

Article

Torque Ripple Reduction in DITC-Based Switched Reluctance Motors Using Integrated ADRC and Repetitive Control

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Abstract

This study proposes a linear active disturbance rejection control and load-adaptive multi-harmonic repetitive control (LADRC–LAMHRC)-based direct instantaneous torque control strategy to improve the dynamic performance of a three-phase 6/4 switched reluctance motor. Although conventional proportional–integral-based direct instantaneous torque control (PI-DITC) provides satisfactory speed tracking, its performance is limited by pronounced torque ripple and reduced robustness under sudden load variations. In the proposed scheme, the LADRC estimates and compensates for lumped disturbances and model uncertainties, whereas the LAMHRC attenuates the periodic speed-error components associated with the torque ripple and generates an auxiliary torque-compensation command. The effectiveness of the proposed method was evaluated through comparative MATLAB/Simulink simulations with the conventional PI-DITC scheme. At reference speeds of 500 and 1000 r/min, the proposed controller reduced the torque-ripple coefficient from 11.11% to 2.96% and from 11.76% to 2.55%, corresponding to reductions of 73.4% and 78.3%, respectively. When the load torque was increased from 5 to 7 N·m, the maximum speed deviation decreased from 0.45 to 0.05 r/min, corresponding to an 88.9% reduction in maximum speed deviation. For a load reduction from 7 to 5 N·m, the speed deviation decreased from 0.5 to 0.1 r/min, corresponding to an 80.0% reduction. Under the investigated simulation conditions, the proposed scheme achieved a lower torque ripple and improved load disturbance rejection compared with the conventional PI-DITC scheme.

Keywords: switched reluctance motor; torque ripple; repetitive control; active disturbance rejection control; torque sharing function; direct instantaneous torque control; extended state observer



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1. Introduction

In recent years, switched reluctance motors (SRMs) have emerged as promising candidates for high-performance electric drive applications due to their rugged structure, low manufacturing cost, high efficiency, and superior fault-tolerant characteristics. Because SRMs do not possess rotor windings or permanent magnets, they exhibit enhanced thermal stability and mechanical robustness under harsh operating conditions [1,2]. These unique advantages make SRMs highly attractive for various applications, including electric vehicles, aerospace propulsion systems, industrial automation, and renewable energy conversion systems [3–5]. Despite the numerous advantages of SRMs, their practical implementation in high-performance drive systems is still limited by several inherent challenges.

One of the most critical issues is the presence of significant torque ripple, which arises from the nonlinear inductance profile and doubly salient structure of the machine [6,7]. This torque ripple not only deteriorates the overall dynamic performance of the drive system but also leads to unwanted acoustic noise and mechanical vibrations [8,9]. In addition, SRM drives often suffer from speed oscillations, particularly under sudden load variations and parameter uncertainties. These issues become more severe in high-precision applications, where smooth torque production and fast dynamic response are required [10–12]. Therefore, improving torque smoothness and ensuring stable speed regulation remain key engineering challenges in SRM drive systems [13–15]. Moreover, the accurate identification of SRM parameters is difficult because the electromagnetic characteristics vary with the rotor position and operating conditions. The specialized doubly salient geometry may also increase the manufacturing and implementation complexity. Various control strategies have been developed to improve the performance of SRM drives, including conventional proportional–integral (PI) control, fuzzy logic control, sliding mode control, model predictive control (MPC), and active disturbance rejection control (ADRC). Among these methods, PI-based approaches are widely adopted because of their simple structures and ease of implementation [16–19]. However, their control performance is highly sensitive to parameter variations and external disturbances, particularly in nonlinear operating conditions. Advanced nonlinear control techniques, such as sliding mode control and model predictive control, can improve the dynamic response and robustness to a certain extent; nevertheless, issues such as chattering phenomena, high computational burden, and complex parameter tuning still limit their practical applicability in real-time SRM drive systems [20–23]. Recently, the ADRC has attracted increasing attention due to its strong disturbance estimation capability and robustness against system uncertainties. Although the ADRC can effectively enhance transient performance, its ability to suppress periodic torque ripple remains insufficient under varying operating conditions. Similarly, the repetitive control (RC) demonstrates good performance in tracking periodic signals [24,25]. However, its disturbance rejection capability may degrade in the presence of parameter uncertainties and sudden load disturbances. Therefore, existing control methods still face significant challenges in simultaneously achieving strong robustness, fast dynamic response, and effective torque ripple minimization in SRM-drive applications.

Although considerable research efforts have been devoted to improving the performance of DITC-based SRMs, several important issues remain insufficiently addressed in the existing literature. Most previous studies have primarily focused on either disturbance rejection enhancement or periodic torque ripple suppression individually, whereas limited attention has been given to the coordinated integration of both objectives within a unified control framework [26–28]. Conventional ADRC methods mainly emphasize dynamic disturbance compensation and transient response improvement; however, their effectiveness in mitigating periodic torque ripple under nonlinear operating conditions is still inadequate [29]. Similarly, repetitive control techniques are generally designed to suppress periodic errors; however, their robustness against parameter uncertainties and abrupt load disturbances remains relatively weak in practical SRM drive applications. Furthermore, relatively few studies have investigated the coordinated use of ADRC and repetitive control within a DITC framework for SRM drives under multiple operating speeds and abrupt load disturbances [30,31].

The torque ripple in SRMs has a strong periodic component, and the RC can learn and compensate for repetitive errors across cycles. Repetitive control is a specialized control strategy designed to eliminate periodic errors and disturbances by incorporating an internal model of the periodic signal into the feedback loop, making it highly effective for mitigating torque ripple in SRM drives, where the disturbance frequency is directly linked to the rotor

speed. However, conventional RC may be slow during transients and less effective under non-periodic disturbances, limiting their use as standalone solutions [32,33].

To overcome the limited torque ripple suppression and load disturbance rejection capability of the conventional PI-DITC for switched reluctance motor drives, this study proposes a coordinated LADRC–LAMHRC-based DITC strategy. In the proposed framework, the LADRC compensates for lumped disturbances and model uncertainties to improve speed regulation, whereas the LAMHRC targets periodic speed-error components associated with commutation-induced torque ripple and adaptively generates an auxiliary torque-compensation command under varying operating conditions. The contributions of this study are threefold. First, the LADRC and LAMHRC were integrated within a unified DITC structure to enhance both the transient and steady-state performance. Second, a speed-error-driven multi-harmonic repetitive compensation mechanism is introduced to reduce periodic speed-error components associated with commutation-induced torque ripple and to generate a smooth auxiliary torque-compensation command. Third, the proposed method was systematically compared with the conventional PI-DITC at reference speeds of 500 and 1000 r/min and under step-load variations from 5 to 7 N·m and from 7 to 5 N·m, respectively. The effectiveness of the proposed strategy was validated through MATLAB/Simulink simulations using a three-phase 6/4 SRM.

The remainder of this paper is organized as follows. Section 2 presents the mathematical model of the switched reluctance motor. Section 3 introduces the proposed LADRC–LAMHRC-based DITC strategy and describes its control architecture. Section 4 presents the simulation setup and discusses the comparative performance results under different speeds and load conditions. Finally, Section 5 concludes the paper and summarizes its main findings.

2. Mathematical Model of SRM

An SRM is a variable-reluctance, salient-pole structure motor with salient poles on the stator and rotor. Unlike ordinary motors that utilize windings on the stator and rotor to generate a rotating magnetic field in the air gap, in an SRM, the excitation windings are placed only on the stator poles, whereas the rotor contains neither windings nor permanent magnets. The phases of an SRM consist of windings placed on diametrically opposite stator poles and connected in series. Depending on the number of stator and rotor poles, SRMs can be classified as three-phase 6/4-pole, four-phase 8/6-pole, and six-phase 12/10-pole. In this study, a three-phase 6/4-pole SRM is considered, as shown in Figure 1.

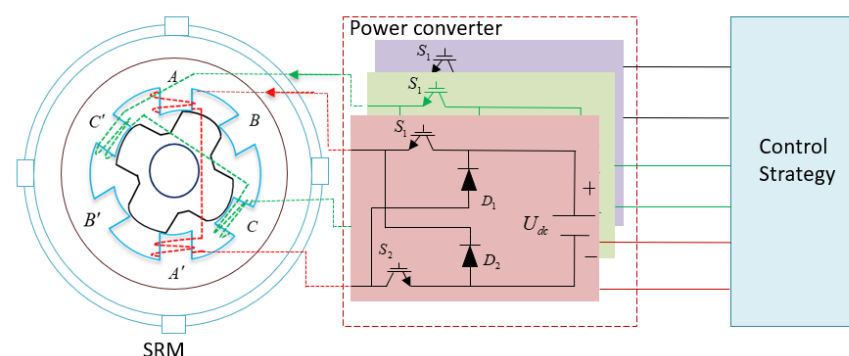


Figure 1. Schematic configuration of the switched reluctance motor.

