RESEARCH ARTICLE

Design and Terminal Sliding Mode Control of Double Stator Bearingless Switched Reluctance Motor

NING HAN1, CHUANYU SUN2, AND HONGCHANG DING1

1 College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China
2 School of Automation and Electrical Engineering, Linyi University, Linyi 276005, China

Corresponding author: Chuanyu Sun (13708983820@163.com)

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ABSTRACT This paper proposes an 18/15/8-pole bearingless switched reluctance motor (BSRM) with good decoupling performance, which optimizes the distance and number of teeth between the inner and outer stator and rotor, reduces the hysteresis force existing during phase change, improves the electromagnetic conversion efficiency, and reduces the interference of forces between torque and levitation. A three-layer rotor structure is used to design the magnetic separation frame, which eliminates the interference of magnetic lines between the torque system and the suspension system. The direct control idea is applied to control the torque and levitation forces. A new reaching law (RL) is proposed, and a torque sliding mode controller and a suspension force sliding mode controller are designed, which replace the traditional terminal sliding mode control and PID control, and improve the robustness of the control system and dynamic response. Ansoft Maxwell 2D software is used to perform electromagnetic analysis to verify the decoupling, and the control simulation model is established by MATLAB/Simulink simulation analysis, and the results are compared with the traditional controller method. The results show that the proposed control system effectively improves the dynamic response speed and robustness of the system, and verifies the effectiveness and superiority of the proposed control method.

INDEX TERMS Bearingless switched reluctance motor, motor, control system, SMC.

I. INTRODUCTION

The bearingless switched reluctance motor (BSRM) concept was first proposed by academics in 1989 and is based on the “principle of minimum reluctance” operation [1], [2], [3]. By applying the magnetic levitation technology to the switched reluctance motor (SRM), the problems of relatively serious heating and low service life of the rotor friction in the high-speed rotation of the traditional switched reluctance motor are effectively solved [4]. Improve the critical speed and service life of the motor. At the same time, it inherits the high reliability and excellent speed regulation performance of the SRM, which has been a research hotspot in the motor field in the past two decades. It can be promoted in many practical industrial fields such as flywheel energy storage systems, electric vehicles, aerospace, etc [1], [5].

However, the traditional BSRM has the problem of coupling torque control and suspension control. To solve these problems, scholars in various countries have mainly conducted a lot of research on structure and control algorithms. At present, there are four types of structural decoupling: mixed stator tooth structure [6], wide rotor tooth structure [7], double stator structure [8], and composite rotor structure [9]. The basic principle of structural decoupling is to separate the magnetic circuit and space of suspension control and torque control, reduce the interference between each other, realize decoupling with space, and be easier to control. For torque control methods, there are mainly current square wave control
and direct torque control. For example, in literature [10], [11], the current chopper control is used to directly adjust the winding current through the current hysteresis loop controller to generate and adjust the required torque. However, the current square wave control requires a cumbersome current calculation process, and the torque control results fluctuate greatly. In literature [12], [13], [14], the direct torque control directly tracks the given torque value, thereby inhibiting the torque and suspension force pulsation, eliminating the current tracking control. The direct control method does not depend on the accurate mathematical model, and has good robustness, avoiding the complex coordinate transformation caused by the selection of stator flux linkage. In addition, to further improve the system control, a signal control method can be introduced. For example, literature [8] used the torque distribution function (TSF) to reduce the torque ripple according to the phase division of the reference torque, but because the PID control cannot achieve the precise tracking of the torque signal, the TSF cannot allocate the torque well, resulting in torque ripple. DSBSRM rotor radial suspension control strategy research is less, rotor suspension control system usually in closed-loop radial displacement control using PID controller to produce a given radial suspension force value. In the torque and suspension control, although the PID controller has a simple structure and reliable operation, it is affected by the motor parameters and has poor anti interference ability, which makes the signal tracking ability have large errors and makes the TSF unable to accurately allocate the torque. The suspension force control is established without rotor eccentricity. The rotor will be eccentric in the actual operation, and the motor model is not accurate. Sliding mode control (SMC), model predictive control, adaptive control, robust control, and other control techniques can be used to reduce the impact of interference. Since SMC is not sensitive to interference and parameter changes, SMC is superior to PID control in robustness and anti-interference [15], [16], [17]. The Terminal sliding mode control (TSMC) strategy introduces a nonlinear function, which can make the system state achieve complete tracking of the desired state within the specified effective time based on ensuring the stability of the sliding film [18]. SMC can also combine the idea of reaching law (RL) [19] to improve the dynamic quality of the sliding mode arrival process, but the existing RL has the contradiction between the arrival speed and the reduction of chattering.

