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ADAPTIVE INTEGRAL BACKSTEPPING CONTROL OF PMSM WITH DIFFERENTIAL TERMS BASED ON PARAMETERS FUZZY SELF-TUNING

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Abstract. *In order to weaken the influence of external load disturbance and internal parameters perturbation on permanent magnet synchronous motor (PMSM) control system and improve the dynamic performance, this paper proposes an adaptive integral backstepping controller (AIBC) strategy for PMSM with differential terms based on parameters fuzzy self-tuning. Firstly, the integral terms of dq axis current following error are introduced into the control law, and by constructing appropriate Lyapunov function, the adaptive law with the differential terms and the control law with the integral terms of the current error are derived to weaken the influence of internal parameters perturbation on current control. At the same time, anti-saturation integrator is introduced to prevent possible saturation problem and improve the dynamic performance of the system. On this basis, the fuzzy theory is introduced into the AIBC, and the fuzzy reasoning module is designed to be applied to the AIBC. According to the speed following error and its rate of change, the speed feedback gain and the adaptive gain are adaptively adjusted online to further improve the dynamic response and reduce the dependence of the algorithm on the accuracy of model parameters. The experimental results show that, compared with traditional backstepping control, the proposed control strategy has better dynamic response and stronger robustness to internal parameters perturbation and external load disturbance.*
Keywords: Permanent magnet synchronous motor, Adaptive integral backstepping control, Fuzzy self-tuning, Parameters perturbation, Load disturbance

1. **Introduction.** Permanent magnet synchronous motors (PMSMs) have been widely applied in industrial applications due to simple structure, high power density and reliable operation [1-3]. However, due to its non-linearity, strong coupling, and the real-time changes of stator resistance, inductance and load torque during its operation [4], it is difficult to achieve the high control performance requirements by using general linear control methods, such as proportional-integral (PI) control [5,6]. In recent years, with the development of control theory, some non-linear control methods have been applied to PMSM, such as sliding mode control (SMC) [7,8], feedback linearization control (FLC)

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[9,10], auto disturbance rejection control (ADRC) [11,12], and backstepping control (BC) [13,14]. Among them, backstepping control has attracted much attention because it is easy to combine with the adaptive parameters estimation technology to weaken the influence of system uncertainties [15,16].

1.1. **Related work.** In the early 1990s, Kokotovic et al. [17] put forward the backstepping control, which provides a feasible idea for the design of nonlinear controller. The theory of backstepping control has attracted wide attention in the field of motor control, because it cannot only achieve complete decoupling of PMSM system, but also simplify the design process [18,19]. In order to ensure the better stability and dynamic performance of the system, adaptive backstepping control (ABC) method is generally used for nonlinear uncertain systems, which combines the backstepping design method with the adaptive control method [20-22]. The adaptive control law is constructed while the feedback control law and Lyapunov function are constructed, which not only meets the requirements of system stability, but also reduces the design steps. For PMSM control system, the adaptive backstepping design method is usually used to design the controller. In [23], an adaptive backstepping controller for PMSM is designed with the inductance of dq axis and load torque as uncertainties. The simulation results show that the designed controller can track the reference speed well, and is robust to parameters uncertainties and load disturbance. However, the control law and adaptive law designed in this paper are complex and unsuitable for engineering application. In [24], the backstepping control strategy is applied to the speed tracking system of PMSM, which simplifies the design process of general system and reduces the number of adjusting parameters in the system control, but it does not consider the influence of the parameters perturbation on the system performance. In [25], adaptive control and backstepping control are combined and applied to speed tracking system of PMSM with uncertain parameters. This method aims at the real-time estimation of resistance and load in the control system, and achieves disturbance suppression to a certain extent. However, it does not consider the influence of the parameters selection of speed backstepping regulator on the performance of the system.

1.2. **Major problems.** In summary, traditional backstepping control strategy cannot meet the performance requirements of the system for robustness to internal and external disturbances and high dynamic response, and there still exist some problems to be studied, mainly in the following two aspects:

- In order to achieve accurate control of the current and speed, the accuracy of internal parameters of backstepping control system is the prerequisite. However, the internal parameters such as stator resistance, and inductance will be perturbed with the change of temperature during the operation of the motor, and the tracking performance of the current and speed will decline. The robustness of the system to the internal parameters perturbation of the motor cannot be guaranteed.
- There is no standard method for parameters tuning of backstepping control algorithm. According to Lyapunov function, only the lower limit of each parameter can be determined, but the exact value of parameters cannot be obtained. Especially when there are many parameters in the controller, the tuning of various parameters becomes particularly difficult [26]. In the controller design, the parameters selection can only be determined by experience and a lot of debugging. The parameters of backstepping controller are usually selected as fixed constant, which limits the dynamic performance of the system to a certain extent.

In order to solve the first problem, the internal parameters perturbation of the motor are estimated in real time by designing the corresponding estimator, which is compensated to the output of the controller to ensure the accuracy of current tracking. However, it is very difficult to deduce the adaptive law because the stator inductances are coupled with each other [27,28]. Therefore, how to ensure the robustness of the backstepping control system to the inductance perturbation needs further research. Aiming at the second problem, many scholars combine fuzzy control or neural network control [29] with adaptive backstepping control to improve the dynamic performance of the system by adjusting the relevant parameters of the backstepping controller by the fuzzy controller [30-33]. However, most of them only consider the requirement of the dynamic response of the system to the speed, and the influence of the inductance perturbation on the control performance is not fully considered. Therefore, how to ensure the robustness of the backstepping control system to the internal inductance perturbation while having excellent dynamic response performance is worth further research.

1.3. **Contributions.** In view of the above two major problems, this paper is to present an adaptive integral backstepping controller (AIBC) for PMSM with differential terms based on parameters fuzzy self-tuning, which effectively suppresses the influence of load torque disturbance and inductance uncertainties of dq axis on the system, and the parameters tuning problem of the controller is effectively solved. The main contributions in this paper are as follows.

- Aiming at the load torque disturbance and inductance uncertainties of dq axis, based on the function of differential and integral in control system, an AIBC with differential terms for PMSM is proposed. Robustness to inductance perturbation does not need to be based on the estimation of its value, and then the problem of deducing adaptive law due to the mutual coupling of the inductance of dq axis is effectively solved.
- Aiming at the parameters tuning problem of the AIBC with differential terms, the fuzzy theory is introduced into the AIBC, and the fuzzy reasoning module is designed to be applied to the AIBC. The design method of the proportion and quantification factor, membership function and fuzzy rules of the fuzzy reasoning module are proposed. The system parameters are adaptively adjusted according to the motor speed error and its change rate, and the dynamic performance of the system is further improved.

The remaining of this paper is organized as follows. In Section 2, the AIBC with differential terms is designed. Section 3 introduces the fuzzy theory into the AIBC, and the fuzzy reasoning module is designed to be applied to the AIBC. Section 4 provides the experimental results that highlight the advantages of the proposed control strategy. At last, we give a conclusion, then references are listed at the end of the paper.