The electromagnetic behavior of the SRM is governed by its doubly salient structure, which results in rotor-position-dependent phase inductance. The mechanical rotor position

is denoted by θ (rad), and the mechanical angular speed is defined as $\omega = \dot{\theta}$. The rotor pole pitch is given by $\theta_p = \frac{2\pi}{N_r}$. For a 6/4 SRM with $N_r = 4$, the pitch of the rotor pole becomes

$$\theta_p = \frac{2\pi}{4} = \frac{\pi}{2} \quad (1)$$

Hence, the phase inductance and torque characteristics are periodic with the rotor pole pitch, $\theta_p = \frac{\pi}{2}$ rad. For the control-oriented simulation adopted in this study, magnetic saturation and mutual inductance between the phases were neglected. Consequently, the phase flux linkage is assumed to vary linearly with the phase current as follows:

$$\psi(i, \theta) = L(\theta)i, \quad (2)$$

Therefore, all subsequent voltage and torque equations are derived under the same linear, unsaturated assumption.

The voltage equation of one phase is given by

$$u = Ri + \frac{d\psi(i, \theta)}{dt}, \quad (3)$$

where u and R denote the phase voltage and phase resistance, respectively.

Substituting Equation (2) into Equation (3) and applying the chain rule yields

$$\frac{d\psi(i, \theta)}{dt} = L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} \frac{d\theta}{dt}. \quad (4)$$

Since the rotor angular speed is defined as $\omega = d\theta/dt$, the phase-voltage equation becomes

$$u = Ri + L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} \omega. \quad (5)$$

Under the same linear unsaturated assumption, the magnetic co-energy of one phase is

$$W_c(i, \theta) = \frac{1}{2} L(\theta) i^2. \quad (6)$$

Therefore, the electromagnetic torque produced by one phase is obtained as

$$T_e(i, \theta) = \left. \frac{\partial W_c(i, \theta)}{\partial \theta} \right|_i = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta}. \quad (7)$$

The total electromagnetic torque T_e used in the mechanical dynamic equation is obtained by summing the individual phase-torque contributions. Equation (7) is valid only under the adopted linear, unsaturated magnetic assumption and is not intended to reproduce the saturated magnetic characteristics of an actual SRM. Validation using experimentally measured or finite-element-derived nonlinear flux-linkage and torque maps is beyond the scope of the present simulation study. The instantaneous electromagnetic torque generated by the SRM must overcome the inertial load, viscous friction, and external load torque. The mechanical dynamic equation is expressed as follows:

$$T_e = J \frac{d\omega}{dt} + B\omega + T_L \quad (8)$$

where T_e is the instantaneous electromagnetic torque, J is the combined moment of inertia of the rotor and coupled load ($\text{kg} \cdot \text{m}^2$), B is the viscous-friction coefficient ($\text{N} \cdot \text{m} \cdot \text{s}/\text{rad}$), ω is the rotor angular speed (rad/s), and T_L is the external load torque ($\text{N} \cdot \text{m}$).

For control-oriented modeling, Equation (8) can also be rewritten in state-space form as:

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - B\omega - T_L) \quad (9)$$

In Equation (9) clearly shows that the SRM speed dynamics are directly influenced by the pulsating electromagnetic torque, making the torque ripple a primary source of speed oscillations, particularly at low speeds.

Direct Instantaneous Torque Control

The DITC directly regulates the instantaneous electromagnetic torque using the measured phase currents and the rotor position. In the present simulation, the torque estimator is implemented using the linear unsaturated electromagnetic model defined in Equation (7). Therefore, no nonlinear $T(i, \theta)$ lookup table or current-dependent inductance model is used.

The DITC-based SRM control system is shown in Figure 2.

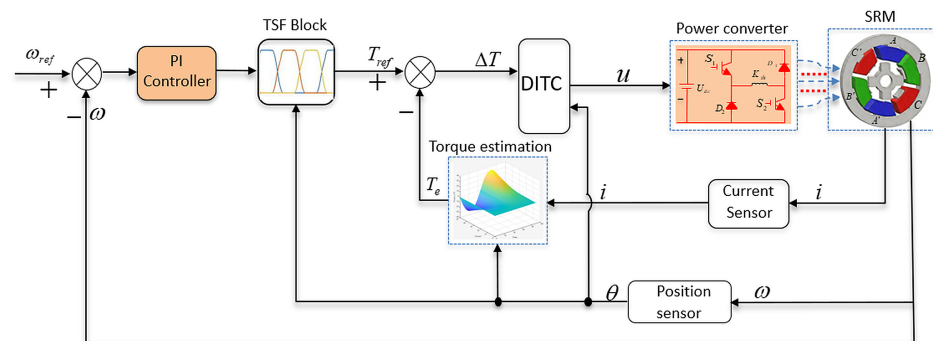


Figure 2. Control structure of the DITC scheme for the SRM.

For an SRM drive employing DITC, each phase of the power converter must generate three discrete voltage states: magnetization, freewheeling, and demagnetization. According to the torque-control command and rotor position, the switching logic selects the appropriate voltage state and applies the corresponding gating signals to the asymmetric half-bridge converter (AHBC). This switching action regulates the phase current buildup and decay, thereby controlling the instantaneous electromagnetic torque and rotor speed. The three operating states of the SRM phase converter are shown in Figure 3.

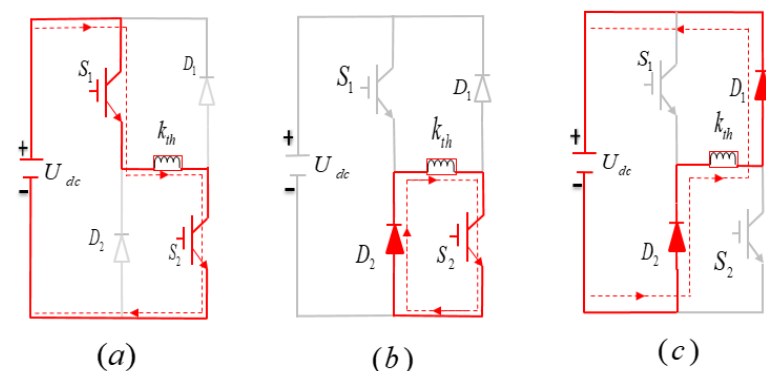


Figure 3. Switching modes of the SRM power converter: (a) magnetization, (b) freewheeling, and (c) demagnetization.

The three converter states are denoted by +1, 0, and −1. State +1 represents magnetization, in which both active switches of the asymmetric half-bridge converter are turned on and $+V_{dc}$ is applied across the phase winding. State 0 represents freewheeling, during

which the phase voltage is approximately zero and the winding current decreases gradually. State -1 represents demagnetization, in which both active switches are turned off and $-V_{dc}$ is applied across the winding through the antiparallel diodes, causing the phase current and electromagnetic torque to decrease rapidly. Under these operating conditions, the three converter states are used to form the available voltage vectors. By selecting the appropriate voltage vector according to the controller output, the desired electromagnetic torque can be produced.

The torque control process during the commutation of phases A and B is shown in Figure 4.

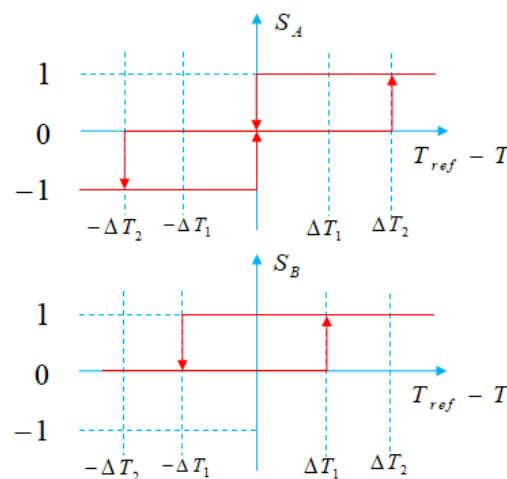


Figure 4. Torque control process for two-phase winding commutation.

For a large positive torque error ($T_{ref} - T > \Delta T_2$), both phases A and B are energized in state $+1$, enabling simultaneous torque production and a rapid increase in the total electromagnetic torque. During commutation, the torque contribution of phase B gradually becomes dominant. When the torque error decreases below zero, phase A is switched to state 0 to suppress torque oscillations. If the torque error decreases further below the inner hysteresis limit $-\Delta T_1$, phase B is also switched to state 0 to prevent excessive torque production. When the torque error reaches the outer lower limit $-\Delta T_2$, phase A enters state -1 to accelerate torque reduction while maintaining the flux linkage of phase B. As the torque error increases above zero, phase A returns to state 0 . Subsequently, when the torque error exceeds ΔT_1 , phase B is reactivated in state $+1$. If the torque error further exceeds ΔT_2 , phase A is also switched to state $+1$. Through this coordinated hysteresis-based switching strategy, the DITC maintains the electromagnetic torque within the prescribed hysteresis bounds while reducing torque ripple in the SRM drive.