Based on the medical application of BSRM and the summary of existing research, this paper proposes an 18/15/8 pole BSRM with excellent comprehensive performance and good decoupling performance. Compared with the traditional BSRM, the motor has two stators, a torque stator, and a suspension stator, with the optimized stator and rotor tooth number, and has a permanent magnet and excitation combined suspension force output system. Firstly, the structure and working principle are introduced, and then the decoupling analysis is verified. In terms of control, due to the high requirements for reliability and accuracy, the direct control method is adopted. Based on the fast TSMC idea [20], the sliding mode controllers are designed for torque and suspension control respectively to replace the original PID control to improve the tracking ability of the control signal and improve the dynamic response-ability. A new RL combining exponential RL and power RL is introduced in fast TSMC to improve the arrival speed and reduce chattering. At the same time, the torque control is divided into inherent torque and disturbance torque in the torque sliding mode controller, and the non-singular TSMC [21] is used to accurately control the disturbance torque to suppress its chattering. In suspension control, when the rotor is eccentric, permanent magnet and excitation will occur permanent magnet and electromagnetic conversion, and the instability of the system increases. Double hysteresis control is introduced based on TSMC control. Finally, the control simulation model is established through MATLAB/Simulink simulation analysis to verify the effectiveness and superiority of the proposed NRLTSMC torque controller and NRLTSMC suspension controller.

II. MOTOR STRUCTURE

A. STRUCTURE AND OPERATION PRINCIPLE OF MOTOR

As shown in Fig.1, the structure, winding mode, and phase division of 18/15/8-pole DSBSRM are shown. The motor is composed of the external stator, rotor, spacer ring, suspension rotor ring, and internal stator. The winding of the coil adopts a single winding mode. 18 pole outer stator is divided into three phases, such as A1+ and A1-, A2+ and A2-, A3+ and A3- constitute a pair of magnetic poles, and then three pairs of magnetic poles constitute A phase, B phase, and C phase constitute the same. The rotor is divided into a torque rotor and a suspension rotor ring, which is connected by the magnetic isolation ring made of magnetic isolation material. The inner stator is 8 poles, and the inner stator teeth are alternately distributed by permanent magnet and excitation, forming a four-phase excitation phase of M1, M2, M3, M4 and a four-phase permanent magnet phase of N1, N2, N3, N4.

The operation principle of the motor is shown in Fig.2. When a phase is connected, the force magnetic line generated by the torque winding will enter the adjacent torque tooth, forming a closed-loop of ‘stator tooth-air gap-torque tooth-air gap-stator tooth’. According to the ‘minimum reluctance principle’, the counterclockwise torque is generated. The
The suspension system adopts differential control of permanent magnet and excitation. When the rotor is in an ideal position, the electromagnetic winding stops working, and the bias magnetic field of the permanent magnet is evenly distributed on the inner stator and ring core to maintain the rotor stability. When the rotor is offset, the corresponding electromagnetic winding is electrified, and the magnetic line is generated in a specific direction, which is superimposed or offset with the magnetic line of the permanent magnet bias magnetic field, to cause the magnetic flux change in the specified direction, resulting in a specific suspension force to control the rotor displacement.

### B. DECOUPLING PERFORMANCE

The motor rotor has good decoupling performance by using a magnetic isolation ring to separate the torque system and suspension system. Maxwell 2D software is used to establish a 2D simulation model for decoupling analysis [22], [23]. The motor parameters are shown in Table 1 below.

