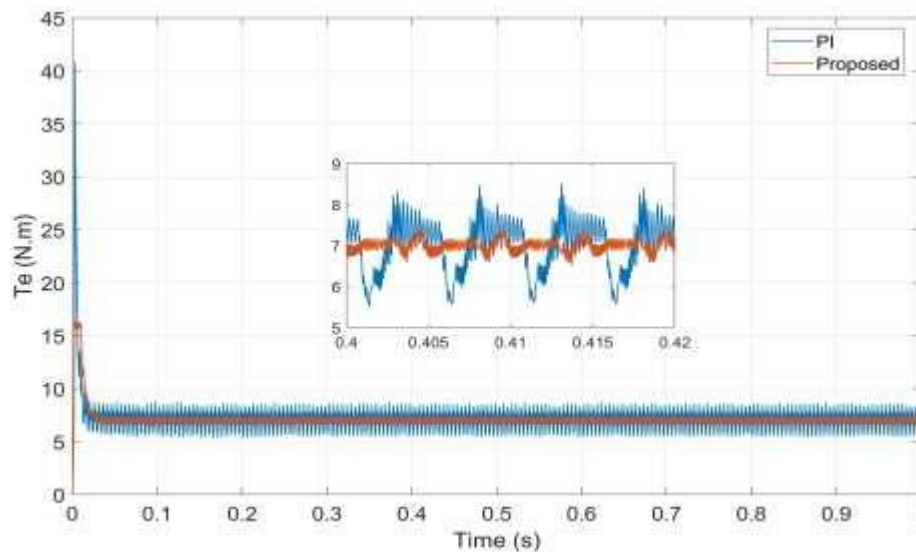


Fig. 6. Electromagnetic torque response at 1000 rpm and 7 N·m: comparison between the conventional PI-TSF and the proposed HHO-EDSA-PI-hybrid-TSF.

The four-phase torque contributions obtained without optimization are presented in Fig. 7.

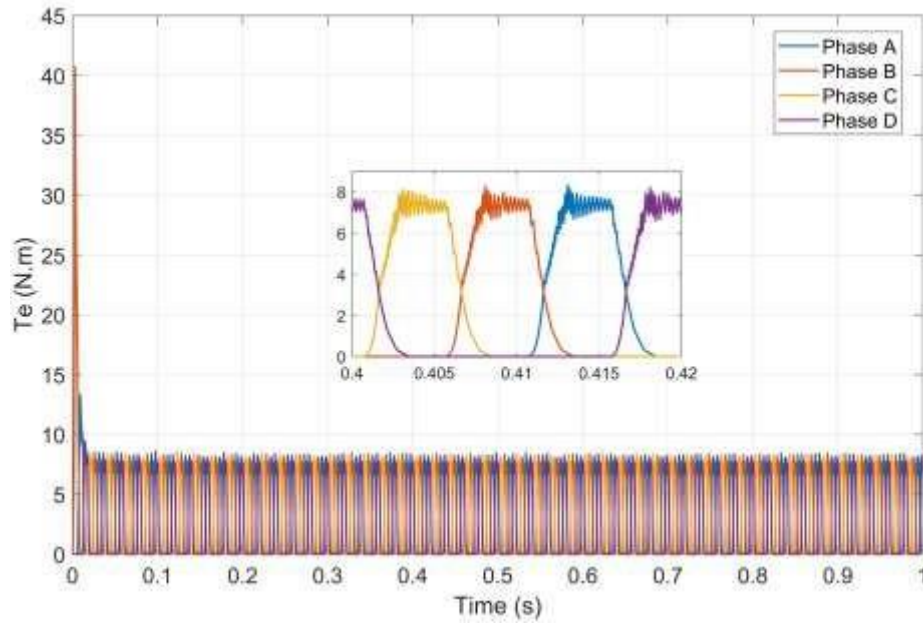


Fig. 7. Four-phase torque contributions at 1000 rpm and 7 N·m using the conventional PI-TSF configuration.

The phase torque waveforms demonstrate the sequential torque production of phases A–D. Significant oscillations are visible in the active regions, which contribute to the ripple observed in the total electromagnetic torque.

The corresponding optimized/proposed phase torque waveforms are shown in Fig. 8.