2. Design of the AIBC with Differential Terms for PMSM.

2.1. **Design of adaptive backstepping controller with differential terms.** According to field oriented control (FOC) theory, the mathematical model of PMSM in dq axis can be expressed as

$$\begin{bmatrix} u_q \\ u_d \end{bmatrix} = \begin{bmatrix} R_s + pL_q & n_p\omega_r L_d \\ -n_p\omega_r L_q & R_s + pL_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} n_p\omega_r\psi_f \\ 0 \end{bmatrix} \tag{1}$$

where i_d and i_q are the current of dq axis, u_d and u_q are the voltage of dq axis, L_d and L_q are the stator inductance of dq axis, R_s is the stator resistance, ω_r is the mechanical angular speed of the rotor, n_p is the number of pole pairs, and ψ_f is the rotor flux.

Transform (1) into

$$\begin{cases} \dot{i}_d = \dfrac{u_d}{L_d} - \dfrac{R_s}{L_d} i_d + n_p \omega_r \dfrac{L_q}{L_d} i_q \\ \dot{i}_q = \dfrac{u_q}{L_q} - \dfrac{R_s}{L_q} i_q - n_p \omega_r \dfrac{L_d}{L_q} i_d - n_p \omega_r \dfrac{\psi_f}{L_q} \end{cases} \tag{2}$$

The electromagnetic torque expression of PMSM is as follows

$$T_e = \frac{3n_p}{2} \left[\psi_f i_q + (L_d - L_q) i_d i_q \right] \tag{3}$$

The equation of mechanical motion is

$$T_e = T_L + B\omega_r + J \frac{d\omega_r}{dt} \tag{4}$$

where T_e is the output electromagnetic torque, T_L is the load torque, J is the moment of inertia, B is the viscous friction coefficient. By combining (3) with (4), the following formula is obtained

$$\dot{\omega}_r = \frac{3n_p \psi_f}{2J} i_q + \frac{3n_p}{2J} (L_d - L_q) i_d i_q - \frac{B}{J} \omega_r - \frac{1}{J} T_L \tag{5}$$

Considering (5) as the first subsystem and (2) as the second, the PMSM control system is a nonlinear system composed of speed control subsystem and current control subsystem. Therefore, the backstepping control method can be used to design the speed controller of PMSM. The specific design steps are as follows.

Step 1: Define the reference speed as ω_r^*, then the speed following error is

$$e_\omega = \omega_r^* - \omega_r \tag{6}$$

Formula (6) is differentiated to obtain

$$\dot{e}_\omega = \frac{1}{J} \left[T_L + B\omega_r - \frac{3n_p}{2} \psi_f i_q - \frac{3n_p}{2} (L_d - L_q) i_d i_q \right] \tag{7}$$

Define Lyapunov function as

$$V_1 = \frac{e_\omega^2}{2} \tag{8}$$

Formula (8) is differentiated to obtain

$$\dot{V}_1 = e_\omega \dot{e}_\omega = \frac{e_\omega}{J} (B\omega_r + T_L) - \frac{3n_p}{2J} e_\omega \left[\psi_f i_q + (L_d - L_q) i_d i_q \right] \tag{9}$$

Define k_ω as speed feedback gain, and take it positive constant, then (9) is converted to

$$\dot{V}_1 = -k_\omega e_\omega^2 + \frac{e_\omega}{J} \left[T_L + B\omega_r - \frac{3n_p}{2} (L_d - L_q) i_d i_q - \frac{3n_p}{2} \psi_f i_q + k_\omega J e_\omega \right] \tag{10}$$

T_L and J are considered as uncertain parameters for estimation, and ideal virtual control variables i_d^* and i_q^* are defined as

$$\begin{cases} i_d^* = 0 \\ i_q^* = \dfrac{2}{3n_p \psi_f} \left(\hat{T}_L + B\omega_r + k_\omega \hat{J} e_\omega \right) \end{cases} \tag{11}$$

where $\hat{T}_L$ and $\hat{J}$ are load torque and inertia estimation respectively. Bring Formula (11) into (7), and the speed error can be reorganized into the following equation

$$\dot{e}_\omega = \frac{1}{J} \left(-\tilde{T}_L + \frac{3n_p}{2} \psi_f e_q + \frac{3n_p}{2} (L_d - L_q) e_d i_q - k_\omega \hat{J} e_\omega \right) \tag{12}$$

where $\tilde{T}_L = \hat{T} - T_L$. Define the dq axis current error e_d and e_q as

$$\begin{cases} e_d = i_d^* - i_d \\ e_q = i_q^* - i_q \end{cases} \tag{13}$$

The differential terms of the dq axis current error are

$$\begin{cases} \dot{e}_d = \dfrac{R_s i_d - n_p \omega_r L_q i_q - u_d}{L_d} \\ \dot{e}_q = \dfrac{2\left(k_\omega \hat{J} - B\right)}{3 n_p \psi_f J}\left[\dfrac{3 n_p \psi_f}{2} e_q + \dfrac{3 n_p}{2}\left(L_d - L_q\right) e_d i_q - k_\omega \hat{J} e_\omega\right] \\ \qquad - \dfrac{2\left(k_\omega \hat{J} - B\right)}{3 n_p \psi_f J}\tilde{T}_L + \dfrac{R_s i_q + n_p \omega_r L_d i_d + n_p \omega_r \psi_f - u_q}{L_q} \end{cases} \tag{14}$$

Step 2: In order to make the differential term of the q axis current error appear in the derived adaptive law, the Lyapunov function is defined as

$$V = V_1 + \frac{1}{2}e_d^2 + \frac{1}{2}e_q^2 + \frac{1}{2\gamma_1}\left(\tilde{T}_L + k_m J e_q\right)^2 + \frac{1}{2\gamma_2}\tilde{J}^2 \tag{15}$$

where γ_1 and γ_2 are adaptive gains, and they are positive constant. $\tilde{J} = \hat{J} - J$ is the estimation error of moment of inertia, k_m is the differential gain of q axis current. Formula (15) is differentiated to obtain