![Magnetic density distribution](image)

**FIGURE 3.** Magnetic density distribution.

**TABLE 1.** 18/15/8-pole DSBSRM specific parameters.

| Parameters                                      | 18/15/8 DSBSRM |
|------------------------------------------------|----------------|
| The outer diameter of the outer stator          | 80mm           |
| The internal diameter of the external stator    | 52mm           |
| Rotor cooling diameter                          | 51mm           |
| The inner diameter of the rotor                 | 24mm           |
| Torque tooth height                             | 9mm            |
| The outer diameter of the inner stator          | 23mm           |
| The inner diameter of the inner stator          | 8mm            |
| The thickness of the external stator yoke       | 5mm            |
| Ring core thickness                             | 4mm            |
| Airgap thickness                                | 0.5mm          |
| The axial length of the motor                   | 100mm          |
| Torque tooth pole arc                           | 8°             |
| External stator tooth pole arc                  | 8°             |
| Internal stator tooth pole arc                  | 15°            |
| Length of the magnetization direction of permanent magnet | 2mm         |
| Torque winding turns                            | 100            |

Fig. 3 shows the magnetic density diagram when the currents of the torque winding A phase and the suspension winding four phases are both 3A. We can see that both the torque system and the suspension system form a separate closed loop. The magnetic lines are evenly distributed on the rotor and stator, and there is no interference between the magnetic densities. Therefore, the suspension system and the torque system are not affected in terms of magnetic flux. The three pairs of winding of one-phase torque winding are symmetrically distributed in the center, and the axial force generated by them offset each other does not affect the suspension force. Moreover, the magnetic flux generated by the levitation system does not generate torque on the rotor ring, so the levitation system does not affect the torque system when operating. In conclusion, the torque system and suspension system have good decoupling performance, which provides the basis for independent control of the torque system and suspension system.

### III. DESIGN OF SLIDING MODE CONTROLLER

#### A. DESIGN OF NEW SLIDING MODE REACHING LAW (NRL)

Sliding mode motion includes two processes: reaching motion and sliding mode motion. The system tends to the switching surface from any initial state until the motion reaching the switching surface is called approaching motion, which is a process of $s \rightarrow 0$. According to the principle of sliding mode variable structure, the reach ability condition of sliding mode only ensures that any motion point in the state space reaches the switching surface in a finite time, and there is no restriction on the specific trajectory of reaching motion [19]. The reaching law method can improve the dynamic quality of reaching motion. The traditional exponential RL is designed as follows [3]:

$$\frac{ds}{dt} = -\lambda_1 \text{sgn}(s) - \lambda_2 s, \lambda_1 > 0, \lambda_2 > 0$$

(1)

where: $s$ is the sliding mode plane, $\lambda_1$ and $\lambda_2$ are the switching gain and linear gain, respectively. $\lambda_1 \text{sgn}(s)$ is the
constant-speed approximation term, and $\lambda_2s$ is the pure exponential approximation term. The increase of parameter $\lambda_2$ increases the arrival speed and sliding chattering. The contradiction between increased arrival speeds and reduced sliding jitters is inevitable. Therefore, the traditional exponential reaching law is improved by referring to the power reaching law and quasi-sliding mode to ensure that the chattering is reduced while the arrival speed increases.

1) Combining the idea of power convergence law, $|s|^{\alpha}$ and $|s|^{\alpha^2}$ are introduced in the isokinetic and exponential terms, where 0 $< \alpha < 1$, 0 $< \alpha^2 < 1$, then before reaching the sliding mode motion $|s|^{\alpha} > 1, |s|^{\alpha^2} > 1$, then we have $(\lambda_1 sgn (s) + \lambda_2 s) < (\lambda_1 |s|^{\alpha} sgn (s) + \lambda_2 |s|^{\alpha^2} s)$, when reaching the sliding mode motion state then $|s|^{\alpha} < 1, |s|^{\alpha^2} < 1$, then we have $(\lambda_1 sgn (s) + \lambda_2 s) > (\lambda_1 |s|^{\alpha} sgn (s) + \lambda_2 |s|^{\alpha^2} s)$. A higher arrival speed with a lower jitter can be guaranteed.