The proposed phase torque waveforms exhibit a more controlled torque-sharing process. The smoother transition between the outgoing and incoming phases reduces the abrupt variation in the combined torque contribution. This behavior explains the improvement observed in the total electromagnetic torque waveform.

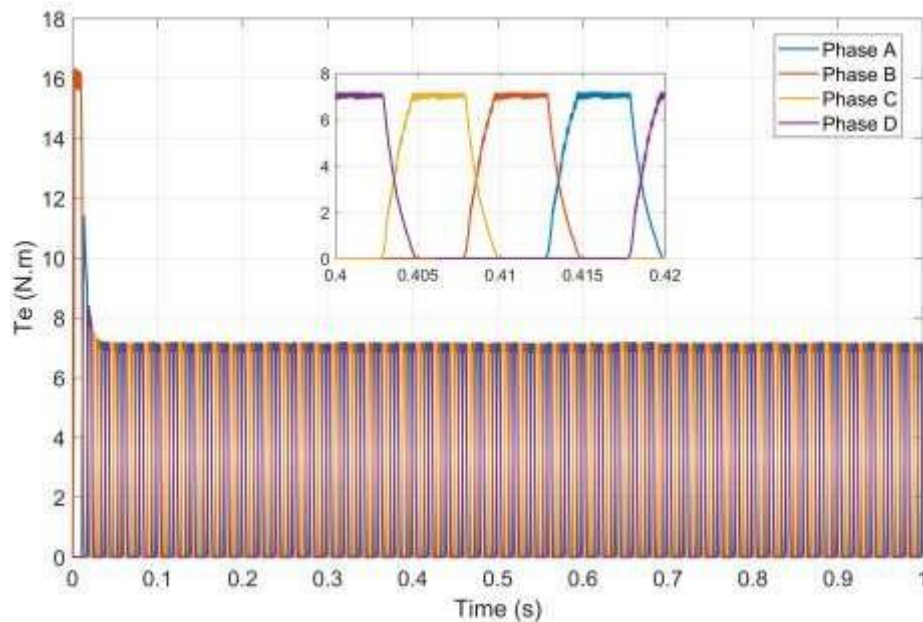


Fig. 8. Four-phase torque contributions at 1000 rpm and 7 N·m using the proposed HHO-EDSA-PI-hybrid-TSF configuration.

For this operating condition, the conventional PI-TSF configuration produces a torque-ripple factor of 47.15%, whereas the proposed configuration reduces this value to 12.80%. The corresponding reduction is

$$R_{1000} = \frac{47.15 - 12.80}{47.15} \times 100 = 72.89\%. \quad (55)$$

Therefore, the proposed strategy achieves a 72.89% reduction in the torque-ripple factor at 1000 rpm and 7 N·m.

C. Quantitative Comparison

Table II summarizes the torque-ripple performance of the two control configurations at the two investigated operating points.

Table II. Torque-Ripple Comparison Between the Conventional and Proposed Control Strategies.

Operating condition	PI-TSF (%)	Proposed (%)	Reduction (%)
500 rpm, 5 N·m	56.92	20.12	64.65
1000 rpm, 7 N·m	47.15	12.80	72.89

The results clearly demonstrate the effectiveness of the proposed approach at both operating points. At 500 rpm and 5 N·m, the torque-ripple factor is reduced from 56.92% to 20.12%, corresponding to a 64.65% reduction. At 1000 rpm and 7 N·m, the ripple decreases from 47.15% to 12.80%, corresponding to a 72.89% reduction.

The larger relative improvement obtained at 1000 rpm and 7 N·m indicates that the proposed strategy remains effective under the higher-speed and higher-load operating condition. The results also demonstrate that the improvement is not restricted to a single operating point.

D. Discussion of the Torque-Ripple Reduction

The obtained results can be attributed to the complementary roles of the adaptive PI controller and the proposed TSF. The EDSA-PI controller modifies the proportional and integral gains according to the speed error and its rate of change. This provides a more flexible speed-control action than the fixed gains of the conventional PI controller.

At the same time, the proposed hybrid smooth TSF modifies the desired phase torque trajectories during the rising and falling intervals. Rather than changing the complete DITC structure, the proposed function retains the fundamental torque-sharing sequence while introducing a smooth component into the transition regions. The resulting phase torque trajectories provide a smoother transfer of torque between consecutive phases. Because the total electromagnetic torque is the sum of the four phase torque contributions, improving the phase-to-phase transition directly contributes to reducing the resultant torque ripple.

