Research Article

Linearized Fraction Order Control and Stability Analyses for Switched Reluctance Motor Drives

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The nonlinearity and double salient pole of the switched reluctance motor make the control difficult and the torque fluctuation is large. To achieve good control performance, this study introduces a novel linearized fractional-order controller with the disturbance observer to regulate the speed and torque of a switched reluctance motor. Based on fractional differential calculus theory, the fractional-order proportional integral controller is designed. The disturbance observer is introduced to overcome the influence of nonlinearity on the switched reluctance motor and reduce the torque fluctuation. By using the extended state in the disturbance observer, the disturbances are estimated and compensated to achieve linearization and determinism. The parameter values of the proposed controller are obtained by employing the trial-and-error method. The frequency-domain analysis of the proposed controller shows that it has a good suppression performance for medium- and high-frequency disturbances. Through simulation, the performance of the system is analyzed. The results show good performance of the controller in speed change, current, and torque fluctuation reduction.

1. Introduction

With the popularization of electric vehicles, the application of switched reluctance motor (SRM) in electric vehicles has attracted increasing attention in recent years. Electric motor, that is, the core energy conversion unit, is one of the key technologies of electric vehicles [1, 2]. To improve the power conversion efficiency, the electric motor has to satisfy specific performance and efficiency requirements [3]. SRM is one of the possible solutions because of its numerous advantages, such as the inherent simple structure, ruggedness, low cost, easy cooling, high torque density, and high speed operation [4, 5]. SRMs have no permanent magnets [6, 7]. However, the high noise, difficulty in controlling, and torque ripple prevent the SRM from applying in a large extent [8].

To improve the characteristics and operating performance of SRM, the research is mainly carried out on the motor structure design and control strategy in recent years [9–11]. Because of its simplicity and ease of implementation, the proportional, integral, and/or derivative control has been applied widely in the field of engineering. Due to the double salient pole structure of SRM, the stator current is not smooth and discontinuous; the nonlinearity and uncertain parameters of the SRM make it difficult for conventional controllers to obtain the good performance. In [12], the robust controller is used for speed control and output torque command. A look-up table is used to determine the phase current reference value. This table considers the linear equivalent mechanical properties. In [13], the fuzzy control strategy is presented, the inputs of which are the current power error and the variation of error. The output variable is the switching angle. It tries to overcome the influence of nonlinearity through a reasonable combination of fuzzy rules. In [14], the linearized models are established for saturated and unsaturated conditions, which are used to control the motor combined with PI controller and back-EMF compensation as disturbance. For overcoming motor parameter uncertainty and noise interference, a model predictive controller and Kalman model adjusted by the adaptive regulator are designed for current control of SRM drives to improve the control performance [15]. For fast
response and insensitivity to noise, a digital PWM current controller is used for the SRM, which adopts the model information, small feedback gain, and parameter adaption to reduce the noise sensibility [16]. In [17], an adaptive terminal sliding mode control is used to the torque control of SRM to suppress torque ripple. This control method with a designed reaching law has good torque ripple suppression. In [18], an adaptive fuzzy control strategy is used and is used for speed adjustment of linear SRM. In terms of reducing torque fluctuation, the direct torque control and direct force control are proposed to regulate the rotor radial position in real time to reduce the torque ripple of SRM [19], and the current and flux linkage-sharing method are designed to reduce the torque ripple of SRM [20]. In [21], a hybrid many-optimizing liaison gravitational search algorithm based on the optimizing liaison and gravitational search algorithm is proposed to adaptively adjust the parameters of speed and current PI controllers to reduce torque ripple. The global optimum is uncertain. In [22], a discrete time model and multiobjective cost function are designed to predict the state of the system to reduce the torque ripple. In [23], a direct instantaneous torque control strategy based on a fractional-order proportion integration differentiation controller is proposed to reduce the torque ripple of the system and improve the dynamic performance. In [24], the vector proportional integral control and the modular open-winding converter are designed to generate sinusoidal current to reduce the torque ripple and motor vibration. It requires the cooperation of hardware and software. Li et al. [25] reduce the torque ripple by establishing an off-line torque-sharing function, but it is necessary to obtain the static flux linkage characteristics in advance. In [26], to overcome the nonlinear driving characteristics of SRM drives, a linearizer is integrated into the controller to compensate the nonlinearity. Active control approaches and feedback control can also be introduced into SRM control [27, 28].