2) Based on the idea of quasi-sliding mode, a new saturation function $f(s)$ is designed to replace the signal function $sgn(s)$ to reduce the chattering caused by the signal delay and the inherent inertia of the system. The design requirements of $f(s)$ are as follows:

$$f(s) \text{ is odd}$$
$$f(s) = 1 \text{or } s \in \mathbb{R} \text{ if } f(s) = 1$$

where, the smooth sigmoid $(s)$ are used to replace the signal function $sgn(s)$, and the sigmoid $(s)$ trajectory converges to the set around the equilibrium point, which is more in line with the actual control application.

$$\text{sigmoid}(s) = \frac{2}{1 + e^{-cs}} - 1, \quad c > 0$$

Since $s \in \mathbb{R}$, $-1 < \text{sigmoid}(s) < 1$, to ensure the speed of arrival, the piecewise function $f(s)$ is introduced to combine sigmoid $(s)$ with $sgn(s)$:

$$F(s) = \begin{cases} 
\text{sgn}(s), & |s| > \sigma \\
\text{sigmoid}(s), & |s| < \sigma 
\end{cases}$$

The following figure is the function image of $F(s)$ and $sgn(s)$:

The NRL obtained is:

$$ds/dt = -\lambda_1 |s|^{\alpha} F(s) - \lambda_2 |s|^{\alpha^2} s, \quad \lambda_1 > 0, \lambda_2 > 0$$

To verify whether the proposed NRL can converge to a stable state in finite time and verify its stability, we choose the Lyapunov equation $\dot{V} = s \cdot \dot{s} \leq 0$.

Then:

$$\dot{V} = \begin{cases} 
-\lambda_1 |s|^{\alpha} \text{sgn}(s) \cdot s - \lambda_2 |s|^{\alpha^2} s^2, & |s| > \sigma \\
-\lambda_1 |s|^{\alpha} \text{sigmoid}(s) \cdot s - \lambda_2 |s|^{\alpha^2} s^2, & |s| < \sigma 
\end{cases} \leq 0$$

where $\lambda_1$ and $\lambda_2$ are both positive, $\text{sgn}(s) \cdot s$, sigmoid $(s) \cdot s$, and $s^2$ are non-negative, so the above equation holds. Therefore, the proposed NRL is asymptotically stable under the Lyapunov equation, which proves that the proposed NRL holds [27].

**B. NRL-BASED TSMC DESIGN FOR TORQUE AND SUSPENSION**

According to the dynamic principle, the motor torque balance equation of DSSBSRM is:

$$\frac{d\omega}{dt} = \frac{T_e}{J} - \frac{B \cdot \omega}{J} - r$$

where $J$ is the rotational inertia, $B$ is the friction coefficient, $T_e$ is the electromagnetic torque, and $r$ is the sum of disturbances.

$$r = \Delta a \cdot \omega + \Delta b \cdot T_e + T_L$$

where: $T_L$ is the load torque, and $\Delta a$ and $\Delta b$ are the internal disturbance parameters.

Taking the reference torque $T_e = T_{e1} + T_{e2}$, $T_{e1}$ is the inherent torque without considering the load and internal interference, and $T_{e2}$ is the interference torque caused by internal and external interference. The solution of $T_{e1}$ is as follows:

Taking the speed tracking error $e_w$ as the difference between the reference torque $w^*$ and the actual torque $w$:

$$e_w = w^* - w$$

First, the sliding mode plane $s_w$ is designed:

$$s_w = e_w = w^* - w$$

When the error enters the fast Terminal sliding mode, there is:

$$s_1 = s_w + \mu s_w Q^P = 0$$

where: $\mu > 0$, Q and P are positive odd numbers.