$$\begin{aligned} \dot{V} &= e_\omega \dot{e}_\omega + e_d \dot{e}_d + e_q \dot{e}_q + \frac{1}{\gamma_1}\tilde{J}\dot{\tilde{J}} + \frac{1}{\gamma_2}\left(\tilde{T}_L + k_m J e_q\right)\left(\dot{\tilde{T}}_L + k_m J \dot{e}_q\right) \\ &= -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 + e_d\left[\frac{R_s i_d - n_p \omega_r L_q i_q - u_d}{L_d} + \frac{3 n_p}{2J}\left(L_d - L_q\right) e_\omega i_q + k_d e_d\right] \\ &\quad + e_q\left[\frac{2\left(k_\omega J - B\right)}{3 n_p \psi_f J}\alpha - \frac{2\left(k_\omega \hat{J} - B\right)}{3 n_p \psi_f J}k_\omega \hat{J} e_\omega + \frac{2 k_m \left(k_\omega J - B\right)}{3 n_p \psi_f}e_q + k_m e_\omega\right. \\ &\quad \left. + \frac{3 n_p \psi_f}{2J}e_\omega + k_q e_q + \frac{R_s i_q + n_p \omega_r L_d i_d + n_p \omega_r \psi_f - u_q}{L_q}\right] + \tilde{J}\left[\frac{1}{\gamma_2}\dot{\tilde{J}} - \frac{k_\omega}{J}e_\omega^2 + \frac{2 k_\omega k_m}{3 n_p \psi_f}e_q^2\right. \\ &\quad \left. + \frac{2 k_\omega e_q}{3 n_p \psi_f J}\alpha\right] + \left(\tilde{T}_L + k_m J e_q\right)\left[\frac{1}{\gamma_1}\left(\dot{\tilde{T}}_L + k_m J \dot{e}_q\right) - \frac{e_\omega}{J} - \frac{2\left(k_\omega \hat{J} - B\right)}{3 n_p \psi_f J}e_q\right] \end{aligned} \tag{16}$$

where $\alpha = \frac{3 n_p \psi_f}{2}e_q + \frac{3 n_p}{2}\left(L_d - L_q\right) e_d i_q$, k_d and k_q are positive constant. In order to ensure the global asymptotic stability of the system, the actual control laws and adaptive law are selected as

$$\begin{cases} u_d = R_s i_d - n_p \omega_r L_q i_q + \dfrac{3 n_p}{2J}\left(L_d - L_q\right) L_d e_\omega i_q + k_d L_d e_d \\ u_q = R_s i_q + n_p \omega_r L_d i_d + n_p \omega_r \psi_f + k_q L_q e_q + L_q k_m e_\omega \\ \qquad + \dfrac{2 L_q}{3 n_p \psi_f J}\left(k_\omega J - B\right)\left[\dfrac{3 n_p \psi_f}{2}e_q + \dfrac{3 n_p}{2}\left(L_d - L_q\right) e_d i_q\right] \\ \qquad - \dfrac{2 k_\omega \left(k_\omega \hat{J} - B\right) L_q}{3 n_p \psi_f J}\hat{J} e_\omega + \dfrac{2 k_m \left(k_\omega J - B\right) L_q}{3 n_p \psi_f}e_q + \dfrac{3 n_p L_q}{2J}\psi_f e_\omega \end{cases} \tag{17}$$

$$\begin{cases} \dot{\hat{T}}_L = \gamma_1 \left[\dfrac{e_\omega}{J} + \dfrac{2\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J} e_q \right] - k_m J \dot{e}_q \\ \dot{\hat{J}} = -\gamma_2 \left\{ -\dfrac{k_\omega e_\omega^2}{J} + \dfrac{2k_\omega k_m}{3n_p\psi_f} e_q^2 \right\} - \gamma_2 \left\{ \dfrac{2k_\omega e_q}{3n_p\psi_f J} \left[\dfrac{3n_p\psi_f}{2} e_q \right.\right. \\ \qquad \left.\left. + \dfrac{3n_p}{2} \left(L_d - L_q\right) e_d i_q \right] \right\} \end{cases} \tag{18}$$

Introduce the above control law and adaptive law into (16), then

$$\dot{V} = -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 \tag{19}$$

Because $k_\omega > 0$, $k_d > 0$ and $k_q > 0$, then $\dot{V} \leq 0$. According to Lyapunov asymptotic stability theorem, the system is asymptotically stable.

2.2. **Design of the AIBC.** Formula (1) is an ideal mathematical model of PMSM without considering the factors such as damper winding and harmonics of motor rotor. However, in the process of motor operation, the error of dq axis inductances measurement will seriously affect the control performance of dq axis current, and may even cause the collapse of motor control system. For such problem, uncertainties can generally be observed by designing observers. However, from Formula (2), it can be seen that the dq axis inductances exist on the denominator of their current equation respectively, and are coupled with each other, so it is difficult to deduce the adaptive law. In this section, the error integrals of dq axis current are introduced into the control law, and the AIBC for PMSM is designed to reduce the following error of dq axis current and the influence of parameters uncertainty on the system.

Define θ_d as the integral of d axis current error, and $\theta_d = \int_0^t e_d(\tau)d\tau$. Define θ_q as the integral of q axis current error, and $\theta_q = \int_0^t e_q(\tau)d\tau$, and Lyapunov function is defined as

$$V = \frac{1}{2}e_\omega^2 + \frac{1}{2}e_d^2 + \frac{1}{2}e_q^2 + \frac{1}{2}k_{di}\theta_d^2 + \frac{1}{2}k_{qi}\theta_q^2 + \frac{1}{2\gamma_1}\tilde{T}_L^2 + \frac{1}{2\gamma_2}\tilde{J}^2 \tag{20}$$

where k_{di} and k_{qi} are integral gains of dq axis current respectively, and $k_{di} > 0$, $k_{qi} > 0$. Formula (20) is differentiated to obtain

$$\begin{aligned} \dot{V} = & -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 + e_d \left[\frac{R_s i_d - n_p\omega_r L_q i_q - u_d}{L_d} + \frac{3n_p}{2J}\left(L_d - L_q\right) e_\omega i_q \right. \\ & \left. + k_d e_d + k_{di}\theta_d \right] + e_q \left[\frac{2\left(k_\omega J - B\right)}{3n_p\psi_f J}\alpha - \frac{2\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J} k_\omega \hat{J} e_\omega + \frac{3n_p\psi_f}{2J} e_\omega + k_q e_q \right. \\ & \left. + k_{qi}\theta_q + \frac{R_s i_q + n_p\omega_r L_d i_d + n_p\omega_r\psi_f - u_q}{L_q} \right] + \tilde{J}\left[\frac{1}{\gamma_2}\dot{\hat{J}} - \frac{k_\omega}{J}e_\omega^2 + \frac{2k_\omega e_q}{3n_p\psi_f J}\alpha \right] \\ & + \tilde{T}_L \left[\frac{1}{\gamma_1}\dot{\hat{T}}_L - \frac{e_\omega}{J} - \frac{2\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J} e_q \right] \end{aligned} \tag{21}$$

where $\alpha = \frac{3n_p\psi_f}{2}e_q + \frac{3n_p}{2}\left(L_d - L_q\right) e_d i_d$. In order to ensure the stability of the system, the control law and the adaptive law are selected respectively as

$$\begin{cases} u_d = R_s i_d - n_p \omega_r L_q i_q + \dfrac{3n_p}{2J}\left(L_d - L_q\right) L_d e_\omega i_q + k_d L_d e_d + k_{di} L_d \theta_d \\ u_q = R_s i_q + n_p \omega_r L_d i_d + n_p \omega_r \psi_f + k_q L_q e_q + k_{qi} L_q \theta_q \\ \qquad + \dfrac{2L_q}{3n_p \psi_f J}(k_\omega J - B)\left[\dfrac{3n_p \psi_f}{2} e_q + \dfrac{3n_p}{2}\left(L_d - L_q\right) e_d i_q\right] \\ \qquad - \dfrac{2k_\omega\left(k_\omega \hat{J} - B\right) L_q}{3n_p \psi_f J}\hat{J} e_\omega + \dfrac{3n_p L_q}{2J}\psi_f e_\omega \end{cases} \tag{22}$$

$$\begin{cases} \dot{\hat{T}}_L = \gamma_1 \left[\dfrac{e_\omega}{J} + \dfrac{2\left(k_\omega \hat{J} - B\right)}{3n_p \psi_f J} e_q\right] \\ \dot{\hat{J}} = -\gamma_2 \left\{-\dfrac{k_\omega e_\omega^2}{J} + \dfrac{2k_\omega e_q}{3n_p \psi_f J}\left[\dfrac{3n_p \psi_f}{2} e_q + \dfrac{3n_p}{2}\left(L_d - L_q\right) e_d i_q\right]\right\} \end{cases} \tag{23}$$

