Fuzzy Adaptive Tracking Control with Back Stepping for Nonlinear Alternating Current Motor Systems

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With the development of power electronics technology, microelectronics technology, and modern motor control theory, the fully digitalized permanent magnet synchronous motor servo system with high-performance control strategy has been rapidly promoted. The standard linear control approach is unable to satisfy the control needs of the high-performance system because the AC motor is a highly coupled nonlinear multivariable system. The study proposes a novel fuzzy adaptive tracking control method for nonlinear systems based on inverse stepping and fuzzy logic systems. This method is further optimized by introducing new adaptive parameters, enabling continuous self-adjustment and ensuring control accuracy throughout the control process. The fuzzy basis function is used to approximate the nature of the nonlinear function, and the controller is designed through the online parameter adaptive way to design the controller, which is finally applied to the AC motor system. The results showed that for the same system equation, the control algorithm proposed by the study had a more accurate tracking effect compared with the comparison algorithm, the control input u of the comparison algorithm had a much higher pulse than the study control input when the system was just started. Moreover, all the signals in the closed-loop system are bounded, and the tracking effect was good. x1 did not have a very large error in the beginning of the tracking. Maintaining it in a very small range, it could track the target function yd very quickly. Even if the load torque changes at t=5, a small tracking error e was still maintained. Because the load torque changes, L started to make small adjustments to achieve the tracking error e within a certain accuracy range. x1 could track the target function yd very quickly. At this time, because the parameter L was constantly being adjusted, the tracking error e was further reduced until the tracking error e was achieved within the required accuracy range, and the tracking effect was very stable. Within the range, the tracking effect was very stable. From the change of rotor angular velocity x2, the initial oscillation was violent. However, with the adjustment of parameters, the system was gradually stabilized. The fuzzy adaptive back stepping control speed went from decreasing to increasing before 0.55s, and was stabilized at 150 rads, i.e., the reference speed, around 0.65s. The q-axis current varied smoothly with the continuous change of the input voltage, and the d-axis current varied smoothly with the change of the input voltage. The back stepping adaptive control method proposed by the research can accurately estimate the load torque, can accurately and quickly realize the speed in different motor tracking control advantages for the high-performance control of nonlinear motors provide a better direction, and then can provide a new way for the improvement of the AC drive system, which is of great significance for research.

Povzetek: Predstavljena je nova metoda za mehki adaptiven nadzor s povratno zanko za nelinearne sisteme izmeničnih motorjev. Dosežek omogoča natančno sledenje in hitro prilagoditev spremembam navora, kar izboljšuje zmogljivost nelinearnih motorjev.

1 Introduction

The phenomena of nonlinearity and time lag are common in the objective world and in the control of industrial systems. Nonlinearity, uncertainty, and time lag in alternating current motor (ACM) systems from time to time lead to degradation of the performance of the controlled system, which brings inconvenience to the application of control theory methods [1]. Commonly used methods for designing system controllers include back stepping, which can systematize and structure the design process of controlling V-functions and controllers by back stepping, and can control a nonlinear system (NC) with relative order n, eliminating the limitation of the classical passive design with relative order 1 [2-3]. In addition, fuzzy logic system (FLS) ensures its system control effect through better system rules and parameter design in the tracking control (TC) of the system, which is specifically a system composed of fuzzy concept and fuzzy logic (FL). When it is used to act as a controller, it is called FL controller. Nowadays, fuzzy adaptive tracking control (FATC) is one of the hotspots in the development and research of nonlinear ACM systems at home and abroad, and many experts realize the value of the FATC model for the application in NC. Therefore, some experts have carried out related researches on the problem of nonlinear ACM system. Yang et al. used a fuzzy switching dynamic adaptive control approach to study the H∞ stochastic TC problem for uncertain fuzzy Markov hybrid switching systems. An applied study was used to confirm the suggested method's efficacy [4]. For the asymptotic tracking problem of NC with unknown virtual control coefficients (UVCC), Yang et al. proposed a new adaptive control framework. Arithmetic example was used to confirm the control scheme's efficacy [5]. Yao proposed a new fixed time FATC method. The controller was designed using barrier Lyapunov function (BLF) and FLS in the framework of back stepping technique. Simulation examples confirmed this control method's superiority and efficacy [6].