Then from formulas (9), (11), and (12):

$$s = w^* \frac{T_{e1} - B \cdot \dot{\omega}}{J} + \mu s_w Q^P = 0$$

So, the expression of the $T_{e1}$ function is:

$$T_{e1} = J w^* + B w^* - B s_w + J \mu s_w Q^P$$

Take the error $\varrho$:

$$\varrho = e_w - \left( w^* - \int \frac{T_{e1}}{J} - \frac{B \cdot \omega}{J} \right) dt$$

Combined with the above equation, there is:

$$\dot{\varrho} = \frac{w^* T_{e1} + T_{e2} - B \cdot \omega}{J} - r - w^* + \frac{T_{e1}}{J} - \frac{B \cdot \omega}{J}$$

Derivation from (16)

$$\varrho = -\frac{T_{e2}}{J} - \dot{\varrho}$$

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To improve the response speed of internal and external interference and eliminate the singular problem in the solving process, the nonsingular fast Terminal sliding mode is selected:

$$z = \beta + \beta \dot{q}^{p/q} = 0$$  \hspace{1cm} (18)

where $\beta > 0$, $0 < p/q < 1$, and $p$ and $q$ represent positive odd numbers, respectively.

On the above derivation:

$$\dot{z} = \dot{\beta} + \dot{\beta} \dot{q}^{p/q-1} \cdot \ddot{q}$$  \hspace{1cm} (19)

Introductory (5) NRL has

$$\dot{z} = -\lambda_{21} |q|^a F(z) - \lambda_{22} |q|^2 z$$  \hspace{1cm} (20)

In conjunction (8), (19) and (20):

$$\dot{\sigma} + \beta \dot{q}^{p/q-1} \cdot \ddot{q} = -\lambda_{11} |q|^a F(z) - \lambda_{12} |q|^2 z + \ddot{x}$$  \hspace{1cm} (21)

Then:

$$T_{e2} = J \cdot \frac{q}{\beta p} \cdot \dot{q}^{(q-p)/q} \left( \lambda_{11} |q|^a F(z) + \lambda_{12} |q|^2 z + \ddot{x} \right)$$  \hspace{1cm} (22)

Then:

$$\dot{x} = \int J \cdot \frac{q}{\beta p} \cdot \dot{q}^{(q-p)/q} \left( \lambda_{11} |q|^a F(z) + \lambda_{12} |q|^2 z + \ddot{x} \right)$$  \hspace{1cm} (23)

So, the reference torque $T_e$ is:

$$T_e = T_{e1} + T_{e2} = J\ddot{x} + B\dot{x} - B\dot{s}_w + J\mu s_w^{QP} + \int J \cdot \frac{q}{\beta p} \cdot \dot{q}^{(q-p)/q} \left( \lambda_{11} |q|^a F(z) + \lambda_{12} |q|^2 z + \ddot{x} \right)$$  \hspace{1cm} (24)

Then, the torque NRL-TSMC simulation block diagram obtained by combining (24) with MATLAB/Simulink simulation is shown in Fig. 5:

According to the dynamic principle, the motor suspension balance equation of DSSBSRM is:

$$F = m \ddot{x} - R$$  \hspace{1cm} (25)

where: $F$ is suspension force, $m$ is rotor mass, $m$ is the sum of disturbances, and $x$ is rotor displacement.

Taking the rotor displacement tracking error $e_x$ as the difference between the reference displacement $x^*$ and the actual displacement $x$:

$$e_x = x^* - x$$  \hspace{1cm} (26)

First design the sliding mode plane $s_x$:

$$s_x = e_x = x^* - x$$  \hspace{1cm} (27)

When the error enters the fast Terminal sliding mode, there is:

$$s_2 = s_x + \xi s_x^{q/p} = 0$$  \hspace{1cm} (28)

According to (5), NRL in the suspension controller can be expressed as:

$$\dot{s}_2 = -\lambda_{21} |s_x|^a F(s_2) - \lambda_{22} |s_x|^2 s_2$$  \hspace{1cm} (29)