Introduce the above control law and adaptive law into (21), then

$$\dot{V} = -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 \tag{24}$$

Because $k_\omega > 0$, $k_d > 0$ and $k_q > 0$, then $\dot{V} \le 0$. According to Lyapunov asymptotic stability theorem, the system is asymptotically stable.

2.3. **Design of the anti-saturation torque observer.** The backstepping control strategy mentioned above did not consider the constraint of the system. However, in PMSM control system, such constraint exists. For the torque observer, the estimated value should be less than the maximum load torque allowed by the motor system, i.e., $\left|\hat{T}_L\right| \le T_{\max}$. At the same time, it can be seen from (23) that $\hat{T}_L$ contains integral term of the speed error e_ω and q axis current error e_q. In the process of motor startup or speed regulation, the input values of e_ω and e_q may be larger. Therefore, in the process of motor operation, the existence of large input signals and torque constraint lead to the integral saturation of the torque observer, which affects the dynamic performance of the system. To solve this problem, an anti-saturation integrator is introduced to enable the observer to exit the saturation state as soon as possible. Taking the torque adaptive law expressed in (18) as an example, the specific process of the algorithm is illustrated. The structure of the anti-saturation torque observer is shown in Figure 1. In the figure, $K = 2\gamma_1 / 3n_p \psi_f J$.

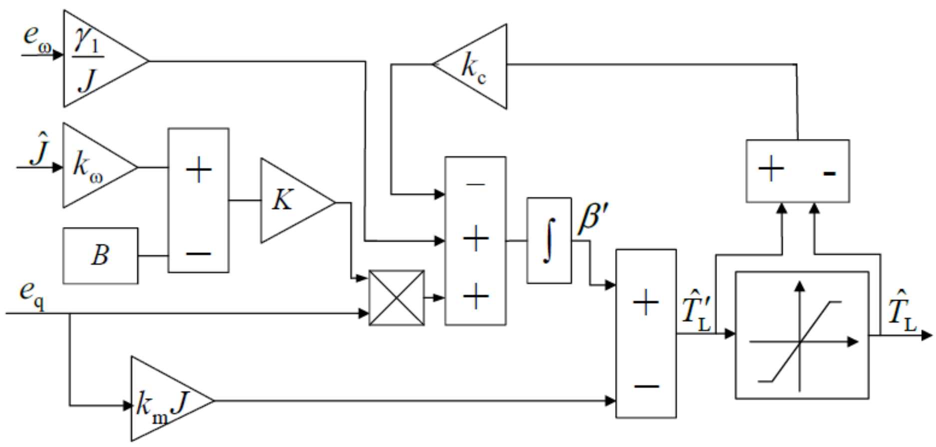


FIGURE 1. Structure of the anti-saturation torque observer

Under unsaturated condition,

$$\begin{aligned}\hat{T}_L = \hat{T}'_L &= \int_0^t \frac{\gamma_1}{J} e_\omega(\tau)d\tau + \int_0^t \frac{2\gamma_1\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J} e_q(\tau)d\tau - k_m J e_q \\ &= \int_0^t \beta(\tau)d\tau - k_m J e_q = \beta' - k_m J e_q\end{aligned} \tag{25}$$

where $\beta = \frac{\gamma_1}{J}e_\omega + \frac{2\gamma_1\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J}e_q$, $\beta' = \int_0^t \beta(\tau)d\tau$. When $\hat{T}'_L$ enters the positive saturation range, the observed value of the torque is the maximum value of the torque $T_{\max}$, and when $\hat{T}'_L$ enters the negative saturation range, the observed value of the torque is the minimum value of the torque $T_{\min}$, i.e.,

$$\hat{T}_L = \begin{cases} T_{\max} & \hat{T}'_L \geq T_{\max} \\ \hat{T}'_L & -T_{\max} < \hat{T}'_L < T_{\max} \\ -T_{\max} & \hat{T}'_L \leq -T_{\max} \end{cases} \tag{26}$$

Under this condition,

$$\beta'(t) = \int_0^t \left[\beta(\tau) - k_c\left(\hat{T}'_L - \hat{T}_L\right)\right] d\tau \tag{27}$$

where k_c is the desaturation adjustment coefficient. When the torque observer is saturated and the value of k_c is large, according to (27), β' will decrease rapidly, so that $\hat{T}'_L$ can withdraw from saturation state and the torque observation value can be restored to (25).

2.4. **Design of the integration algorithm.** Aiming at the load disturbance and parameters uncertainty of PMSM, adaptive backstepping controller with differential terms and the AIBC are designed respectively. Meanwhile, in order to avoid the problem of integration saturation, the anti-saturation integrator is introduced. These methods can be used separately or jointly according to the actual situation. Under the combined use, the motor control system can have the better anti-disturbance ability and dynamic performance.

2.4.1. *Design of the AIBC with differential terms.* The Lyapunov function is defined as

$$V = \frac{1}{2}e_\omega^2 + \frac{1}{2}e_d^2 + \frac{1}{2}e_q^2 + \frac{1}{2}k_{di}\theta_d^2 + \frac{1}{2}k_{qi}\theta_q^2 + \frac{1}{2\gamma_1}\left(\tilde{T}_L + k_m J e_q\right)^2 + \frac{1}{2\gamma_2}\tilde{J}^2 \tag{28}$$