Based on the measured phase currents and rotor position, the DITC determines the conduction intervals of the power switches and selects the appropriate voltage vector according to the instantaneous torque error. This enables the electromagnetic torque to track its reference within a predefined hysteresis band, thereby limiting the torque ripple. Nevertheless, conventional DITC relies on a finite set of discrete voltage vectors and does not fully exploit the magnitude and dynamic characteristics of torque error signals. Consequently, its control action may become insufficient during phase commutation, rapid transients, and load variations, leading to residual torque pulsations and degraded disturbance rejection performance. Therefore, further enhancement of the DITC framework is required to improve the torque-tracking accuracy, utilize the available error information more effectively, and achieve a smoother and more robust SRM operation.

3. Design of the Proposed LADRC–LAMHRC-Based DITC Strategy

3.1. Torque Sharing Function

The TSF is a reference generation strategy used in SRM drives to distribute the total reference torque among the conducting phases to reduce torque ripple and ensure smooth commutation [21]. To address this issue, a torque distribution function is designed considering the balance between the increase in the conducting phase torque and the decrease in the turning-off phase torque in the commutation overlap region. This ensures that the combined torque of each phase at each rotor position is the same, that is, the reference torque. The mathematical model is as follows:

$$\begin{cases} T_k(\theta) = T_{\text{ref}} f_k(\theta), & k = 1, 2, \dots, m \\ \sum_{k=1}^m f_k(\theta) = 1, & 0 \leq f_k(\theta) \leq 1 \end{cases} \quad (10)$$

In Equation (10), T_{ref} denotes the total reference torque, T_k represents the torque of the k th phase, m is the number of motor phases, θ is the rotor position, and $f_k(\theta)$ is the torque distribution function. The torque distribution function can take various forms depending on the actual operating conditions of the motor, including linear, power, exponential, sine, and cosine functions.

$$f_k(\theta) = \begin{cases} \frac{1}{2} - \frac{1}{2} \cos\left(\frac{\pi(\theta - \theta_{\text{on}})}{\theta_{\text{ov}}}\right), & \theta_{\text{on}} \leq \theta < \theta_{\text{on}} + \theta_{\text{ov}} \\ 1, & \theta_{\text{on}} + \theta_{\text{ov}} \leq \theta < \theta_{\text{off}} \\ \frac{1}{2} + \frac{1}{2} \cos\left(\frac{\pi(\theta - \theta_{\text{off}})}{\theta_{\text{ov}}}\right), & \theta_{\text{off}} \leq \theta < \theta_{\text{off}} + \theta_{\text{ov}} \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

In Equation (11), θ_{on} is the conduction angle, θ_{off} is the turn-off angle, and θ_{ov} denotes the overlap region between two adjacent phases.

3.2. Linear Active Disturbance Rejection Control Design

The LADRC is an effective robust control strategy that improves system performance by estimating and compensating for internal uncertainties and external disturbances in real time using an LESO. Owing to its simple parameter tuning, fast dynamic response, and strong disturbance rejection capability, the LADRC has been widely applied in nonlinear motor drive systems to enhance operational stability and control robustness under varying operating conditions [24]. This formulation reduces model dependency and enhances robustness under parameter variations and nonlinear operating conditions of SRM. The structure of the LADRC speed-control scheme with a linear extended state observer is shown in Figure 5.

For the SRM mechanical subsystem, the rotor dynamics are expressed as

$$J\dot{\omega}_m = T_e - B\omega_m - T_L, \quad (12)$$

where J is the rotor inertia, B is the viscous-friction coefficient, T_e is the electromagnetic torque, and T_L is the load torque. Equation (12) can be rewritten in the standard first-order LADRC form as

$$\dot{\omega}_m = f(\omega_m, T_L) + b_0 T_e, \quad b_0 = \frac{1}{J}, \quad (13)$$

where the lumped disturbance is defined as

$$f(\omega_m, T_L) = -\frac{B}{J}\omega_m - \frac{T_L}{J} + \Delta f, \quad (14)$$

and Δf represents unmodeled dynamics and parameter uncertainties.

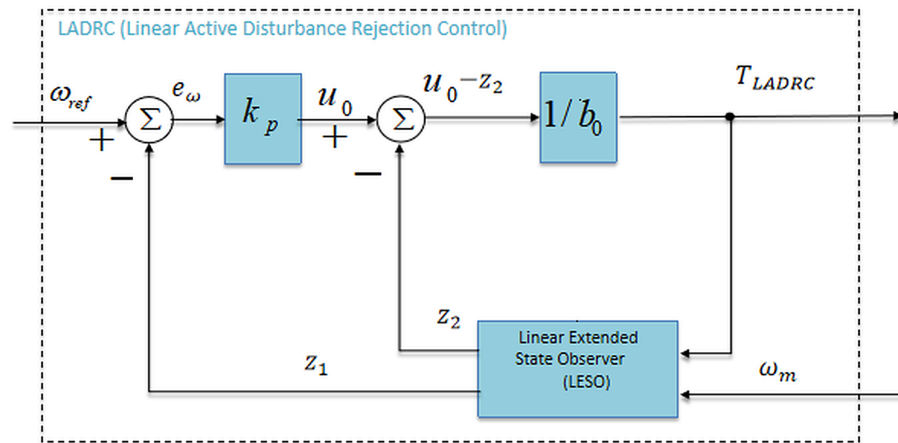


Figure 5. Structure of the LADRC speed-control scheme with a linear extended-state observer.

A second-order linear extended-state observer is employed to estimate the rotor speed and the lumped disturbance:

$$\dot{z}_1 = z_2 + b_0 T_{LADRC} - 2\omega_o(z_1 - \omega_m). \quad (15)$$

$$\dot{z}_2 = -\omega_o^2(z_1 - \omega_m), \quad (16)$$

where z_1 and z_2 denote the estimated rotor speed and total disturbance, respectively, and ω_o is the observer bandwidth. The speed-tracking error is defined as

$$e_\omega = \omega_m^* - z_1, \quad (17)$$

and the nominal control signal is given by

$$u_0 = k_p e_\omega, \quad k_p = \omega_c, \quad (18)$$

where ω_c denotes the controller bandwidth. Accordingly, the reference electromagnetic torque is generated as

$$T_{LADRC}(k) = \text{sat}_{[T_{e,\min}, T_{e,\max}]} \left(\frac{u_0(k) - z_2(k)}{b_0} \right). \quad (19)$$

where $T_{LADRC}(k)$ denotes the nominal electromagnetic torque command generated by the LADRC, and $T_{e,\min}$ and $T_{e,\max}$ denote its lower and upper saturation limits, respectively.

3.3. Load-Adaptive Multi-Harmonic Repetitive Controller

The LAMHRC comprises four parallel repetitive control branches associated with the selected 6th-, 12th-, 18th-, and 24th-order periodic components. The corresponding circular memory lengths were derived from the nominal repetitive period expressed in sampling intervals. An error-based load-adaptive mechanism adjusts the learning gain, memory retention factor, and compensation bound according to the detected operating condition. Branch-dependent sample-index phase-shift terms are introduced to reduce the effect of

implementation delay, whereas memory-state damping, state-increment limitation, output-rate limitation, and adaptive saturation are employed to prevent excessive compensation during abrupt error variations and rotor position transients. The resulting compensation signal was subsequently processed using a first-order discrete low-pass filter to attenuate high-frequency fluctuations and improve the control smoothness. The remaining controller parameters were selected through simulation-based tuning to obtain a suitable compromise between periodic-error attenuation, transient response, and bounded closed-loop behavior over the investigated load conditions.

The control structure of the proposed sample-domain load-adaptive multi-harmonic repetitive controller is shown in Figure 6.

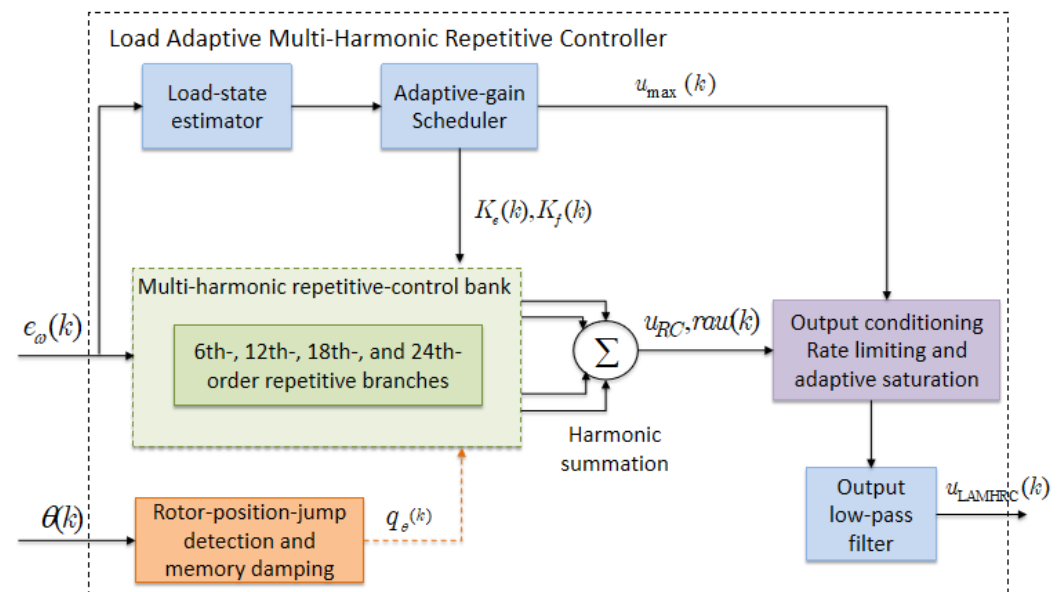


Figure 6. Control structure of the sample-domain load-adaptive multi-harmonic repetitive controller.