The adaptive event-triggered control (ETC) problem for uncertain NCs with complete state constraints was studied by Jin et al. Asymmetric BLF and back stepping approach were used to create an adaptable ETC solution for the system under consideration. Through simulation, this control method's efficacy was assessed [7]. A novel fuzzy active disturbance rejection control (FADRC) technique was presented by Ye et al. To increase the motion control accuracy of omnidirectional mobile robots (MY3-OMR). The outcomes showed that the technique effectively raised the control accuracy of MY3-OMR trajectory tracking while having superior tracking and robustness [8]. A class of TC issues with finite-time adaptive fuzzy for uncertain NCs with a certain performance was studied by Sun et al. According to the results, the strategy could bound all of the closed-loop system (CLS)'s signals and converge the output tracking error (TE) to a predetermined tiny region in finite time, according to the finite-time stability theory [9]. For the TC problem of finite-time consistency of nonlinear multi-intelligent body systems, Zhang et al. suggested a finite-time fuzzy adaptive consistency tracking mechanism. The outcomes showed that the other signals of the multi-intelligent body system were bounded and that the consistency TE converged to a small neighborhood of the origin in finite time when the suggested control protocol was used [10]. Liang et al. studied the TC problem for nonlinear unbounded feedback systems. Using the bound estimation method in conjunction with the backpropagation methodology, a novel nonlinear adaptive asymptotic control law (CL) was presented. It was demonstrated that the research-designed controller could ensure that the TC error asymptotically converged to zero and that all signals containing the state variables and the adaptive law were bounded, in contrast to the current adaptive TC schemes. Simulation examples were used to confirm the efficacy of the suggested approach and the control system's performance [11].

In summary, for the TC of NC and systems, researchers have dealt with and studied the TC of H∞ stochastic, a class of output-constrained unrestricted feedback uncertain NC, full state-constrained uncertain NC, finite time-consistent TC of nonlinear multi-intelligent body systems, and TC problems of nonlinear unconstrained feedback systems. Nevertheless, the application of back stepping to enhance the control of nonlinear ACM systems is not sufficiently comprehensive. Consequently, the study initiates a research project on uncertain systems with nonlinear functions and time lag terms in the system. To investigate the parameters like current in the ACM system, this involves modeling the unknown functions in the system and then creating the fuzzy adaptive controller (FAC) based on back stepping and adaptive techniques that are creatively merged with FLS. Every signal in the CLS is guaranteed to be consistently constrained by the intended FAC, and the TE will converge to a suitably small neighborhood around the origin. The results of the research are anticipated to serve as a basis and point of reference for the creation of TC for NC and a technical foundation for adaptive control of the ACM system. Based on the aforementioned studies, a new direct and indirect adaptive fuzzy TC scheme is proposed to be applied to the ACM system.

The first part of the article structure of this research focuses on the TC algorithm process of NC adaptive fuzzy based on back stepping and FL designed in this research, which is also the focus as well as the innovation point. The experimental verification based on the algorithm designed in the first part is explicitly described in the second part, which also examines the findings of the experimental data. The experimental results are concluded in the third part, which also discusses the design's drawbacks and prospective directions for advancement.

Table 1: Summary table of related work

Reference number	Author	Key methods	Key technological improvements
[4]	Yang et al.	Adaptive fuzzy control based on back stepping method	Reduced the impact of modeling errors and parameter estimation errors, proved that the closed-loop system state is bounded, and the tracking error converges to a smaller neighborhood of zero.

[5]	Yang et al.	Adaptive control of nonlinear multi agent systems	Solved the problem of heterogeneous nonlinear factors and ensured convergence effect within a finite time.
[6]	Yao	Control of non affine stochastic high order multi agent systems	Ensure the stability of all signals in the closed-loop system.
[7]	Jin et al.	Control of electromechanical servo system based on finite time	Proved that the tracking error of the system converges within a finite time.
[8]	Ye et al.	Adaptive control method based on fuzzy logic system and back stepping method	Solved the problem of unknown nonlinear dynamics and improved the robustness of the system.
[9]	Sun et al.	Adaptive control of multimodal systems	Improved the stability and performance of the system.
[10]	Zhang et al.	Control method based on fuzzy logic system and back stepping method	The fault-tolerant control problem for multi-agent systems meets the specified performance requirements.
[11]	Liang et al.	Formation control of multi agent systems	Solved the difficulties in optimal control and improved the accuracy and robustness of formation control.