In order to ensure the stability of the system, the control law and the adaptive law are selected respectively as

$$\begin{cases} u_d = R_s i_d - n_p\omega_r L_q i_q + \frac{3n_p}{2J}\left(L_d - L_q\right) L_d e_\omega i_q + k_d L_d e_d + k_{di} L_d \theta_d \\ u_q = R_s i_q + n_p\omega_r L_d i_d + n_p\omega_r \psi_f + k_q L_q e_q + k_q L_m e_\omega + k_{qi} L_q \theta_q \\ \qquad + \frac{2L_q}{3n_p\psi_f J}(k_\omega J - B)\left[\frac{3n_p\psi_f}{2}e_q + \frac{3n_p}{2}\left(L_d - L_q\right)e_d i_q\right] \\ \qquad - \frac{2k_\omega\left(k_\omega \hat{J} - B\right)L_q}{3n_p\psi_f J}\hat{J}e_\omega + \frac{3n_p L_q}{2J}\psi_f e_\omega + \frac{2k_m\left(k_\omega J - B\right)L_q}{3n_p\psi_f}e_q \end{cases} \tag{29}$$

$$\begin{cases} \dot{\hat{T}}_L = \gamma_1\left[\frac{e_\omega}{J} + \frac{2\left(k_\omega \hat{J} - B\right)}{3n_p\psi_f J}e_q\right] - k_m J \dot{e}_q \\ \dot{\hat{J}} = -\gamma_2\left\{-\frac{k_\omega e_\omega^2}{J} + \frac{2k_\omega k_m}{3n_p\psi_f}e_q^2 + \frac{2k_\omega e_q}{3n_p\psi_f J}\left[\frac{3n_p\psi_f}{2}e_q + \frac{3n_p}{2}\left(L_d - L_q\right)e_d i_q\right]\right\} \end{cases} \tag{30}$$

2.4.2. *System stability analysis.* According to (28), it is known that $V(e_\omega, e_q, e_d)$ is positive definite, and it has the infinite upper bound. By introducing the above control law and adaptive law into $\dot{V}(e_\omega, e_q, e_d)$, then

$$\dot{V} = -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 \tag{31}$$

When k_ω, k_d, and k_q are positive constant, then $\dot{V} \le 0$, and $V(e_\omega(t), e_q(t), e_d(t)) \le V(e_\omega(0), e_q(0), e_d(0))$. Considering that $V(e_\omega(0), e_q(0), e_d(0))$ is bounded, then $V(e_\omega(t), e_q(t), e_d(t))$ is non-incremental bounded. Thus

$$\lim_{t\to\infty} \int_0^t \dot{V}(e_\omega(\tau), e_q(\tau), e_d(\tau))\, d\tau < \infty \tag{32}$$

Because $\ddot{V} = -2k_\omega e_\omega \dot{e}_\omega - 2k_d e_d \dot{e}_d - 2k_q e_q \dot{e}_q$, and $\dot{e}_\omega$, $\dot{e}_d$, $\dot{e}_q$, e_ω, e_d, e_q, are all bounded, $\ddot{V}$ is bounded, and $\dot{V}$ is uniformly continuous. According to Lyapunov lemma, when $t \to \infty$, $\dot{V}(t) \to 0$. According to Barbalat lemma, e_ω, e_d and e_q all converge to zero, i.e.,

$$\begin{cases} \lim\limits_{t\to\infty} \omega_r(t) = \omega_r^* \\ \lim\limits_{t\to\infty} i_q(t) = i_q^* \\ \lim\limits_{t\to\infty} i_d(t) = i_d^* \end{cases} \tag{33}$$

After the above analysis, the designed AIBC with differential terms can make the system globally asymptotically stable, and the tracking error approaches zero, so as to achieve the target of speed and current tracking.

3. **Design of Fuzzy Self-Tuning Adaptive Integral Backstepping Controller.** To solve the problem of torque disturbance and inductance uncertainty of PMSM, an adaptive integral backstepping controller with differential terms is designed. In order to ensure the global asymptotic stability of the system, the parameters of controller such as k_ω, k_d and k_q are positive constant, that is, the feedback gain of the control system is fixed positive value, which limits the dynamic performance of the system to a certain extent. In this section, the parameters of the backstepping controller will be self-tuned online through the fuzzy inference system, so as to improve the dynamic performance of the system.

Two-dimensional structure of the fuzzy system is adopted. Its input are the speed error e_ω and its change rate e_c, and its output are k_ω and γ_1 of the backstepping module. Based on the mathematical model of PMSM and the changing law of motor operation state, quantization and proportion factor are estimated, and the membership function and fuzzy rules of the fuzzy system are designed.

3.1. **Quantitative factor estimation.** The input of the fuzzy system of the fuzzy self-tuning backstepping controller are the speed error e_ω and its change rate e_c. Fuzzy domain of the input selects standardization domain $[-1, 1]$. If the input speed reference signal is a step signal, the maximum values of e_ω and e_c are obtained at the moment of motor start-up. Define maximum input reference speed $\omega_{ref\_\max}$, i.e., $-\omega_{ref\_\max} \le e_\omega \le \omega_{ref\_\max}$, then quantization factor of e_ω is selected as

$$k_{i1} = \frac{n_{i\_\max}}{u_{i\_\max}} = \frac{1}{\omega_{ref\_\max}} \tag{34}$$

where $n_{i\_\max}$ and $u_{i\_\max}$ are respectively the maximum value of the fuzzy domain and the actual domain of the input.

When the motor starts, e_c reaches its maximum value $e_{c\_\max}$, i.e.,

$$e_{c\_\max} = \frac{\omega_{ref\_\max}}{T_s} \tag{35}$$

where T_s is the control cycle of the system, then the quantification factor of e_c is chosen as

$$k_{i2} = \frac{1}{e_{c\_\max}} = \frac{T_s}{\omega_{ref\_\max}} \tag{36}$$

The fuzzy values n_{i1} and n_{i2} of input fuzzy reasoning are selected as

$$n_{i1} = \begin{cases} 1 & e_\omega k_{i1} \geq 1 \\ e_\omega k_{i1} & -1 \leq e_\omega k_{i1} \leq 1 \\ -1 & e_\omega k_{i1} \leq -1 \end{cases} \tag{37}$$

$$n_{i2} = \begin{cases} 1 & e_c k_{i2} \geq 1 \\ e_c k_{i2} & -1 \leq e_c k_{i2} \leq 1 \\ -1 & e_c k_{i2} \leq -1 \end{cases} \tag{38}$$

3.2. **Proportional factor estimation.** The output of the fuzzy reasoning module is speed feedback gain k_ω and adaptive gain γ_1. The fuzzy domain N_0 of output is selected as $[0, 2]$. If the range of values of k_ω and γ_1 are $(0, k_{\omega\_\max})$ and $(0, \gamma_{1\_\max})$ respectively, the proportion factors of k_ω and γ_1 are chosen as

$$\begin{cases} k_{o1} = \dfrac{k_{\omega\_\max}}{2} \\ k_{o2} = \dfrac{\gamma_{1\_\max}}{2} \end{cases} \tag{39}$$

3.3. **Proportional factor estimation.** The conversion of precise variables into fuzzy variables mainly depends on the membership function, so the design of membership function has a great influence on the performance of the fuzzy controller. Before that, the fuzzy subset should be determined. When the number of fuzzy subset is large, the control accuracy can be improved, but this also increases the number of fuzzy rules, the difficulty of design and implementation and the computational complexity of the controller will increase. Considering the zero state of the variable, the fuzzy subset usually takes the odd number. The fuzzy subset of all variables of the fuzzy system is 7. e_ω, e_c, k_ω, and γ_1 all correspond to [Negative Big, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Big], i.e., [NB, NM, NS, ZE, PS, PM, PB].