SRM winding inductance changes with current and rotor position, which makes it difficult for conventional PI control to meet the operating conditions of the motor. In this study, a fractional-order PI$^\lambda$ controller with a disturbance observer is proposed for the SRM drives. $\lambda$ is an adjustable parameter, which helps to getting a large phase angle allowance design for the SRM drives design. To deal with the uncertainty of internal parameters and nonlinearity of the system, the disturbance observer is used to estimate the disturbances and compensate it from the output of the fractional-order PI$^\lambda$ controller. This study is organized as follows. Section 2 introduces the mathematical model of the SRM. Section 3 presents the control structure design procedure of the proposed speed controller. Section 4 demonstrates the validation results and comparisons with the PI control and the fractional-order control methods. Finally, conclusions are given in Section 5.

2. Mathematical Model of the SRM Drives

SRM is a double salient pole synchronous motor with no windings or permanent magnet on the rotor. The electromagnetic torque is generated by the push-pull reluctance force.

The relation between the phase voltage ($U_k$), the phase current ($i_k$), and the flux linkage ($\Psi_k$) for the $k^{th}$ phase SRM is expressed as [29]

$$U_k = R_k i_k + \frac{d\Psi_k}{dt}, \quad (1)$$

where $R_k$ is the resistance of the $k^{th}$ phase stator winding. The mathematical equation of the motor flux linkage $\Psi_k$ is expressed as

$$\Psi_k = L_k(i_k, \theta) \cdot i_k, \quad (2)$$

where $L_k(i_k, \theta)$ is the self-inductance of the $k^{th}$ phase, $\theta$ is rotor position, and $i_k$ is excitation current. According to (1) and (2), the phase voltage of the $k^{th}$ phase SRM can be denoted as

$$U_k = R_k i_k + \left (L_k + i_k \frac{\partial L_k}{\partial i_k} \right) \frac{di_k}{dt} + i_k \frac{\partial L_k}{\partial \theta} \frac{d\theta}{dt}, \quad (3)$$

The first term in the right-hand side of (3) is the voltage drop of the resistor in the $k^{th}$ phase circuit. The middle term is the induced electromotive force generated by the alteration of the phase current. The last term is related to the energy conversion from electromagnetic energy to mechanical energy.

The electromagnetic torque of the SRM is described as

$$T_e = J \frac{d^2 \theta}{dt^2} + B \frac{d\theta}{dt} + T_i, \quad (4)$$

where $J$, $B$, and $T_i$ are the moment of inertia, coefficient of viscous friction, and load torque, respectively.

3. Linearized Controller Design

In this section, the fractional-order linearized controller for SRM with a disturbance observer is discussed. First, the fractional-order PI$^\lambda$ controller is established. Then, the uncertainty of internal parameters and external disturbance torque are considered through developing the disturbance observer that uses the extended state to observe the uncertainties. Finally, stability of the linearized controller is analyzed.

3.1. Fractional-Order PI$^\lambda$ Control. Fractional-order calculus can be expressed by the calculus operator of fractional-order and integral order [30]:

$$a D_t^\lambda = \begin{cases} \frac{d^\lambda}{dt^\lambda}, & \text{R}(\lambda) > 0, \\ 1, & \text{R}(\lambda) = 0, \\ \int_a^t (dt)^{-\lambda}, & \text{R}(\lambda) < 0, \end{cases} \quad (5)$$

where $a$ is the lower bound of the calculus operator, $t$ is the upper bound of the calculus operator, $\lambda$ is the order number of the calculus operator, and $\text{R}(\lambda)$ represents the real part of
\( \lambda. \) When \( R(\lambda) \) is equal to zero, \( D^\lambda_i \) represents integer-order calculus. \( D^\lambda_i \) indicates fractional differentiation when \( R(\lambda) \) is greater than zero. \( D^\lambda_i \) indicates the fractional integral when \( R(\lambda) \) is less than zero.

The fractional-order PI\(^\lambda \) controller model of SRM drives can be defined as
\[
T^*_e = K_p \cdot \Delta \omega + K_i \cdot D^{-\lambda} \cdot \Delta \omega,
\]
where \( T^*_e \) and \( \Delta \omega \) are the torque reference and speed error, respectively. \( K_p \) and \( K_i \) are the proportional and integral coefficients of the controller, respectively.

### 3.2. The Disturbance Observer.

The speed equation of the SRM is defined as
\[
\int \frac{d\omega}{dt} = T_e - B \omega - T_i,
\]
where \( \omega \) is the angular speed.

In (7), the variation of \( J, B, \) and \( T_i \) influences the speed control performance of SRM. It can be rewritten as
\[
\dot{\omega} = \frac{1}{T_e} \left( T_e - B \omega - T_i \right),
\]
where \( b = 1/J \) and \( x_2 = f(t) = -1/(B\omega + T_i) \).