Despite the recent proposal of numerous enhanced nonlinear control methods, including feedback linearization and sliding mode control, there may still be inherent constraints when addressing specific categories of NCs, such as those exhibiting strong coupling, multiple variables, and time-varying parameters.

The proposed FAC combines the advantages of FLSs and back stepping methods, which can more effectively handle nonlinear factors in the system. FLSs can approximate any nonlinear function, while the back stepping rule can ensure the stability of the system. The combination of the two enhances the controller's ability to handle complex NCs. By introducing adaptive technology, FAC can adjust the parameters of the controller in real time to adapt to changes in system parameters. This adaptive capability enables the controller to maintain stable control performance in the face of parameter changes, thereby improving the robustness of the system. In terms of algorithm design, this study focuses on optimizing the computational process of the controller, aiming to reduce computational complexity while maintaining control accuracy. By designing reasonable algorithms and optimizing strategies, FAC can meet the high real-time requirements of application scenarios.

Discussion: The study innovatively proposes a new control framework by combining FLSs with back stepping methods. This fusion not only overcomes the limitations of each method, but also leverages the advantages of both in nonlinear approximation and stability assurance, providing a new approach to the control of NCs. Most existing methods often face difficulties in dealing with time-delayed systems, as the time delay can affect the stability and performance of the system. By introducing appropriate fuzzy rules and adaptive adjustment mechanisms, the study effectively dealt with the time delay term in the system, improving the stability and tracking performance of the controller.

In terms of differences or unique discoveries, FAC demonstrates significant advantages in nonlinear processing capability, robustness, and real-time performance compared to the latest methods. For example, in simulation experiments, FAC can converge to the desired trajectory faster and maintain more stable control performance as parameters change or external disturbances occur. A comprehensive investigation is undertaken into the adaptability of particular application scenarios for uncertain systems with nonlinear functions and time delay terms, and targeted solutions are put forth. This targeting makes FAC more adaptable and valuable in similar application scenarios.

In terms of significant progress, the proposal of FAC not only achieved innovation in control algorithms, but also provided new perspectives and ideas in control theory. This theoretical innovation contributes to the further development of nonlinear control theory. The advantages of FAC in terms of performance, robustness, and real-time performance, as well as its adaptability to specific application scenarios, make this research result applicable to a number of fields, including motor control, aerospace, robotics, and others.

2 Methods and materials

Nonlinear control systems have a wide range of applications in many fields and are important in the control of robotics, ecosystems and economic systems in addition to general engineering systems. The study innovatively proposes a fuzzy adaptive tracking control for nonlinear systems (FATCNS) method based on back stepping and FL to improve the speed, controllability and stability of ACM systems.

2.1 Tracking study of fuzzy adaptive nonlinear ACM system based on back stepping

Back stepping has become a mainstream tool for controlling NC and combining back stepping with fuzzy control (FC) can enhance the stability and other properties of the system [12-13]. It is able to make the original higher order systems simple using virtual control variables [14]. The primary goal is to build the Lyapunov function (LF) of the CLS recursively in order to create a feedback controller. The selected CL is the integrated solution, and it is chosen so that the derivatives of the LF along the CLS trajectory have a particular quality that guarantees the boundedness of the CLS trajectory and the convergence to the equilibrium point [15-16]. The back stepping design approach is applicable to both linear systems and NCs [17]. Since existing ACMs are generally NC, the study focuses on applying back stepping to NC, which is mathematically modeled as in Equation (1).

$$\begin{cases} \dot{x}_i = \xi_i(\bar{x}) + \zeta_i(\bar{x}_i)x_{i+1}, 1 \le i \le n-1 \\ \dot{x}_n = \xi_i(x) + \zeta_i(x)u, \\ y = x_1 \end{cases} \tag{1}$$

In Equation (1), $x = [x_1, x_2, ..., x_n]^T \in R^n$ denotes the state variables of the system, u, y denote the inputs and outputs of this system. $\bar{x}_i = [x_1, x_2, ..., x_n]^T$, $\xi_i(\cdot)$, $\zeta_i(\cdot)$ denote the nonlinear function of position. The control of back stepping is shown in Fig. 1.