Then the combination (25), (28), and (29) can be obtained:

$$\dot{s}_2 = -\lambda_{21} |s_x|^a F(s_2) - \lambda_{22} s_2 = x^* \frac{F + R}{m} + \frac{\xi}{\beta} s_x^{q/p} \cdot \dot{s}_x$$  \hspace{1cm} (30)

Then:

$$F = m \left( \ddot{x} + \xi s_x^{q/p} \cdot \dot{s}_x + \lambda_{21} |s_x|^a F(s_2) + \lambda_{22} |s_x|^2 s_2 \right) - R$$  \hspace{1cm} (31)

Then combined with (31) in MATLAB/Simulink simulation of suspended NRL-TSMC simulation block diagram is shown in Fig.6 below:

**IV. CHARACTERISTIC ANALYSIS AND MODEL VALIDATION**

For the 18/15/8 pole DSBSRM control method, the torque system and the suspension system are independently controlled by the analysis in Section 2.2. For torque control, double closed-loop direct instantaneous torque control based on a Terminal sliding mode controller is adopted. The outer
loop is the speed control loop, and the inner loop is the torque control loop. The reference torque $T_r$ is output by the Terminal sliding mode controller, and then the reference torque of each phase is reasonably distributed according to the set opening angle, overlap angle, and turn-off angle by using the chord torque distribution function (TSF) so that the motor runs smoothly in commutation. The excellent tracking ability of the sliding mode controller can better suppress the torque fluctuation. In this paper, the motor string torque distribution formula (32) and the torque phase distribution diagram are as follows:

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

(32)

where $\theta$ is the rotor position angle, $\theta_{on}$ and $\theta_{off}$ are the phase turn-on angle and turn-off angle, and $\theta_{ov}$ is the phase current commutation overlap angle.

Then the reference torque of each phase is different from the actual torque, and the hysteresis controller controls the power converter to control the opening and closing of each phase of the motor to realize the stable operation of the motor torque.

For the suspension system control, the direct instantaneous suspension force control based on the Terminal sliding mode controller is adopted. The double closed-loop control is adopted with the outer loop as the displacement and the inner loop as the suspension force. The displacement difference is used as the input value of the sliding mode controller to obtain the reference suspension force as the output value. Then, the reference suspension force and the actual suspension force are used as the difference to control the power converter through the double hysteresis controller, control the opening and closing of each phase of the suspension force and realize the displacement control of the rotor. Fig.8 is the schematic diagram of the double hysteresis controller. Taking the suspension force in the x-axis direction as an example, $F_{re}$ is the reference value of suspension force, $F$ is the actual value of suspension force, the error $\Delta F$ of the two is the input, $\varepsilon_{min}$, and $\varepsilon_{max}$ are the limits of internal and external hysteresis control respectively, and $S(A)$ is the switching signal of suspension winding. The suspension system uses the combination strategy of permanent magnet bias and control winding, so the decoupling effect of the x-axis and y-axis is also very good. The eccentricity control of the x-axis and y-axis can become two independent control systems. However, when the x-axis is eccentric, the permanent magnet and electromagnetic are transformed, and the instability of the system is also increased. Therefore, the direct instantaneous suspension force control using a double hysteresis controller is adopted.

Combined with the above analysis, based on MATLAB/Simulink simulation analysis. Build 18/15/8 pole DSBSRM control simulation model, as shown in Fig.9.
V. SIMULATION ANALYSIS

To verify whether the above control method can achieve the design control effect, the simulation experiment is carried out based on MATLAB/Simulink platform, and the 18/15/8 pole DSBSRM control simulation model is established.