Based on (9), the second-order nonlinear extended state observer can be constructed, by which the state \( x_1 \) and the extended state \( x_2 \) are observed. In the extended state, nonlinear feedback is used to observe the disturbance terms:
\[
\begin{align*}
\Delta \omega &= \ddot{x}_1 - \omega, \\
\ddot{x}_1 &= \ddot{x}_2 - \beta_1 \Delta \omega + bT_e, \quad \ddot{x}_2 = -\beta_2 \text{fal}(\Delta \omega, \alpha, \delta),
\end{align*}
\]
where \( \ddot{x}_1 \) and \( \ddot{x}_2 \) are the observations of \( x_1 \) and \( x_2 \), respectively. \( \text{fal}(\Delta \omega, \alpha, \delta) \) is a continuous power function with a continuous linear segment near zero. \( \delta \) is the length of the linear segment. \( \beta_1 \) and \( \beta_2 \) are the feedback gain. \( \text{fal}(\Delta \omega, \alpha, \delta) \) can be expressed as
\[
\text{fal}(\Delta \omega, \alpha, \delta) = \begin{cases} 
\left| \Delta \omega \right|^\alpha \cdot \text{sign}(\Delta \omega), & \left| \Delta \omega \right| > \delta, \\
\frac{\Delta \omega}{\delta^{1-\alpha}}, & \left| \Delta \omega \right| \leq \delta.
\end{cases}
\]

The input of SRM drives can be described as \( T^*_e = T_e + f(t)/b \). It can further be written as \( T^*_e = T_e + \ddot{x}_2/b \) according to the expression of observer. Substituting \( T_e \) into the speed (8), the result can be obtained as follows:
\[
\dot{\omega} \approx bT^*_e,
\]

### 3.3. The Construction of the Controller.

The input signals of the observer are the speed of SRM and the torque of the fractional-order PI\(^\lambda \) controller. The observation of speed is taken as the feedback signal. The observations of disturbances are compensated to the output of the fractional-order PI\(^\lambda \) controller. Through compensating the observation of disturbances, the linearization of nonlinear and uncertain objects is realized, and SRM drives are controlled by linear classical control. The structural schematic of the optimized controller is shown in Figure 1.

### 3.4. Stability Analysis of the Controller.

To analyze the stable performance of the system, (10) is rewritten as
\[
\begin{align*}
\Delta \omega &= \ddot{x}_1 - \omega, \\
\ddot{x}_1 &= \ddot{x}_2 - \beta_1 \Delta \omega + bT_e, \quad \ddot{x}_2 = -\beta_2 \chi \Delta \omega,
\end{align*}
\]
where \( \chi = \text{fal}(\cdot)/\Delta \omega \).

Based on (8) and (9) and (13), the expression can be obtained as
\[
\begin{align*}
\dot{\omega} &= bT_e + f(t), \\
\ddot{x}_1 &= \ddot{x}_2 - \beta_1 (\ddot{x}_1 - \omega) + bT_e, \quad \ddot{x}_2 = -\beta_2 \chi (\ddot{x}_1 - \omega),
\end{align*}
\]

From the Laplace transform of (14), the equation can be obtained and expressed as
\[
\begin{align*}
\mathcal{L}[s \omega] &= b \mathcal{L}[\dot{\omega}] + \mathcal{L}[f(t)], \\
\mathcal{L}[s \ddot{x}_1] &= \mathcal{L}[\ddot{x}_2] - \beta_1 (\mathcal{L}[\ddot{x}_1] - \mathcal{L}[W]), \quad \mathcal{L}[s \ddot{x}_2] = -\beta_2 \chi (\mathcal{L}[\ddot{x}_1] - \mathcal{L}[W]),
\end{align*}
\]

The transfer function between the estimation of disturbance \( \ddot{x}_1(s) \) and disturbance \( f(s) \) can be written as
\[
G_{X2F}(s) = \frac{\ddot{x}_2(s)}{F(s)} = \frac{\beta_2 \chi}{s^2 + \beta_1 s + \beta_2 \chi}
\]

The parameters \( \alpha \) and \( \delta \) are set to 0.5 and 0.01 to reduce the calculation time, facilitate practical applications, and prevent nonlinear feedback from degenerating into linear feedback. The function is written as
\[
\chi = \frac{\text{fal}(\Delta \omega, 0.5, 0.01)}{\Delta \omega} = \begin{cases} 
\left| \Delta \omega \right|^{0.5}, & \Delta \omega < -0.01 \text{or} \Delta \omega > 0.01, \\
10, & \left| \Delta \omega \right| \leq 0.01.
\end{cases}
\]

To evaluate the controller’s ability to suppress disturbances and stability through frequency domain analysis, assuming \( \beta_1 = 2 \times 10^4 \) and \( \beta_2 = 6 \times 10^2 \), when \( \chi \) is equal to 0.1, 1, and 10, separately, the magnitude-frequency characteristic curves of (16) are shown in Figure 2. Figure 3 shows the phase frequency characteristic.