The proposed LAMHRC was implemented in the sample domain, and its repetitive-memory updates were driven by the discrete-time rotor-speed tracking error, defined as

$$e_\omega(k) = \omega^*(k) - \omega_m(k), \quad (20)$$

where $\omega^*(k)$ and $\omega_m(k)$ denote the reference and measured rotor speeds, respectively.

Four parallel repetitive-control branches are employed for the selected harmonic set $\mathcal{H} = \{6, 12, 18, 24\}$. The sample-domain memory length of the h th branch is determined by

$$N_h = \max \left\{ \text{round} \left(\frac{N_0}{h} \right), N_{\min} \right\}, \quad h \in \mathcal{H}, \quad (21)$$

where N_0 is the nominal repetitive period expressed in sampling intervals and $N_{\min}$ prevents excessively short memory buffers.

Let $j_h(k) \in \{1, \dots, N_h\}$ denote the current circular-buffer write index and p_h the branch-dependent phase-shift index. The corresponding read address and recalled memory state are expressed as

$$\begin{aligned} r_h(k) &= 1 + \text{mod}(j_h(k) - p_h - 1, N_h), \\ x_h^d(k) &= B_h[r_h(k)], \end{aligned} \quad (22)$$

where $B_h[\cdot]$ denotes the circular-memory buffer of the h th branch. For each investigated operating speed, N_0 was selected through simulation-based tuning as the nominal repetitive-memory length in sampling intervals. The unconstrained learning update is given by

$$x_h^{\text{raw}}(k) = K_e(k)e_\omega(k) + K_f(k)x_h^d(k), \quad (23)$$

where $K_e(k)$ is the adaptive learning gain and $K_f(k)$ is the memory-retention factor. To prevent abrupt changes in the stored compensation state, the state increment is constrained as

$$x_h(k) = x_h^d(k) + \text{sat}\left(x_h^{\text{raw}}(k) - x_h^d(k), -\Delta x_{\max}, \Delta x_{\max}\right). \quad (24)$$

The updated state is stored at the current write location, after which the circular-buffer index is advanced:

$$\begin{aligned} B_h[j_h(k)] &\leftarrow x_h(k), \\ j_h(k+1) &= 1 + \text{mod}(j_h(k), N_h). \end{aligned} \quad (25)$$

The outputs of the parallel repetitive-control branches are combined according to

$$u_{\text{RC,raw}}(k) = \sum_{h \in \mathcal{H}} K_h x_h(k), \quad (26)$$

where K_h denotes the weighting coefficient of the h th branch. To characterize the operating condition, an exponentially smoothed absolute-speed-error index is introduced:

$$E_a(k) = \lambda E_a(k-1) + (1-\lambda)|e_\omega(k)|, \quad 0 < \lambda < 1. \quad (27)$$

The adaptive controller parameters are collected in the vector

$$\Theta(k) = \begin{bmatrix} K_e(k) & K_f(k) & U_{\max}(k) \end{bmatrix}^T, \quad (28)$$

where $U_{\max}(k)$ is the adaptive compensation bound.

Based on the detected operating condition, the controller parameters are smoothly adjusted toward their target values according to

$$\Theta(k) = \Theta(k-1) + \alpha_g[\Theta^*(k) - \Theta(k-1)], \quad 0 < \alpha_g < 1, \quad (29)$$

where $\Theta^*(k)$ denotes the operating-state-dependent target vector and α_g is the parameter-transition coefficient. Rotor position is used only for transient memory protection. To avoid incorrectly detecting normal angular wraparound as a position jump, the wrapped position variation is defined as

$$\Delta\theta_w(k) = \left| \text{mod}\left(\theta(k) - \theta(k-1) + \frac{\Theta_w}{2}, \Theta_w\right) - \frac{\Theta_w}{2} \right|, \quad (30)$$

where $\Theta_w = 2\pi$ for rotor position expressed in radians and $\Theta_w = 360^\circ$ for rotor position expressed in degrees.

When the wrapped position variation exceeds the prescribed threshold, all repetitive-memory branches are strongly attenuated:

$$B_h(k^+) = \begin{cases} \gamma_\theta B_h(k^-), & \Delta\theta_w(k) > \theta_{\text{th}}, \\ B_h(k^-), & \Delta\theta_w(k) \leq \theta_{\text{th}}, \end{cases} \quad h \in \mathcal{H}, \quad (31)$$

where $\gamma_\theta = 0.01$ is the memory-damping factor. This protection mechanism suppresses outdated learned information but does not determine the memory address used for learning or retrieval.

After the initial memory-filling interval, the raw repetitive-control signal is processed by output-rate limitation and adaptive saturation, followed by a first-order discrete low-pass filter:

$$\begin{aligned} u_r(k) &= u_r(k-1) + \text{sat}(u_{\text{RC,raw}}(k) - u_r(k-1), -\Delta u_{\text{max}}, \Delta u_{\text{max}}), \\ u_s(k) &= \text{sat}(u_r(k), -U_{\text{max}}(k), U_{\text{max}}(k)), \\ u_{\text{LAMHRC}}(k) &= \alpha_f u_s(k) + (1 - \alpha_f) u_{\text{LAMHRC}}(k-1), \quad 0 < \alpha_f \leq 1. \end{aligned} \quad (32)$$

where $u_r(k)$ denotes the rate-limited repetitive-control signal, $u_s(k)$ denotes the adaptively saturated signal, and Δu_{max} is the maximum permissible change in $u_r(k)$ per sampling interval. Furthermore, $U_{\text{max}}(k)$ is the adaptive compensation bound, and α_f is the coefficient of the first-order discrete low-pass filter.

The output of the LAMHRC, $u_{\text{LAMHRC}}(k)$, is processed by a proportional–integral compensator to generate the auxiliary torque command:

$$T_{\text{LAMHRC}}(k) = K_{p,\text{RC}} u_{\text{LAMHRC}}(k) + K_{i,\text{RC}} \sum_{\ell=0}^k u_{\text{LAMHRC}}(\ell) T_s, \quad (33)$$

where $K_{p,\text{RC}}$ and $K_{i,\text{RC}}$ denote the proportional and integral gains of the compensator, respectively, and T_s is the sampling period. The resulting signal $T_{\text{LAMHRC}}(k)$ is expressed in $\text{N} \cdot \text{m}$ and represents the auxiliary periodic torque-compensation command.

The total electromagnetic torque reference is obtained by combining the nominal torque command generated by the LADRC and the auxiliary torque command generated by the LAMHRC:

$$T_{\text{ref}}(k) = T_{\text{LADRC}}(k) + T_{\text{LAMHRC}}(k). \quad (34)$$

The total electromagnetic torque reference is supplied to the torque-sharing function and the inner DITC loop.

As shown in Figure 7, the reference and feedback speed signals were supplied to the LADRC and LAMHRC units through their respective error formulations. The LADRC uses the observer-estimated speed and the lumped-disturbance estimate to generate the nominal torque command. In contrast, the LAMHRC uses the measured rotor-speed tracking error to generate the filtered repetitive-control output $u_{\text{LAMHRC}}(k)$. This signal is subsequently processed by the PI compensator to obtain the auxiliary torque-compensation command $T_{\text{LAMHRC}}(k)$. The resulting auxiliary torque command is then added to the nominal torque command generated by the LADRC to form the total electromagnetic torque reference $T_{\text{ref}}(k)$. The measured phase currents and rotor position were fed back to the torque estimator and switching logic. Rotor position information is additionally supplied to the LAMHRC only for transient memory protection; it is not used as an angular-bin index or as a position-based address for storing or retrieving repetitive compensation information. The conventional PI-DITC and proposed LADRC–LAMHRC strategies were evaluated using identical motor parameters, sampling conditions, converter constraints, reference commands, and load profiles to ensure a fair comparison. For the PI-DITC scheme, the controller gains were selected to obtain a stable speed response with a limited overshoot and acceptable settling time. For the proposed method, the LADRC controller and observer bandwidths were selected to achieve rapid disturbance estimation while limiting the amplification of the high-frequency components. The LAMHRC learning gain, memory retention factor, and compensation bound were constrained within the prescribed ranges.