For the simulation of motor torque control, to highlight the advantages of NRLTSMC control, the traditional PID direct torque control and the direct torque control of SMC with conventional exponential RL are used as the simulation experimental control group. Take ideal reference speed $n^*$ and torque load $T_L$ as experimental variables, and other independent variables are preliminarily set, and the opening angle $\theta_{on}$ is set to 0.5°; the overlap angle $\theta_{ov}$ is set to 3°; the turn-off angle $\theta_{off}$ is set to 9°. The proportional and integral parameters in the PID controller are set to 2.18 and 0.52, respectively, and those in the NRLTSMC are set to $\mu = 482$, $Q = 27$, $P = 29$, $\alpha_1 = 0.42$, $\alpha_2 = 0.63$, $\lambda_{11} = 48$, $\lambda_{12} = 2$, $\beta = 10$, $q = 11$, $p = 13$.

Fig.10, Fig.11, and Fig.12 are the curves of speed and torque controlled by three controllers when the load is $0\,N\cdot m$, $2\,N\cdot m$, $4\,N\cdot m$, and the reference speed is from 1500r/min to 1800r/min. The mark red thickening part in the diagram is the speed rising stage. We can see from the rough view that the dynamic response-ability of SMC is significantly better than that of PID under three load conditions, while the dynamic response-ability of NRLTSMC is better than that of SMC, whether in the start-up stage or the reference speed change. In torque ripple suppression, NRLTSMC also showed a smaller torque ripple. When the load is $4\,N\cdot m$, the PID control cannot meet the control requirements, and the actual control speed cannot reach the reference speed. To accurately analyze the data, the data in Fig.10, Fig.11, and Fig.12 are quantitatively analyzed and arranged as follows:

To quantitatively analyze the torque, the total torque data is measured by (33), and $P$ is the torque ripple rate.

$$ P = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{ave}}} $$ (33)
According to the data analysis. When the reference speed is 1500 n/min. At a no-load, the NRLTSMC control arrives at a stabilization time reduced by 0.00401 s compared to SMC, 0.01513 s compared to PID, and torque pulsation reduced by 0.12 and 0.52 compared to SMC and PID, respectively. At a load of 2 N.m, the NRLTSMC control arrives at a stabilization time reduced by 0.00373 s compared to SMC, and 0.03358 s compared to PID. At a load of 4 N.m, the NRLTSMC control reduced the stabilization time by 0.00375 s and the torque pulsation by 0.004 compared to the SMC. When the reference speed is 1800 n/min. At a no-load, the NRLTSMC control reaches stability in 0.0027 s less than SMC, 0.0044 s less than PID, and torque pulsation is 0.35 and 0.49 less than SMC and PID, respectively. At a load of 4 N.m, the NRLTSMC control reduced the stabilization time by 0.0029 s and the torque pulsation by 0.005 compared to the SMC. We can see that the torque ripple under NRLTSMC control is significantly reduced, and the speed acceleration is significantly improved, which proves the effectiveness of the NRLTSMC controller. In this paper, NRLTSMC control has a better torque ripple suppression effect and dynamic response ability than SMC and PI control methods.

For radial displacement suspension control, according to [8], the x-axis and y-axis directions of suspension structure have good decoupling. Therefore, the y-axis direction is selected for the simulation experiment. To highlight the superiority of NRL design, the direct suspension force control of the SMC controller with traditional exponential RL is used as the control group. In the simulation process, the parameters are set as \( \lambda_1 = 2, \lambda_2 = 48, q = 5, p = 9, \xi = 3, \alpha = 0.41, \alpha_2 = 0.71 \). Moreover, the disturbance is relatively fixed in the suspension force control, so the external disturbance \( F_L \) is set to a constant value. In the control, the initial reference displacement is set to 0, the deviation of \(-0.15 \) mm is given at 0 s, the deviation of 0.5 mm is added at 0.2 s,

where: \( T_{\text{max}}, T_{\text{min}}, \) and \( T_{\text{ave}} \) are the maximum, minimum, and average resultant torque in the sampling interval.