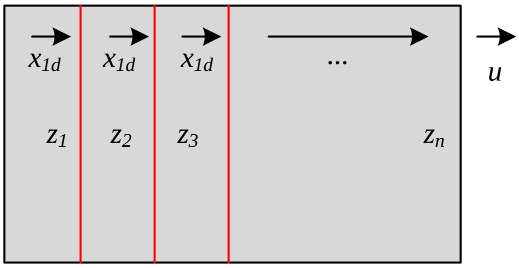


Figure 1: Control of back stepping method

In Fig. 1, the error variable is first defined, the Lyapunov control function is selected, the virtual control system is introduced, and the operation is repeated to obtain the actual control system and control inputs (CIs). Back stepping is a recursive design method for NCs, where the nonlinearity does not have to have linear boundaries, and the special lower triangular structure of the system is utilized to derive a stable CL by constructing Lyapunov step by step, and finally obtaining a lawful controller [18]. The research needs to further optimize the control method of back stepping-based fuzzy adaptive NC by introducing new adaptive parameters, so that it can continuously self-adjust during the control process to meet the requirements of control accuracy. In the problem description, the control objective is to design an adaptive control system, given a tracking target signal y_d, so that the output y can quickly track the target signal y_d, and the control accuracy is guaranteed to be δ. Meanwhile, all the variables of the system are bounded, and it is assumed that the y_d derivative can be found. In addition, it is assumed that for $1 \le i \le n$, $\zeta_i(\cdot)$ is a smooth nonlinear function that cannot be determined with a known sign and is strictly positive or negative definite. Therefore, there exist constants m and M such that $\zeta_i(\cdot)$ satisfies as in Equation (2).

$$0 < m \le \zeta_i(\cdot) \le M < 0 \tag{2}$$

In Equation (2), M and m are used for analysis only and do not parameterize the controller design. For the nonlinear alternating current system, through the non-traditional coordinate transformation, back stepping and LFs are used to design an auxiliary controller makes the system globally asymptotically stable bounded and the TE is stabilized. The design concept is presented here, and Fig. 2 depicts the flow of the control scheme.

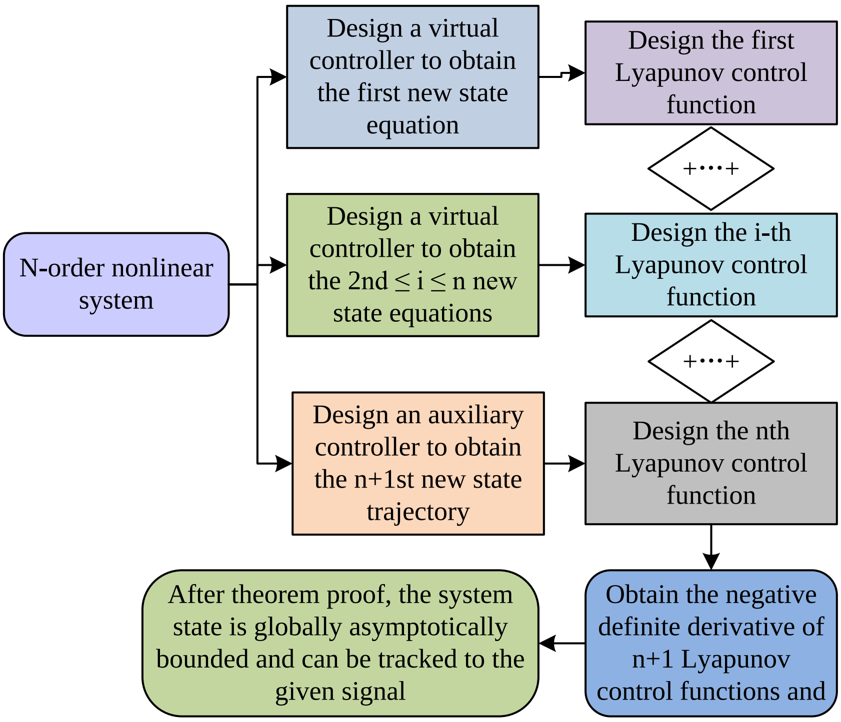


Figure 2: Tracking control of nonlinear AC power systems using back stepping method and Lyapunov function

In Fig. 2, the study is based on the example of an n-order system containing the design of n-step back stepping. The last control signals are acquired gradually by the relevant LFs and merged to finish the CL's overall design. Firstly, the error variables of the system are defined as in Equation (3).

$$\begin{cases} z_1 = x_1 - y_d \\ z_2 = x_2 - \alpha_1 \\ \dots \\ z_n = x_n \end{cases} \tag{3}$$