State-increment limitation, output-rate limitation, adaptive saturation, memory damping, and first-order low-pass filtering were incorporated to prevent excessive compensation and suppress abrupt transients. Because a formal Lyapunov-based stability proof was not developed, the closed-loop behavior was assessed numerically under the investigated operating conditions. The rotor speed, electromagnetic torque, phase currents, observer states, and controller outputs remained bounded during the startup, steady-state operation, and step-load disturbances, with no sustained oscillation or divergence observed. These results provide numerical evidence of bounded closed-loop operation within the tested operating range but should not be interpreted as a general analytical proof of stability.

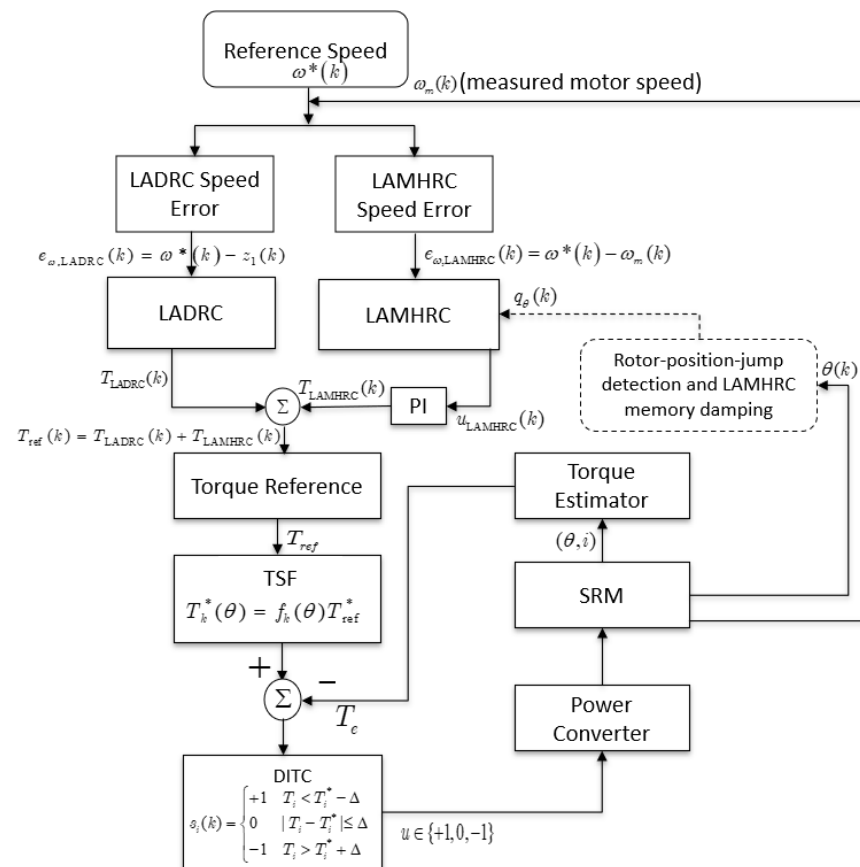


Figure 7. Overall control architecture of the proposed LADRC–LAMHRC-based DITC scheme for the SRM.

4. Simulation Setup and Validation Methodology

The proposed LADRC–LAMHRC-based DITC strategy was validated through comparative simulations conducted in MATLAB/Simulink R2024b using a three-phase 6/4 SRM-drive model. To ensure a fair assessment, the proposed controller and conventional PI-DITC scheme were evaluated using identical motor parameters, converter topology, sampling conditions, reference commands and load profiles. The validation considered steady-state and transient operations at reference speeds of 500 and 1000 r/min, together with step-load transitions from 5 to 7 N·m and from 7 to 5 N·m. The comparative evaluation was based on the settling time, steady-state speed error, maximum speed deviation, electromagnetic torque ripple, and load-disturbance rejection capability. The results were further quantified using numerical tables and the percentage of improvements. The control structure was implemented on a three-phase 6/4 SRM, as shown in Figure 8.

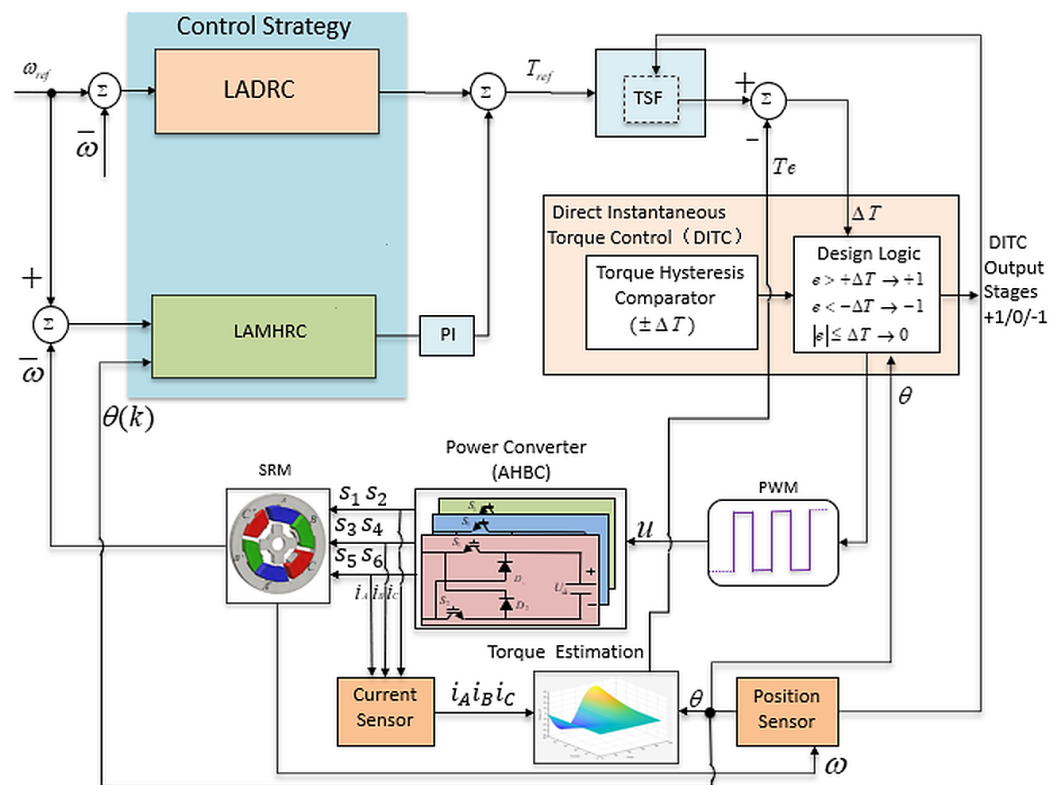


Figure 8. MATLAB/Simulink platform implementation of the proposed LADRC–LAMHRC-based DITC scheme for the SRM.

4.1. Simulation Parameters

The PI-controller gains for the 500 and 1000 r/min operating conditions are listed in Table 1. The principal SRM parameters used in the simulations are listed in Table 2 below.

Table 1. PI-controller gain settings.

Speed (rpm)	Parameter	Value
500	Kp	2.9
	Ki	2.22
1000	Kp	0.99
	Ki	0.7

Table 2. Simulation parameters of the 6/4 SRM.

Parameter	Value
Stator/rotor poles (N_s/N_r)	6/4
Rated voltage (V_{dc})	240 V
Given speed	500 rpm and 1000 rpm
Stator resistance (R)	0.5 Ω
Friction coefficient (B)	0.02 N·m·s/rad
Minimum inductance ($L_{\min}$)	0.00067 H
Maximum inductance ($L_{\max}$)	0.0236 H

This study compared the traditional PI and integrated LADRC–LAMHRC control strategies based on the DITC. The simulation control parameters used in the manuscript to compare the two strategies are listed in Tables 1 and 2.

4.2. Dynamic Performance at Different Speeds Under the Same Constant Load

1. Dynamic-response comparison between the conventional PI-DITC and the proposed LADRC–LAMHRC schemes at a reference speed of 500 r/min.

In Figure 9 shows the dynamic response of the conventional PI-based DITC system at a reference speed of 500 r/min. The controller achieves a rapid speed transient with a settling time of approximately 0.015 s and a negligible steady-state speed error. Nevertheless, a noticeable steady-state electromagnetic torque ripple persists. During the interval from 0.05 s to 0.07 s, the maximum, minimum, and average electromagnetic torque values are approximately 4.35 N · m, 3.90 N · m, and 4.05 N · m, respectively, resulting in a torque-ripple coefficient of approximately 11.11%.