The controller adopts an extended state observer composed of the extended state using nonlinear feedback, which has good suppression performance for medium- and high-frequency disturbances. With the increase of \( \chi \), the controller has a smaller phase lag. Therefore, the disturbances
can be estimated in the shortest time and immediately cancelled, which reduces the influence of uncertainty interference on the system and greatly improves the control quality. The low-frequency disturbance suppression ability of the observer is enhanced, which improves the robustness of the control system.

4. Results and Discussion

In this section, the proposed controller is implemented to control the SRM to verify the effectiveness in MATLAB/Simulink software. The 60 kW, 3000 rpm, and three-phase 6/4 SRM model is adopted. The conventional PI controller is utilized to be the current control loop. By comparing the control response curves corresponding to controllers of different orders, the order of fractional integration is selected and set as −0.65. Then, for the ESO, the smaller the α, the smaller the estimation error and the stronger the adaptability of ESO to the uncertainty and disturbance of the system model. α is set as 0.25. δ is the length of the linear segment which is set as 0.01. The parameters of the power function are obtained as follows: \( \beta_1 = 2 \times 10^{-4} \) and \( \beta_2 = 6 \times 10^{-5} \).

The performances between the PI controller, the fractional-order controller, and the proposed controller are compared. As shown in Figure 1, the estimated variable of the disturbance observer is added to the output of the fractional-order controller. To verify the impact of this compensation method on the SRM drives, the speed response and torque response are simulated and analyzed.
The SRM drives start without the load. The speed reference is set as 500 rpm, 1500 rpm, and 3000 rpm, respectively. The load torque changes from zero to 30 N·m starting from 0.1 s under 500 rpm and remains constant in the running operation. The load torque changes from zero to 30 N·m starting from 0.2 s under 1500 rpm and 3000 rpm because the speed rise time becomes longer at start-up.

Figures 4–6 show the response results of the PI controller, the fractional-order PI controller, and the proposed controller, including speed response curves, torque response curves, and phase current curves.

Figure 4 shows that, with the PI controller, the speed fluctuation during a sudden load change is 1.5 rpm, and the speed fluctuation is 0.6 rpm during steady-state operation. Figure 5 shows that, with the fractional-order PI controller, the speed fluctuation during a sudden load change is 1.2 rpm, and the speed fluctuation is 0.3 rpm during steady-state operation. Figure 6 shows that, with the proposed controller, the speed fluctuation during a sudden load change is 1.4 rpm, and the speed fluctuation is 0.5 rpm during steady-state operation. Among them, the...
speed tracking error when using fractional-order PI control is relatively large. The torque fluctuations during steady-state operation are 16.5 N·m, 10 N·m, and 8 N·m, respectively. It can be seen that the speed and torque fluctuation are effectively alleviated with the proposed control method.

Figures 7–12 show the response results of the PI controller, the fractional-order PI controller, and the proposed controller at 1500 rpm and 3000 rpm, respectively. With the increase of rotational speed of the SRM, the proposed control method maintains a good control effect. The effect of the PI controller and the fractional-order controller becomes worse. At 3000 rpm, the rotational speed and torque fluctuation of the SRM become larger, resulting in serious deterioration of system performance.

Figures 13–15 show the no-load dynamic response of the PI controller, the fractional-order controller, and the proposed controller at 500 rpm. The proposed control method has good dynamic response characteristics and smaller torque and current fluctuations.
Figure 12: Response results of the proposed controller at 3000 rpm.

Figure 13: Dynamic responses of the PI controller at 500 rpm.
**Figure 14:** Dynamic responses of the fractional-order PI controller at 500 rpm.

**Figure 15:** Dynamic responses of the proposed controller at 500 rpm.
5. Conclusions

In this study, to overcome the nonlinear effects and achieve good control performance, the fractional-order PI controller with the disturbance observer has been devised. Fractional-order integral is introduced to the conventional proportional integral controller though the order of calculus $\lambda$. In the SRM drive, the uncertainties of the internal parameters and external torque are regarded as disturbances and defined as the extended state of the system. The extended state-observing mathematical model is devised. The performance of the controller is improved by compensating the observed disturbances to the output of the fractional-order PI controller, which achieves linearization and determinism of the SRM drives.

The stability of the proposed control strategy is analyzed by calculating the amplitude-frequency characteristics of the system. The control strategy has good disturbance suppression ability and improves the robustness of the system. The values of the proposed controller parameters have been obtained by the trial-and-error method. The performance of SRM drives is tested under speed reference and load disturbance. The proposed controller offers lower fluctuation than the PI and fractional-order PI controller.

Data Availability

The data used to support the findings can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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