In Equation (3), y_d denotes the given tracking signal of the motor system, and the errors z_1, z_2, z_3, ... z_n are defined. In the last step, the adaptive FC is designed and α_1 denotes the virtual controller. The specific design structure will be given below, θ is the adaptive parameter that will be designed into the Lyapunov control function. $\hat{\theta}$ denotes the estimated value of θ and $\tilde{\theta} = \theta - \hat{\theta}$ denotes the error. L denotes the adaptive parameter introduced for more precise control and m_i denotes the adjustable parameter. Since θ is unknown, its estimated value $\hat{\theta}$ is used instead. For θ, the adaptive parameter L and the first Lyapunov control function V_1 have as in Equation (4).

$$\begin{cases} \dot{\hat{\theta}}_i = L z_i S_i(x) - m_i \hat{\theta}_i \\ \dot{L} = \max\{|x_1 - y_d| - \delta, 0\} \\ V_1 = \dfrac{1}{2} z_1^2 + \dfrac{1}{2L} \tilde{\theta}_1^T \tilde{\theta}_1 \end{cases} \tag{4}$$

In Equation (4), δ denotes the maximum TE that can be allowed and m_i denotes the adjustable parameter. By making $L(0) = 1$, it can be observed that $L > 0$ and L are monotonically no decreasing. The derivation of V_1 is carried out, due to the existence of a nonlinear part, in order to optimize the FAC, the universal approximation theorem of the FLS is directly used to replace the nonlinear part, and then the error variable $z_2 = x_2 - \alpha_1$ is customized to obtain the $x_2 = \alpha_1 + z_2$. In which the FLS used in the study is divided into several parts, which are the fuzzy rule base, the inference machine, the simulator, and the defuzzifier. Fig. 3 illustrates the precise link.

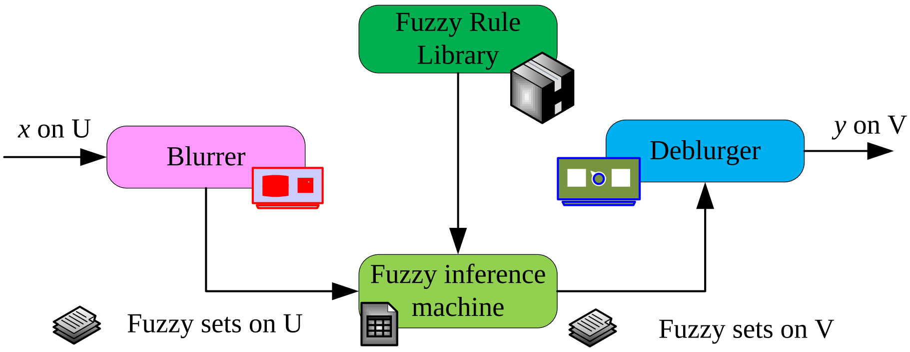


Figure 3: FL system

In Fig.3, FLS refers to a system composed of fuzzy concepts and FL. When it is used as a controller, it is called a FL controller. Due to the arbitrariness in selecting fuzzy concepts and FL, a variety of FLSs can be constructed. Then the virtual control function virtual control function (VCF) is selected and substituted into the sum of squares formula to finally obtain as in Equation (5).

$$V_1 \le -k_1 z_1^2 + z_1 z_2 + \frac{\varepsilon_1^{*2}}{2L} + \frac{m_1}{2L}\theta_1^T\theta_1 - \frac{m_1}{2L}\tilde{\theta}_1^T\tilde{\theta}_1 \quad (5)$$

In Equation (5), $\tilde{\theta}_1^T\tilde{\theta}_1$ denotes the sum-of-squares formula, ε_1 denotes the unknown very small variable, and ε_1^* denotes its known upper limit, $|\varepsilon_1| \le \varepsilon_1^*$. Then it is the 2nd Lyapunov control function that is selected, and its derivatives are derived, where $z_3 = x_3 - \alpha_2$, using the Universal Approximation Theorem in place of the nonlinear part, to optimize the FAC. Due to the presence of the derivatives of the α_1, the structure of the controller is made more difficult, and is put into the next virtual controller in the next virtual controller. The appropriate VCF α_2 is chosen so as to cancel the derivatives of α_1 to eliminate the control difficulty and facilitate the realization, and the α_2 is substituted to obtain as in Equation (6).