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For radial displacement suspension control, according to [8], the x-axis and y-axis directions of suspension structure have good decoupling. Therefore, the y-axis direction is selected for the simulation experiment. To highlight the superiority of NRL design, the direct suspension force control of the SMC controller with traditional exponential RL is used as the control group. In the simulation process, the parameters are set as \( \lambda_1 = 2, \lambda_2 = 48, q = 5, p = 9, \xi = 3, \alpha = 0.41, \alpha_2 = 0.71 \). Moreover, the disturbance is relatively fixed in the suspension force control, so the external disturbance \( F_L \) is set to a constant value. In the control, the initial reference displacement is set to 0, the deviation of \(-0.15 \) mm is given at 0 s, the deviation of 0.5 mm is added at 0.2 s,

where: \( T_{\text{max}}, T_{\text{min}}, \) and \( T_{\text{ave}} \) are the maximum, minimum, and average resultant torque in the sampling interval.

According to the data analysis. When the reference speed is 1500 n/min. At a no-load, the NRLTSMC control arrives at a stabilization time reduced by 0.00401 s compared to SMC, 0.01513 s compared to PID, and torque pulsation reduced by 0.12 and 0.52 compared to SMC and PID, respectively. At a load of 2 N.m, the NRLTSMC control arrives at a stabilization time reduced by 0.00373 s compared to SMC, and 0.03358 s compared to PID. At a load of 4 N.m, the NRLTSMC control reduced the stabilization time by 0.00375 s and the torque pulsation by 0.004 compared to the SMC. When the reference speed is 1800 n/min. At a no-load, the NRLTSMC control reaches stability in 0.0027 s less than SMC, 0.0044 s less than PID, and torque pulsation is 0.35 and 0.49 less than SMC and PID, respectively. At a load of 4 N.m, the NRLTSMC control reduced the stabilization time by 0.0029 s and the torque pulsation by 0.005 compared to the SMC. We can see that the torque ripple under NRLTSMC control is significantly reduced, and the speed acceleration is significantly improved, which proves the effectiveness of the NRLTSMC controller. In this paper, NRLTSMC control has a better torque ripple suppression effect and dynamic response ability than SMC and PI control methods.

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The radial displacement response speed under NRLTSMC control is better than that under CRLSMC control. At 0s, the time to steady state was 0.0115s under NRLTSMC control and 0.016s under CRLTSMC control. At 2s, the time to steady state was 0.0075 s under NRLTSMC control and 0.0115 s under CRLTSMC control. From the above, we can see that the radial displacement control of the NRLTSMC controller has a better dynamic response than CRLSMC control, which can quickly suppress radial displacement pulsation.

VI. CONCLUSION

In this paper, a new 18/15/8-pole DSBSRM is designed to introduce its working principle and decoupling performance. By optimizing the distribution and number of stator and rotor tooth poles, the hysteresis force existing during the commutation of the electromagnetic poles is effectively reduced, and the electromagnetic conversion efficiency is significantly improved. And on the basis of the new structure, the hybrid excitation mode is adopted. Through the integrated work of permanent magnet and excitation, it not only improves the anti-interference performance of the rotor under ideal working conditions, but also enhances the suspension force output capacity. The structure is optimized for the coupling problem of torque and radial levitation force control that exists in conventional BSRM. Due to good decoupling performance, motor torque control and suspension control are independently controlled. Subsequently, the TSMC torque controller and suspension controller of the new RL is designed. The torque of the controller is divided into inherent torque and disturbance torque. The disturbance torque is precisely controlled by nonsingular TSMC and NRL to suppress torque disturbance. Combined with TSF direct instantaneous torque control. The radial suspension control combines the TSMC controller with double hysteresis control to reduce the disturbance between the permanent magnet and the excitation during eccentricity. Then simulation verification is carried out. The direct instantaneous torque control with traditional SMC and PID controller is used as the control group, and the direct suspension force of SMC with CRL is used as the control group. The results show that the motor structure can decouple torque and levitation force, and the new RL TSMC torque controller can effectively reduce the torque ripple and speed jitter to improve the speed dynamic response-ability. The TMC suspension force controller with the new RL has a better dynamic response to ensure the radial stability of the rotor.

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FIGURE 13. Rotor displacement waveform. (a) CRLSMC (b) NRLTSMC.
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