Therefore, the improvement observed in Figs. 3 and 6 is consistent with the phase-level behavior shown in Figs. 5 and 8. The proposed method does not rely exclusively on speed-controller optimization; instead, the controller and TSF improvements act together to improve the torque production process.

E. Comparison With State-of-the-Art Methods

Table III compares the proposed strategy with representative torque-ripple reduction methods reported in the literature. The comparison includes conventional and optimized TSF methods, hybrid TSF strategies, and predictive control approaches.

Early TSF-based studies demonstrated that the shape of the torque-sharing function has a significant influence on the torque ripple, phase current, and usable torque-speed range. In particular, optimized TSF families based on linear, sinusoidal, exponential, and cubic profiles have been investigated with multi-objective criteria involving torque ripple, copper loss, and torque-speed capability [31]. These studies established the importance of optimizing the torque-sharing profile rather than relying on a fixed conventional TSF.

Table III. Comparison of the Proposed Method with Representative State-of-the-Art SRM Torque-Ripple Reduction Methods.

Reference	SRM topology	Operating condition	Control strategy	Torque ripple	Main characteristic
Xue et al. [31]	SRM	Up to 3000 rpm	Optimized TSF	40.4% ^a	Optimization of TSF family considering torque-speed range and copper loss
Ren et al. [26]	3-phase 12/8	Simulation	GA-optimized TSF + MPC	NR ^b	Improved TSF combined with model predictive torque control
Al-Amyal and Szamel [18]	SRM	Low/medium and high speed	Hybrid TSF + overlap-angle control	NR ^b	Online adaptation of the incoming-phase torque reference and overlap angle

Reference	SRM topology	Operating condition	Control strategy	Torque ripple	Main characteristic
Kumar et al. [32]	SRM	Wide speed range	FPA-optimized TSF	NR ^b	Intelligent optimization of TSF and commutation angles
Cai et al. [21]	3-phase 12/8	500 rpm	Partitioned TSF	18.6%	Torque-generation-capability-based partitioning and online torque compensation
Pawar and Nikose [17]	4-phase 8/6	Simulation	SFO-optimized TSF + MPTC	19.5% ^c	Optimization-based predictive torque control with TSF
Li et al. [33]	8/6	400 rpm, 8 N·m	Cooperative MPC-DITC	9.5%	MPC combined with DITC for torque-ripple suppression and disturbance rejection
This work	4-phase 8/6	500 rpm, 5 N·m	HHO-EDSA-PI + hybrid smooth TSF	20.12%	Adaptive speed control combined with a smooth torque-sharing strategy
This work	4-phase 8/6	1000 rpm, 7 N·m	HHO-EDSA-PI + hybrid smooth TSF	12.80%	Improved torque sharing under higher-speed and higher-load operation

^aReported for the proposed TSF1 ($r = 4$) at the investigated high-speed condition.

^bNR: numerical torque-ripple value not reported in the accessible source.

^cReported as the obtained torque-ripple result for the proposed MPTC-SFO method.

More recent approaches have introduced optimization and predictive control into the TSF framework. Ren et al. proposed an improved TSF whose parameters were optimized using a genetic algorithm and combined the resulting TSF with model predictive control. The method was experimentally and numerically validated using a three-phase 12/8 SRM and demonstrated improved torque performance compared with conventional DITC [26]. Similarly, flower-pollination-based optimization has been applied to TSF parameters and commutation angles to improve torque-ripple performance over a wider range of operating conditions [32].

Hybrid TSF methods have also been proposed to address the inability of the actual phase torque to accurately track the predefined reference during commutation, particularly at higher speeds. Al-Amyal and Szamel proposed an adaptive hybrid TSF in which the incoming-phase torque reference is re-profiled according to the torque behavior of the outgoing phase. An additional overlap-angle controller was introduced to compensate for the remaining torque-tracking error [18]. These approaches demonstrate the importance of modifying the torque-sharing profile according to the actual phase torque-generation capability.

More recently, partitioned TSF control has been proposed to account explicitly for the torque-generation capability of individual phases during commutation. Cai et al. experimentally validated the method using a three-phase 12/8 SRM at 500 rpm and reported a reduction in torque ripple from 23% to 18.6% relative to the conventional approach [21]. This result demonstrates the benefit of adapting the torque-sharing process according to the actual electromagnetic characteristics of the machine.