The fuzzy system adopts the form of triangle curve. The corresponding parameters of e_ω and e_c are $[-1, -2/3, -1/3, 0, 1/3, 2/3, 1]$, and the parameters of k_ω and γ_1 are $[0, 1/3, 2/3, 1, 4/3, 5/3, 2]$. The membership curves of e_ω and k_ω are shown in Figure 2, and the curves of e_c and γ_1 are the same as e_ω and k_ω, respectively. Appropriate curve shape can improve the stability and dynamic performance of the system. If the curve shape is slow, the stability of the system is good, and if the curve shape is sharp, the sensitivity is high.

3.4. **Establishment of fuzzy rules.** Fuzzy rules are the core of fuzzy controllers, which are generally summarized by experts or relevant engineers. This paper relies on basic engineering experience to establish fuzzy rules. k_ω can be approximated as the proportional term of PI control, while γ_1 can be approximated as the integral term. When both e_ω and e_c are located in the interval of PB, it can be considered that the electromagnetic torque of the motor system is much smaller than the load torque. In this case, we can increase k_ω, enhance the feedback of speed error on the control output, thereby increasing the electromagnetic torque and reducing the speed error. Similarly, fuzzy rules in other cases

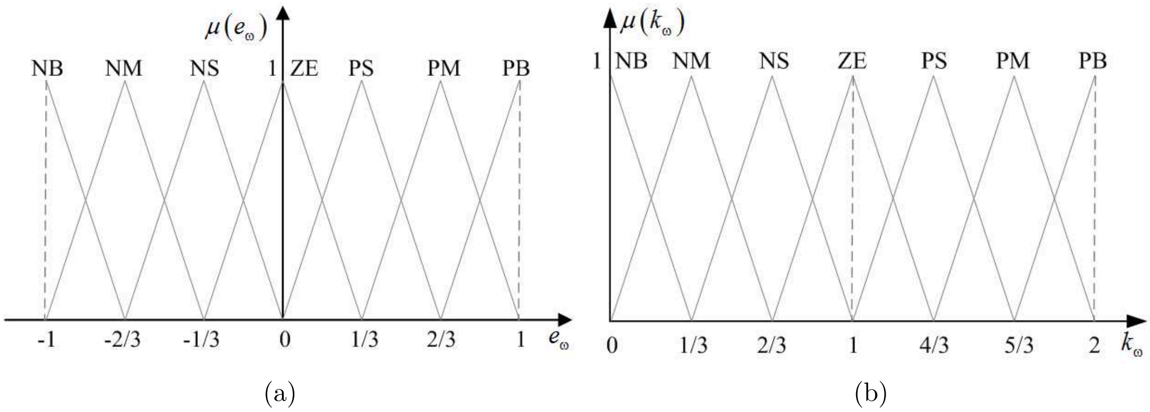


FIGURE 2. Membership function curves, (a) e_ω, (b) k_ω

TABLE 1. Fuzzy rules of k_ω

e_ω \ e_c (k_ω)	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PS	PS	PS	PS	PM	PM
NM	PB	PS	PS	PS	PS	PM	PS
NS	PS	ZE	ZE	ZE	PS	PM	PS
ZE	ZE	ZE	NM	NB	NM	ZE	PS
PS	PS	PS	PS	PS	NS	NS	PM
PM	PM	PS	PS	PS	ZE	ZE	PB
PB	PM	PM	PM	PM	PS	PS	PB

TABLE 2. Fuzzy rules of γ_1

e_ω \ e_c (γ_1)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NB	NB	NB
NM	NM	NM	NS	ZE	NS	NM	NM
NS	NS	ZE	PS	PM	PS	ZE	NS
ZE	ZE	PS	PM	PB	PM	PS	ZE
PS	NS	ZE	PS	PM	PS	ZE	NS
PM	NM	NM	NS	ZE	NS	NM	NM
PB	NB	NB	NB	NB	NB	NB	NB

can be designed. For the design fuzzy rules of γ_1, the main consideration is based on the speed error. In the case of large speed error, in order to avoid large overshoot, the role of integral part should be reduced. In this case, γ_1 should take a smaller value. While in the case of small error, in order to reduce the static error of the system, the integral role should be increased. In this case, γ_1 should take a larger value. The established fuzzy rules of k_ω and γ_1 are shown in Table 1 and Table 2, respectively.

In summary, the structure diagram of the AIBC with dfferential terms based on parameters fuzzy self-tuning is shown in Figure 3.

4. **Experimental Result.** To validate the effectiveness of the proposed control strategy, experimental tests were carried out on a 750 W PMSM testbench. Motor parameters are listed in Table 3 and the experimental tests were carried out on the testbench as

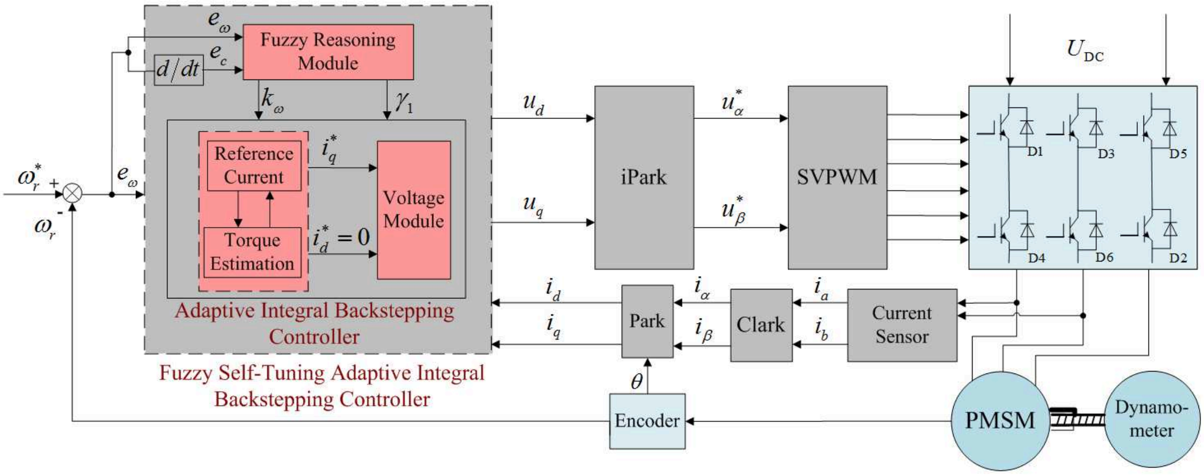


FIGURE 3. Structure diagram of the AIBC with dfferential terms based on parameters fuzzy self-tuning

TABLE 3. Motor parameters

Parameters	Units	Values
Rated power	w	750
Rated voltage	V	220
Rated current	A	4.0
Rated speed	rpm	3000
Rated torque	N·m	2.39
Stator resistance	Ω	2.8
Stator inductance	mH	3.9
Number of poles		4