$$\begin{aligned}\dot{V}_2 &\le -k_1 z_1^2 - k_2 z_2^2 + \frac{\varepsilon_1^{*2}+\varepsilon_2^{*2}}{2L} + \frac{m_1}{2L}(\theta_1^T\theta_1 - \tilde{\theta}_1^T\tilde{\theta}_1) \\ &+ \frac{m_2}{2L}(\theta_2^T\theta_2 - \tilde{\theta}_2^T\tilde{\theta}_2) + \zeta_2(\bar{x}_2) z_2 z_3\end{aligned} \quad (6)$$

After that, the n th Lyapunov control function is calculated, analogous to the above derivation of V_n, the universal approximation theorem is used instead of the nonlinear part, and through the sum-of-squares formula, the suitable VCF is selected, and finally the VCF is obtained as in Equation (7).

$$\begin{cases} V_n \le -A_0 V + \dfrac{B_0}{L} \\ A_0 = \min\{2k_1, 2k_2, ..., 2k_n, -m_1, -m_2, ..., -m_n\} \\ B_0 = \sum_{i=1}^{n}\dfrac{m_i}{2}\theta_i^T\theta_i + \sum_{i=1}^{n}\dfrac{\varepsilon_i^{*2}}{2} \end{cases} \quad (7)$$

In Equation (7), k denotes the controller design parameters (DPs) at step k.

2.2 Adaptive control of asynchronous motors incorporating BSC method and FL

Traditional control is based on models and FC is based on fuzzy mathematics, which is an intelligent control of NC that utilizes the language of fuzzification to achieve effective control of uncertain systems [19]. The study proposes a FATCNS method, which is selected as a typical representative motor of NC, with the motor as the main object of study, centering on the TC of the position of synchronous and asynchronous motors. The study utilizes the fuzzy basis function to approximate the nonlinear function nature, and the controller is designed by online parameter adaptive approach. Fig. 4 depicts the controller's precise structure.

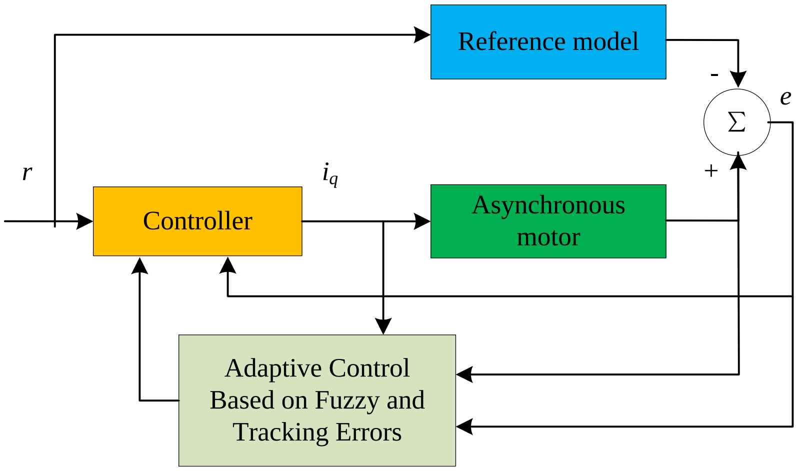


Figure 4: Controller structure

The theoretical foundation of FC and back stepping-based adaptive control provides a framework for the study's proposed class of control methods combining fuzzy and adaptive control. By leveraging the nonlinear portion of FLS, creating a suitable adaptive CL, and adding additional adaptive parameters, these techniques are made to be broadly applicable to NC and address the shortcomings of FC approaches in terms of control accuracy. Research is conducted on asynchronous motors with intricate mathematical models. The mathematical models of asynchronous motors are highly complex and of a considerable order, with parameters that can be readily adjusted. Additionally, the load torque is significant. Consequently, control is more challenging, necessitating the design of a LF and intermediate virtual controllers for each subsystem, obtained in a stepwise manner through the appropriate LF [20]. To simplify the complex model and ignore the influence of other factors, the study uses the coordinate transformation, which is carried out according to the rotating coordinate system (CS) of the rotor magnetic field. Equation (8) represents the asynchronous motor's mathematical model.