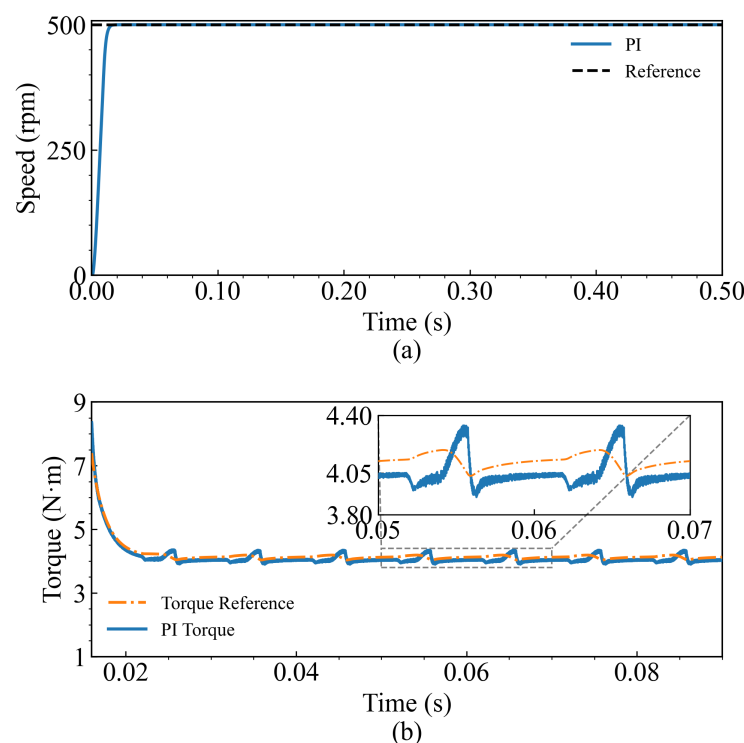


Figure 9. Dynamic response of the PI-DITC controlled SRM at 500 r/min under a constant load condition: (a) speed response and (b) electromagnetic torque response with the corresponding torque reference and enlarged steady-state detail.

In Figure 10 shows the dynamic response of the proposed LADRC–LAMHRC-based DITC strategy. The controller provides a smooth speed response with a settling time of approximately 0.03 s, negligible overshoot, and virtually zero steady-state error. Within the time interval of 0.05–0.07 s, the maximum, minimum, and average electromagnetic torque values are approximately 4.10 N · m, 3.98 N · m, and 4.05 N · m, respectively, yielding a torque-ripple coefficient of approximately 2.96%.

2. Dynamic response comparison between the conventional PI-DITC and the proposed LADRC–LAMHRC schemes at a reference speed of 1000 r/min.

In Figure 11 shows the dynamic response of the conventional PI-DITC system at a reference speed of 1000 r/min. The PI controller provided a rapid speed buildup with a settling time of approximately 0.03 s, negligible overshoot, and no observable steady-state speed error. However, a pronounced electromagnetic torque ripple persisted after the transient period. In the enlarged steady-state interval of approximately 0.065–0.076 s, the maximum, minimum, and average torque values were approximately

5.50 N · m, 4.90 N · m, and 5.10 N · m, respectively, yielding a torque ripple coefficient of approximately 11.76%.

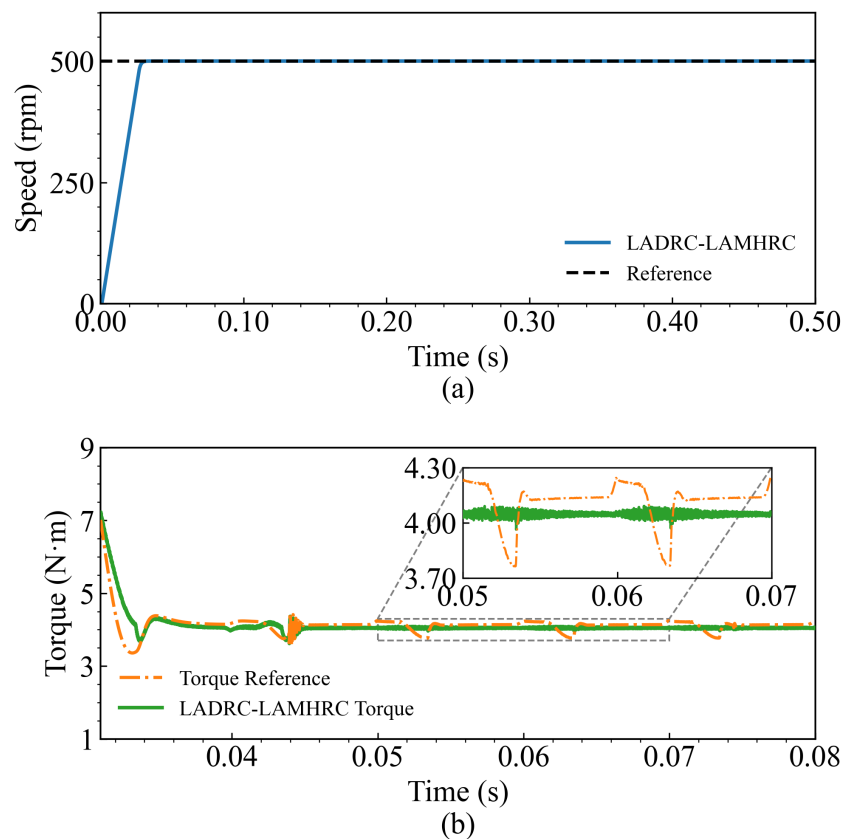


Figure 10. Dynamic response of the LADRC-LAMHRC controlled SRM at 500 r/min under a constant load condition: (a) speed response and (b) electromagnetic torque response with the corresponding torque reference and enlarged steady-state detail.

In Figure 12 shows the dynamic response of the proposed LADRC–LAMHRC-based DITC system at a reference speed of 1000 r/min. The proposed controller achieved a smooth speed buildup with a settling time of approximately 0.055 s, negligible overshoot, and no observable steady-state speed error. Moreover, the electromagnetic torque remained closely regulated around its reference despite the commutation-induced variations in the torque command. In the enlarged steady-state interval of 0.10–0.12 s, the maximum, minimum, and average torque values were approximately 5.16 N · m, 5.03 N · m, and 5.10 N · m, respectively, corresponding to a torque ripple coefficient of approximately 2.55%.

Table 3 compares the electromagnetic torque ripple performance of the conventional PI-DITC and the proposed LADRC–LAMHRC schemes at reference speeds of 500 and 1000 r/min. The PI-DITC scheme produces torque ripple coefficients of 11.11% and 11.76%, respectively, whereas the proposed controller reduces these values to 2.96% and 2.55%, respectively. Consequently, the LADRC–LAMHRC scheme achieves torque ripple reductions of approximately 73.4% at 500 r/min and 78.3% at 1000 r/min. These results demonstrate that the proposed controller provides consistently superior torque ripple suppression over the investigated speed range, with enhanced effectiveness at higher operating speeds.

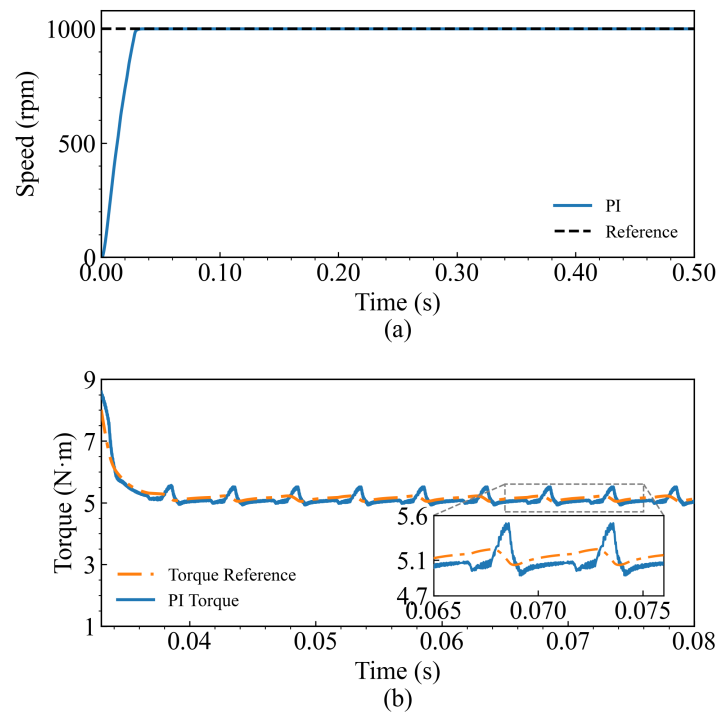


Figure 11. Dynamic response of the PI-DITC controlled SRM at 1000 r/min under a constant load condition: (a) speed response and (b) electromagnetic torque response with the corresponding torque reference and enlarged steady-state detail.