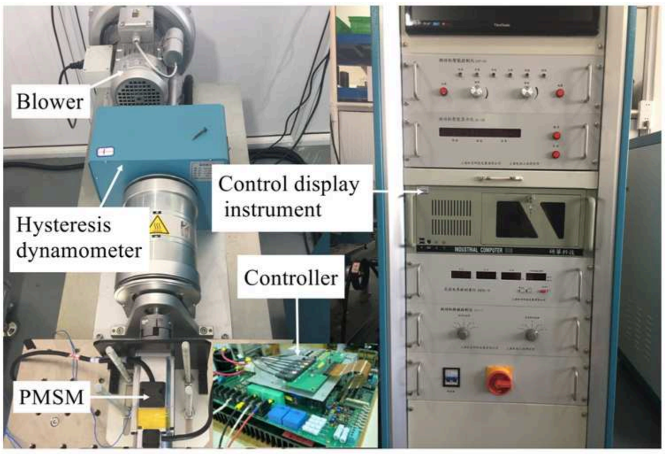


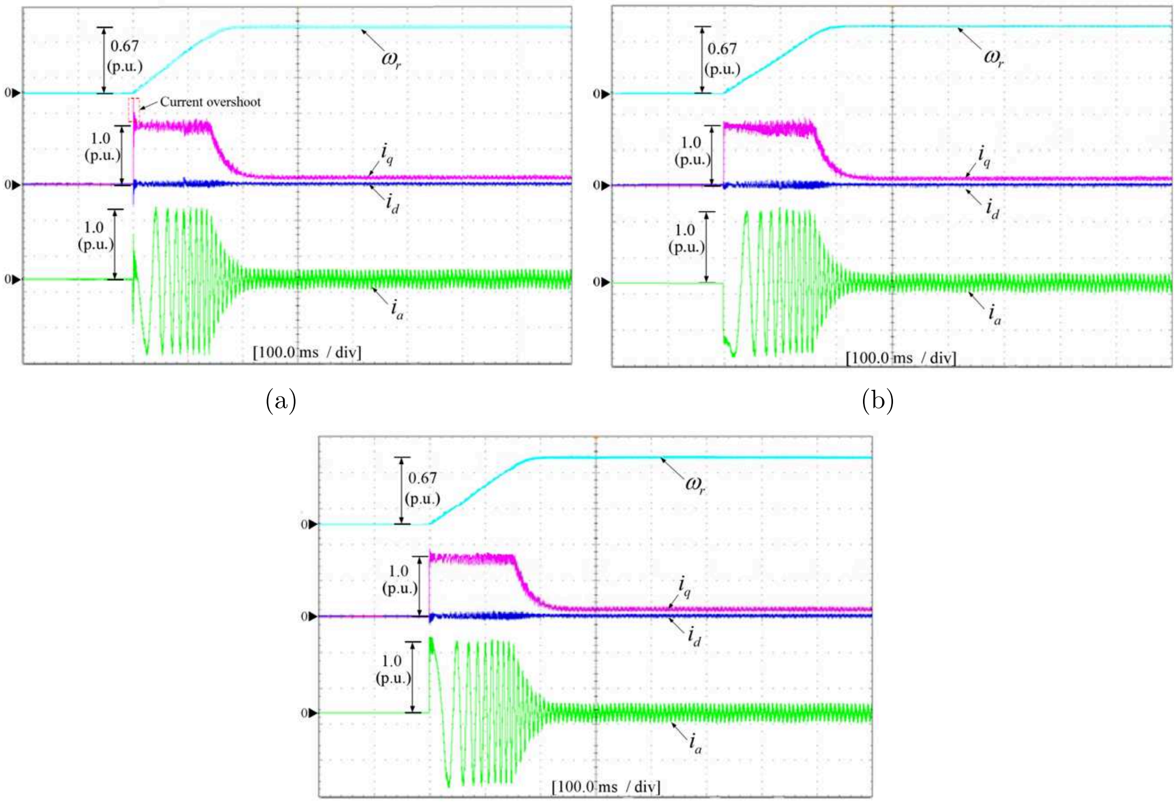
FIGURE 4. Testbench for PMSM drive system

shown in Figure 4, which includes the controlled PMSM, PMSM controller, hysteresis dynamometer, and control display instrument. The load torque of the controlled PMSM is given by the dynamometer controller to simulate the external load disturbance. In the experimental tests, the developed control algorithm is implemented on a 32-bit floating point DSP TMS320F28335, and the actual speed of the rotor is detected by an absolute encoder.

In order to more intuitively reflect the advantages of fuzzy self-tuning adaptive integral backstepping control strategy, the experiment compares it with traditional PI control method and traditional backstepping control method. The comparison is divided into three cases: start-up process, internal parameter perturbation and external load disturbance. The internal parameter perturbation is simulated by selecting internal inductance of the controller as 2.5 times the actual value, and the external disturbance is simulated by giving a sudden change of load. Among them, the parameters of traditional PI controller are optimized after repeated debugging considering both overshoot and response performance. Specifically, the PI parameters of the speed loop are $k_{\omega p} = 500$, $k_{\omega i} = 800$, and the PI parameters of the current loop are $k_{cp} = 1000$, $k_{ci} = 400$. In the traditional backstepping controller, the parameters selection of the controller are the result of repeated debugging under the premise of satisfying Lyapunov stability condition and considering both system vibration and convergence speed. The speed feedback gain k_ω is 50, and the dq axis current regulation parameters k_d and k_q are 250 and 60, respectively. The speed feedback gain k_ω and adaptive gain γ_1 of the fuzzy self-tuning adaptive integral backstepping controller are adjusted online adaptively according to the motor speed error and its rate of change. The selection of the current regulation parameters of dq axis are the same as that of the traditional backstepping controller.