Of particular relevance to the present work, Pawar and Nikose investigated an optimization-based model predictive torque control method for a four-phase 8/6 SRM. Their MPTC-SFO approach combines TSF optimization with model predictive torque control and reported a torque-ripple result of 19.5% [17]. This provides a useful reference because the same four-phase 8/6 topology is considered in the present study.

The proposed method follows a different design philosophy. Instead of replacing the complete DITC structure with a model predictive controller, the present strategy retains the DITC-based torque control architecture and combines two complementary modifications: an HHO-optimized EDSA-PI speed controller and a hybrid smooth TSF. The EDSA-PI controller adapts the control gains according to the speed error and error rate, while the proposed TSF smooths the torque-sharing transitions between the outgoing and incoming phases.

Under the 500 rpm and 5 N·m operating condition, the proposed method achieves a torque-ripple factor of 20.12%. At 1000 rpm and 7 N·m, the torque-ripple factor decreases further to 12.80%. These results are obtained with the same four-phase 8/6 SRM and demonstrate that the proposed strategy can provide substantial torque-ripple suppression without requiring the additional predictive-control layer used in several recent approaches.

The comparison should nevertheless be interpreted with caution because published torque-ripple values are obtained under different motor topologies, load torques, speeds, machine parameters, torque-ripple definitions, and control architectures. Therefore, Table III is intended to position the proposed method within the current research landscape rather than establish a strict numerical ranking.

An important observation is that some state-of-the-art predictive approaches can achieve lower reported torque-ripple values. For example, a recent cooperative MPC–DITC method using an 8/6 SRM reported 9.5% torque ripple at 400 rpm and 8 N·m [33]. However, this result is obtained with a predictive control structure and at a different operating point. Therefore, the contribution of the present work is not simply to obtain the lowest possible ripple value, but to achieve substantial ripple reduction through a comparatively simple combination of adaptive PI control and smooth TSF modification.

Overall, the results demonstrate that the proposed HHO-EDSA-PI-hybrid-TSF strategy provides an effective compromise between torque-ripple performance and controller complexity. The reduction from 56.92% to 20.12% at 500 rpm and 5 N·m, together with the reduction from 47.15% to 12.80% at 1000 rpm and 7 N·m, confirms the effectiveness of the proposed approach under both investigated operating conditions.

VI. Conclusion

This paper presented a torque-ripple reduction strategy for a four-phase 8/6 switched reluctance motor drive based on the combination of an HHO-optimized error- and error-rate-dependent adaptive PI controller and a hybrid smooth torque sharing function. The EDSA-PI controller dynamically adjusts its proportional gain according to the speed-error magnitude and its rate of change, while the integral gain is adapted according to the speed-error magnitude. The hybrid smooth TSF preserves the conventional rising–constant–falling torque-sharing structure and introduces a minimum-jerk component into the transition regions to obtain smoother phase-torque transfer during commutation. The HHO algorithm was employed offline to optimize six EDSA-PI parameters using closed-loop MATLAB/Simulink simulations. The optimized parameters were subsequently fixed during the validation simulations. To provide a consistent comparison, the same hybrid smooth TSF was used with both the reference PI controller and the proposed EDSA-PI controller.

The proposed strategy was evaluated under two operating conditions: 500 rpm with a load torque of 5 N·m and 1000 rpm with a load torque of 7 N·m. At 500 rpm and 5 N·m, the measured steady-state torque ripple decreased from 56.92% for the PI-Hybrid Smooth TSF configuration to 20.12% for the proposed EDSA-PI-Hybrid Smooth TSF configuration, corresponding to a reduction of 64.65%. At 1000 rpm and 7 N·m, the torque ripple decreased from 47.15% to 12.80%, corresponding to a reduction of 72.89%. The electromagnetic and phase-torque waveforms further show that the proposed configuration provides smoother torque behavior under the investigated conditions. Since the same hybrid smooth TSF is maintained in both configurations, the comparison demonstrates the effect of the proposed adaptive speed-control strategy in conjunction with the established torque-sharing mechanism.

The present study is limited to simulation-based validation at two constant operating points. Future work will focus on experimental implementation, evaluation over a wider speed and load range, and investigation of the controller under practical parameter variations and additional operating conditions.

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