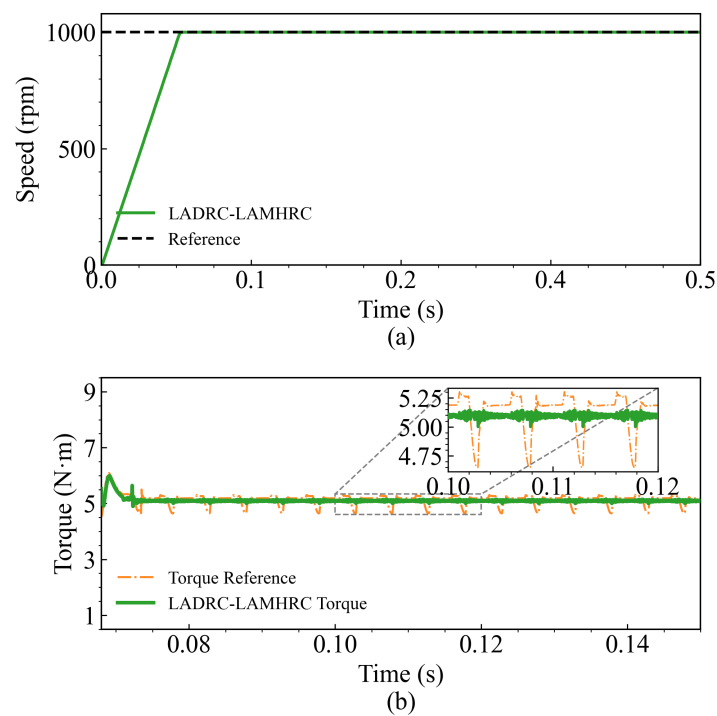


Figure 12. Dynamic response of the LADRC-LAMHRC controlled SRM at 1000 r/min under a constant load condition: (a) speed response and (b) electromagnetic torque response with the corresponding torque reference and enlarged steady-state detail.

Table 3. Comparison of electromagnetic torque ripple at different reference speeds.

Speed (r/min)	Torque Ripple (%)	
	PI	LADRC-LAMHRC
500	11.11	2.96
1000	11.76	2.55

4.3. Disturbance-Rejection Performance of the Proposed Control Scheme

1. Disturbance-response comparison under an increased load at a reference speed of 1000 r/min.

In Figure 13 compares the load-disturbance rejection performances of the conventional PI-DITC and the proposed LADRC-LAMHRC control schemes. The load torque increased from approximately 5 to 7 N·m at 1.0 s. After the load variation, both controllers maintained the motor speed close to the reference value of 1000 r/min. However, the proposed LADRC-LAMHRC scheme exhibited a substantially smaller speed deviation. Under the LADRC-LAMHRC control, the minimum speed was approximately 999.95 r/min, corresponding to a maximum fluctuation of approximately 0.05 r/min. In contrast, the minimum speed obtained using the conventional PI-DITC scheme was approximately 999.55 r/min, corresponding to a maximum fluctuation of approximately 0.45 r/min. Therefore, the proposed controller reduced the maximum speed fluctuation by approximately 88.9%, demonstrating superior load-disturbance rejection capability and enhanced speed regulation robustness.

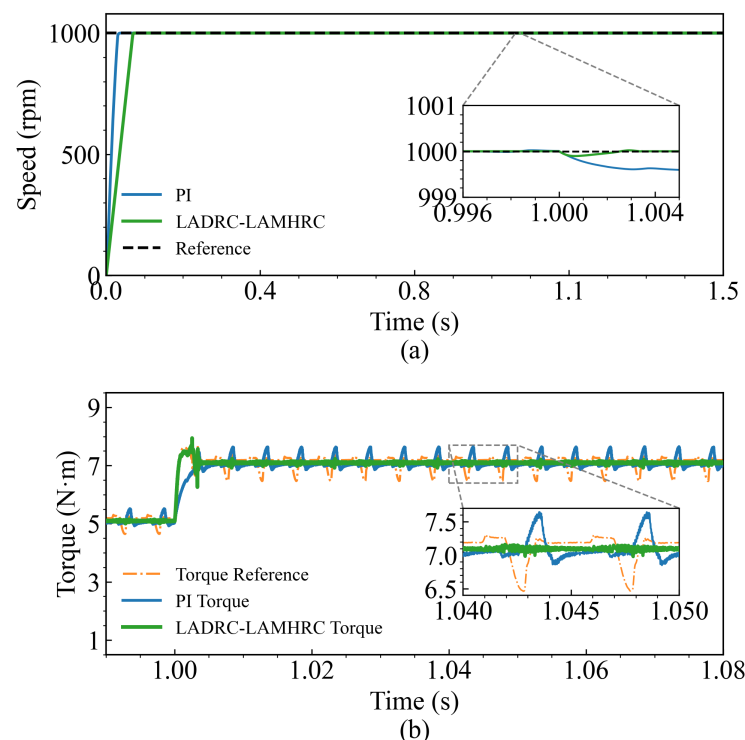


Figure 13. Load-disturbance rejection response of the conventional PI-DITC and proposed LADRC-LAMHRC-based DITC schemes during a sudden load increase: (a) speed responses with an enlarged transient view and (b) electromagnetic torque responses with the corresponding torque reference and an enlarged steady-state view.

2. Disturbance response comparison under decreased load at a reference speed of 1000 r/min.

In Figure 14 compares the load-disturbance rejection performances of the conventional PI-DITC and the proposed LADRC–LAMHRC control schemes under a sudden load reduction at a reference speed of 1000 r/min. The load torque decreased from approximately 7 to 5 N·m at 2.0 s. Following the disturbance, both controllers maintained the motor speed close to the reference value; however, the LADRC–LAMHRC scheme exhibited a markedly smaller transient deviation. Under the proposed controller, the maximum speed was approximately 1000.1 r/min, corresponding to a fluctuation of approximately 0.1 r/min. In contrast, the conventional PI-DITC scheme reached approximately 1000.5 r/min, yielding a fluctuation of approximately 0.5 r/min. Therefore, the proposed method reduced the maximum speed deviation by approximately 80%, demonstrating its superior disturbance rejection capability. Moreover, after load reduction, the electromagnetic torque rapidly decreases to 5 N·m, whereas the LADRC–LAMHRC scheme maintains a substantially lower steady-state torque ripple than the PI-DITC controller.

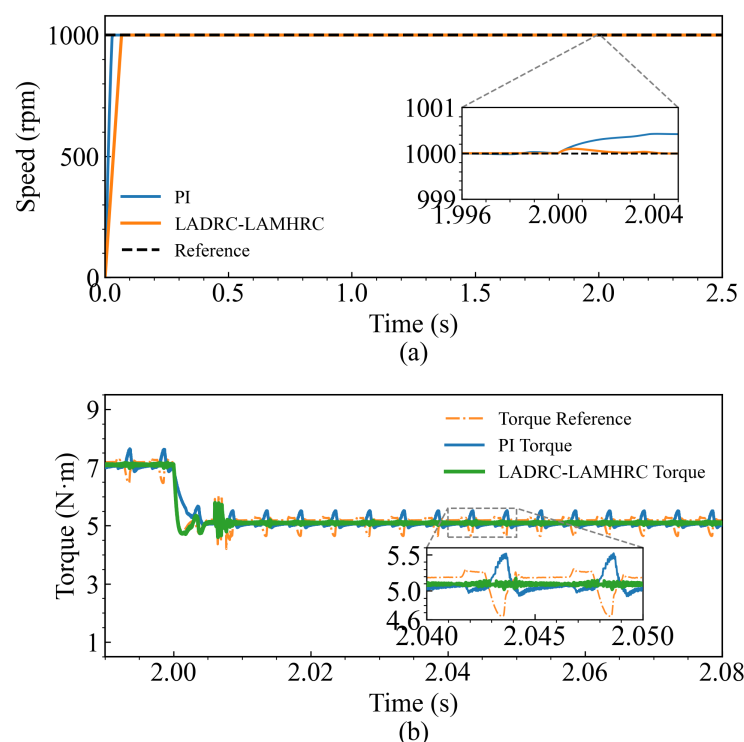


Figure 14. Load-disturbance rejection performance of the PI-DITC-controlled and LADRC–LAMHRC-based DITC-controlled SRM drives during a sudden load decrease: (a) speed responses with an enlarged transient view and (b) electromagnetic torque responses with the corresponding torque reference and an enlarged transient detail.

Table 4 summarizes the load-disturbance rejection performances of the PI and LADRC–LAMHRC schemes at a reference speed of 1000 r/min. For a load increase from 5 to 7 N·m, the PI method exhibited a maximum speed deviation of 0.45 r/min, whereas the proposed LADRC–LAMHRC scheme limited the deviation to 0.05 r/min, corresponding to an 88.9% reduction in the speed deviation. Under a load decrease from 7 to 5 N·m, the speed deviation was reduced from 0.50 r/min with the PI controller to 0.10 r/min with the proposed controller, yielding an 80.0% improvement. These results confirm the superior disturbance rejection capability and enhanced speed regulation robustness of the proposed controller under both increasing and decreasing load conditions.