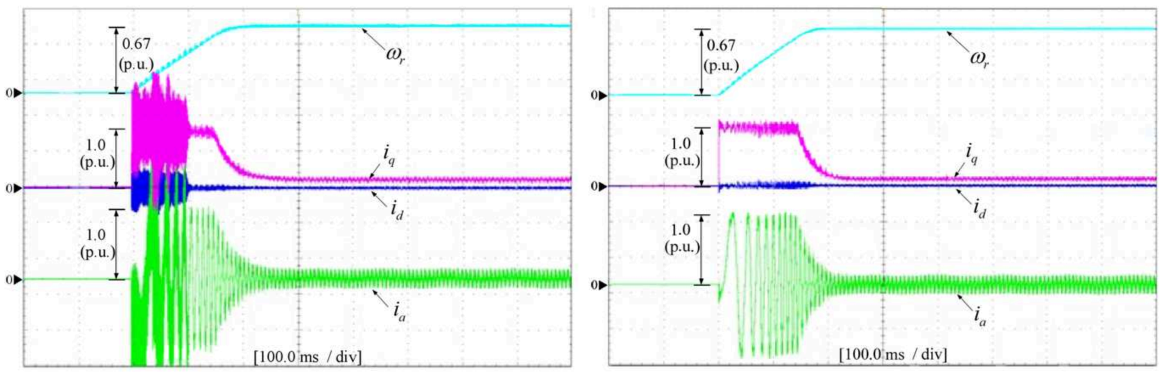
4.1. **Comparison during start-up.** In order to verify the dynamic performance of the fuzzy self-tuning adaptive integral backstepping control, the motor is given 0.67 times the rated speed (2000 rpm) to start under no-load condition. As is shown in Figure 5, the comparisons of actual speed (ω_r), dq axis current (i_d, i_q) and phase current (i_a) during start-up of the motor are made, including traditional PI control (Figure 5(a)), traditional backstepping control (Figure 5(b)) and fuzzy self-tuning adaptive backstepping control (Figure 5(c)). All waveforms are standardized according to the rated value, and the internal parameters of the motor used in the controller are all actual values. The contrast experimental waveforms of Figure 5 show that both PI control and backstepping control show good current control performance when the controller parameters are adjusted to the appropriate value. In the transient phase, i_q can be controlled to its limit (1.0 p.u.). In this paper, the coordinate transformation of current (Clark, Park) and voltage (iPark) adopt equal amplitude transformation, so the peak value of phase current is also controlled to 1.0 p.u., and i_d is controlled to 0 when different controllers are used. However, in the transient phase, both i_q and phase current under PI control have a small overshoot. After analysis, in principle, PI control is based on error adjustment, so it is difficult to avoid overshoot. Traditional backstepping controller and fuzzy self-tuning adaptive backstepping control can ensure that i_q and i_a are not overshoot in transient state, which shows that the traditional backstepping control and the fuzzy self-tuning adaptive integral backstepping control have better dynamic control performance than the PI control.

4.2. **Comparison under internal parameter perturbation.** Similarly, the mismatch between inductance parameter and actual inductance parameter used in the controller are experimentally compared, as is shown in Figure 6, dq axis inductance of the controller is selected as 2.5 times of the actual inductance. Figure 6(a) shows the experimental waveforms in the case of inductance mismatch under traditional backstepping control, and Figure 6(b) shows the experimental waveforms in the case of inductance mismatch under fuzzy self-tuning adaptive integral backstepping control. From Figure 6(a), it can be seen that the dq axis current and phase current under traditional backstepping control have obvious oscillations, and the current control performance is poor. After analysis, the traditional backstepping control is based on the ideal mathematical model of PMSM, which is sensitive to the internal parameters of the motor. The stator inductance error in



(c)

FIGURE 5. Comparison of experimental waveforms during start-up: (a) traditional PI control, (b) traditional backstepping control, (c) fuzzy self-tuning adaptive integral backstepping control

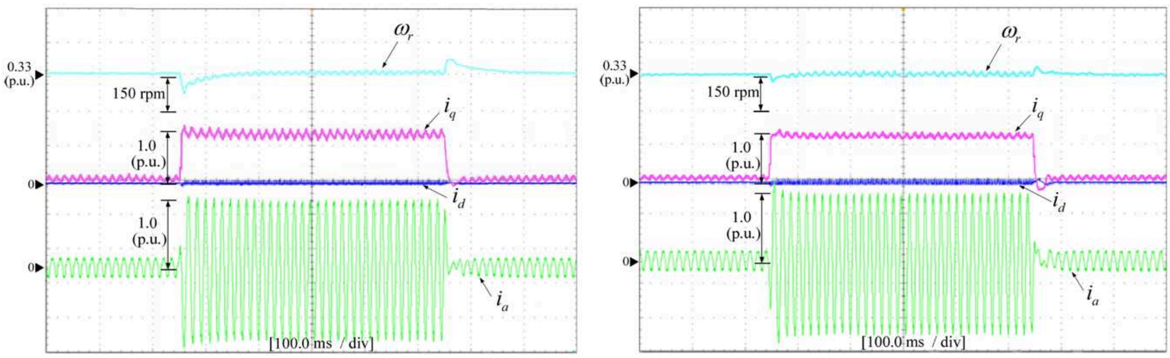


(a) (b)

FIGURE 6. Comparison of experimental waveforms under internal parameter perturbation: (a) traditional backstepping control, (b) fuzzy self-tuning adaptive integral backstepping control

the controller will seriously affect the control effect of the dq axis current, and even make the system collapse. Comparing with the fuzzy self-tuning adaptive integral backstepping control in Figure 6(b), the controller can maintain good current control performance even if the inductance of the controller deviates greatly from the actual inductance. The dq axis current and phase current are stable, and the transient and steady state performance are still good. The analysis shows that the current error caused by the stator inductance error will be compensated by the integral terms because the system introduces the integral terms of the dq axis current following error into the control law, and the dependence of the controller on the accuracy of the system model is greatly reduced.

4.3. **Comparison under external disturbance.** In order to verify the robustness of the fuzzy self-tuning adaptive integral backstepping control to external load disturbance, the loading properties of traditional backstepping control and fuzzy self-tuning adaptive backstepping control are compared. Figure 7 shows the experimental waveforms when the rated load (2.39 N·m) is suddenly added or reduced respectively. The experimental waveforms show that the speed fluctuation of fuzzy self-tuning adaptive integral backstepping control is about 18 rpm while that of traditional backstepping control is 84 rpm when the rated load is suddenly added or reduced. When the load changes abruptly, the speed fluctuation of fuzzy self-tuning adaptive integral backstepping control is less than that of traditional backstepping control, and after sudden loading and unloading, the recovery time of fuzzy self-tuning adaptive backstepping control is also less than that of the traditional one, which indicates that fuzzy self-tuning adaptive integral backstepping control can improve the ability of resisting load disturbance to a certain extent compared with the traditional backstepping control.



(a) (b)

FIGURE 7. Comparison of experimental waveforms under external load disturbance: (a) traditional backstepping control, (b) fuzzy self-tuning adaptive integral backstepping control

5. **Conclusions.** In order to effectively weaken the influence of external load disturbance and internal parameters perturbation on the control system of PMSM and improve the dynamic performance of the system, this paper presents an adaptive integral backstepping control of PMSM with differential terms based on parameters fuzzy self-tuning. The main work includes the following. ① The integral terms of dq-axis current following error are introduced into the control law, and an adaptive integral backstepping controller is designed. The influence of internal parameters perturbation on current control is weakened, and the dependence of the controller on the accuracy of the system model is greatly reduced. ② Fuzzy reasoning module is designed to be applied to the adaptive integral backstepping controller. According to the motor speed error and its rate of change, the speed feedback gain and adaptive gain are adaptively adjusted online. The dynamic response performance of PMSM control system is further improved. Compared with traditional PI control, traditional backstepping control and fuzzy self-tuning adaptive integral backstepping control, the experimental results show that: ① both PI control

and backstepping control can have good current control performance when the controller parameters are adjusted to the appropriate value, and backstepping control is better than PI control in dynamic performance; ② performance of fuzzy self-tuning adaptive integral backstepping control is better than traditional backstepping control in robustness to internal parameters perturbation and external load disturbance.

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