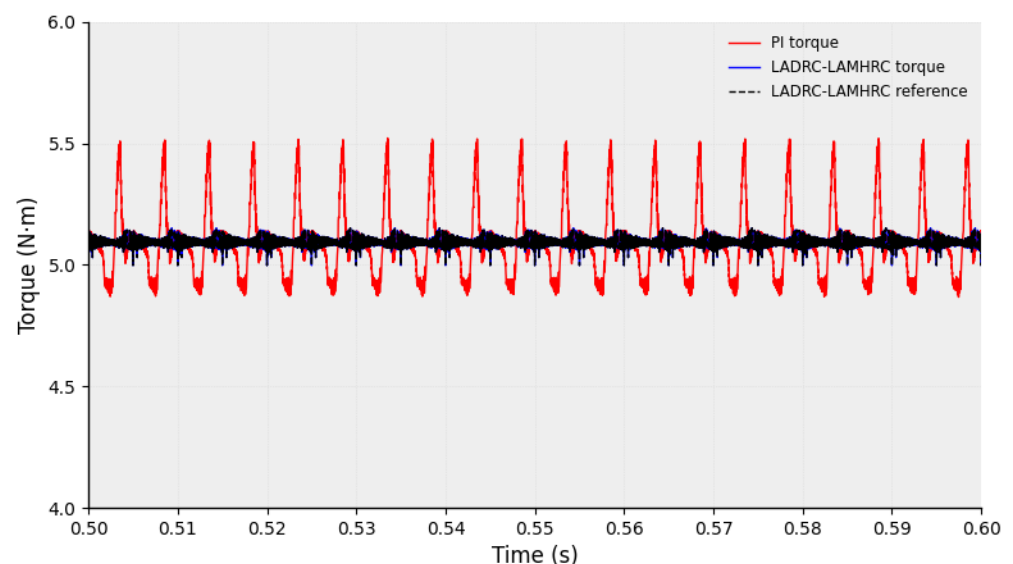
Table 4. Comparative evaluation of load-disturbance rejection response at a reference speed of 1000 r/min.

Load-Torque Variation	Control Scheme	Extreme Rotor Speed	Maximum Speed Deviation	Reduction
5–7 N·m	PI	999.55 r/min	0.45 r/min	–
	LADRC–LAMHRC	999.95 r/min	0.05 r/min	88.9%
7–5 N·m	PI	1000.5 r/min	0.5 r/min	–
	LADRC–LAMHRC	1000.1 r/min	0.1 r/min	80.0%

4.4. Robustness Evaluation

A robustness test was performed by introducing an angle-domain sinusoidal multiplicative disturbance into the controlled system. Unlike a time-domain additive perturbation, this disturbance periodically scales the affected model or control quantity as a function of the rotor's position. Both controllers were tested under identical operating conditions, reference torque, machine parameters, sampling time, and disturbance profiles to ensure a fair comparison.

As shown in Figure 15, the PI-controlled system exhibited pronounced periodic oscillations in the torque. The electromagnetic torque deviated repeatedly from the reference value, producing sharp peaks and valleys throughout the selected interval. This behavior indicates that the PI controller is relatively sensitive to the rotor position-dependent multiplicative uncertainty and has a limited capability to suppress the imposed angular disturbance. In contrast, the LADRC-LAMHRC response remained closely concentrated around the reference torque. Its oscillation amplitude was substantially smaller, and the torque trajectory followed the reference with only minor residual fluctuation. These results confirm the superior disturbance rejection capability of the proposed LADRC-LAMHRC controller.

**Figure 15.** Comparison of PI and LADRC-LAMHRC Electromagnetic Torque Responses with Reference Torque.

The quantitative results in Table 5 support these graphical observations. For the PI controller, the maximum and minimum electromagnetic torques were 5.52 N·m and 4.86 N·m, respectively. Accordingly, the peak-to-peak torque variation was 0.65 N·m. With an average torque of 5.094 N·m, the corresponding torque-ripple percentage was 12.84%. For the LAMHRC controller, the electromagnetic torque was confined to a considerably narrower range, from 4.99 N·m to 5.15 N·m. Its peak-to-peak torque variation was

only 0.15 N · m, whereas the average torque remained nearly unchanged at 5.093 N · m. Consequently, the torque-ripple percentage was reduced to 3.01%.

Table 5. Comparison of electromagnetic torque ripple characteristics under PI and LADRC-LAMHRC control.

Metric	PI Controller	LADRC-LAMHRC Controller
Time interval	0.500–0.600 s	0.500–0.600 s
Maximum torque	5.52 N·m	5.15 N·m
Minimum torque	4.86 N·m	4.99 N·m
Average torque	5.094 N·m	5.093 N·m
Peak-to-peak torque	0.65 N·m	0.15 N·m
Torque ripple ratio	0.12	0.03
Torque ripple percentage	12.84%	3.01%
Comparison metric	Result	
Torque ripple reduction with LADRC-LAMHRC	76.50%	

Torque ripple is quantified using the ripple factor defined as

$$\text{Torque Ripple (\%)} = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \times 100 \quad (35)$$

where $T_{\max}$, $T_{\min}$, and T_{avg} represent the maximum, minimum, and average torque values, respectively.

The stability of the conventional PI-DITC and proposed LADRC–LAMHRC strategies was evaluated under identical motor parameters, sampling conditions, converter constraints, and operating scenarios to ensure a fair comparison. For the PI-DITC, the controller gains were tuned to obtain a stable speed response with a limited overshoot and acceptable settling time. For the proposed method, the LADRC bandwidth and observer gains were selected to achieve rapid disturbance estimation without amplifying the high-frequency dynamics, whereas the LAMHRC learning and forgetting factors were constrained within stable operating bounds. In addition, output saturation, rate limiting, buffer damping, and low-pass filtering were incorporated to prevent excessive control actions and suppress abrupt transients. Because no formal Lyapunov-based proof was developed, closed-loop stability was assessed numerically by verifying that the speed, electromagnetic torque, phase currents, observer states, and control signals remained bounded during the start-up, steady-state operation, speed-reference variations, and step-load disturbances. In all the investigated cases, no sustained oscillations or divergence were observed. These results provide numerical evidence of stable closed-loop operation within the tested range.

4.5. Efficiency and Cost Considerations

This study primarily focused on evaluating the dynamic performance of the proposed LADRC–LAMHRC strategy in terms of speed regulation, torque ripple suppression, and load disturbance rejection. A quantitative comparison of motor efficiency among the investigated control strategies was not presented because the electrical input power, converter conduction and switching losses, and phase copper losses were not comprehensively recorded in the current simulation framework. Consequently, torque ripple reduction and improved dynamic performance are not interpreted as direct evidence of increased motor efficiency, and no unsupported efficiency-improvement claim is made. A comprehensive efficiency comparison requires all control strategies to be evaluated under identical speed and load conditions using consistent measurements of the DC link input power, mechanical output power, RMS phase currents, copper losses, and converter losses. Such an assessment

will be performed through experimental implementation in future studies and will clarify the effect of the proposed control strategy on the overall energy conversion efficiency of SRM.

5. Conclusions

This study proposed an LADRC–LAMHRC-based direct instantaneous torque control scheme to improve the speed regulation, disturbance rejection, and torque ripple suppression performance of a switched reluctance motor drive. The proposed strategy combines the disturbance estimation capability of LADRC with the adaptive compensation characteristics of LAMHRC, thereby enhancing torque regulation while preserving accurate speed tracking. Comparative simulation results against the conventional PI-DITC scheme verified the effectiveness of the proposed controller under different operating conditions. At 500 r/min, the electromagnetic torque ripple coefficient was reduced from 11.11% to 2.96%, corresponding to a reduction of approximately 73.4%. At 1000 r/min, and the torque ripple decreased from 11.76% to 2.55%, representing an improvement of approximately 78.3%. Moreover, when the load increased from 5 to 7 N·m, the maximum speed fluctuation was reduced by 88.9%, whereas an 80.0% reduction was achieved when the load decreased from 7 to 5 N·m. These results demonstrate that the LADRC–LAMHRC scheme provides superior torque ripple attenuation, stronger load disturbance rejection, and improved speed regulation compared with the conventional PI-DITC method. These findings are limited to the investigated simulation conditions and the adopted linear and unsaturated SRM models. Experimental, hardware-in-the-loop, and nonlinear magnetic model validations will be considered in future studies.

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Abbreviations

The following abbreviations are used in this manuscript:

SRM	Switched Reluctance Motor
LADRC	Linear Active Disturbance Rejection Control
RC	Repetitive Control
PI	Proportional–Integral
DITC	Direct Instantaneous Torque Control
MPC	Model Predictive Control
SMC	Sliding Mode Control
TSF	Torque Sharing Function

LPF	Low-Pass Filter
LAMHRC	Load Adaptive Multi-harmonic Repetitive Control
AHBC	Asymmetric Half-Bridge Converter
LESO	Linear Extended State Observer

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