$$\begin{cases} \dot{x}_1 = x_2 + \varphi_1 \\ \dot{x}_2 = \dfrac{a_1}{J} x_3 x_4 - \dfrac{T_L}{J} \\ \dot{x}_3 = b_1 x_3 + b_2 x_2 x_4 + b_3 x_2 x_5 - b_4 \dfrac{x_3 x_5}{x_4} + b_5 u_q \\ \dot{x}_4 = c_1 x_4 + b_4 x_5 \\ \dot{x}_5 = b_1 x_5 + d_2 x_4 + b_3 x_2 x_3 + b_4 \dfrac{x_3^2}{x_4} + b_5 u_d \end{cases} \tag{8}$$

In Equation (8), φ_1 expresses the nonlinear part of the system, J expresses the rotational inertia in the CS. u_q and u_d express the voltage under the CS. T_L expresses the load torque of the motor in the CS. The study selects the appropriate LF at each step and selects the appropriate FL system to approximate the nonlinear part of it, constructs the virtual controller α_i, and obtains the actual FAC in the final step.

The design steps of the FATC machine for an asynchronous motor are as follows. Firstly, given a reference signal y_d, define the error variable $z_1 = x_1 - y_d$ of the system. For the first Lyapunov control function, obtain the adaptive law and the definition of the adaptive parameter L corresponding to $\hat{\theta}$. After derivation, the substitution of the derivation equation of $x_2 = z_2 + y_d$ is obtained from the error variable definition variant. Since the existence of the nonlinear part makes the design of the whole controller complicated, in order to optimize the FAC, the fuzzy approximation theorem is used to approximate the nonlinear part as in Equation (9).

$$\begin{aligned} \dot{V}_1 \le\ & z_1(z_2 + \alpha_1 + \hat{\theta}_1^T S_1(x) + \tilde{\theta}_1 S_1(x) + \varepsilon_1 - \dot{y}_d) \\ & - \frac{1}{L}\tilde{\theta}_1^T (L z_1 S_1(x) - m_1 \hat{\theta}_1) - \frac{\dot{L}}{2L^2}\tilde{\theta}_1^T \hat{\theta} \end{aligned} \tag{9}$$

Using the sum of squares formula and selecting the VCF as in Equation (10).

$$\begin{cases} z_1 \varepsilon_1 \le \dfrac{L}{2} z_1^2 + \dfrac{\varepsilon_1^{*2}}{2L} \\ \alpha_1 = -k_1 z_1 - \hat{\theta}_1^T S_1(x) - \dfrac{L}{2} z_1 + \dot{y}_d \end{cases} \tag{10}$$

In Equation (10), $k_1 > 0$, is the DP of the controller. Substituting the virtual controller, the final result is obtained as in Equation (11).

$$\dot{V}_1 \leq -k_1 z_1^2 + z_1 z_2 + \frac{\varepsilon_1^{*2}}{2L} + \frac{m_1}{2L}\theta_1^T\theta_1 - \frac{m_1}{2L}\tilde{\theta}_1^T\tilde{\theta}_1 \quad (11)$$

Again the 2nd and 3rd Lyapunov control functions are selected, the derivatives are derived and the VCF is selected. Additionally, to remove the influence of the preceding derivative, the nonlinear portion is approximated using the fuzzy approximation theorem. Since the FLS can only utilize the system variables that have already appeared earlier, it needs to be deformed so that it can be more accurately applied to the back stepping control (BSC) to obtain the final Lyapunov control function. In selecting the 4th Lyapunov control function, the $\dot{z}_4 = \dot{x}_4 - \dot{x}_d$ is obtained by defining the error $z_4 = x_4 - x_d$, given another reference signal x_d, in order to facilitate the TC of the system position. There is no nonlinear part in the subsequent substitution results, so FLS is not used for approximation. However, due to the presence of the adaptive parameter L and the form of the adaptive θ, it is necessary to select an FLS, and the study selects an FLS approximating 0 to join as in Equation (12).

$$\begin{aligned} f_4 &= 0 = \theta_4^T S_4(x) + \varepsilon_4 \\ &= \hat{\theta}_4^T S_4(x) + \tilde{\theta}_1^T S_4(x) + \varepsilon_4 \end{aligned} \quad (12)$$

The subsequent steps are the same as in 2 and 3. The actual FAC is constructed for the 5th Lyapunov control function. After derivation, the same operation as in 2 and 3 is performed, but in the selection of the actual control u_d as in Equation (13).

$$u_d = \frac{1}{b_5}\left(-k_5 z_5 - b_4 z_4 - d_2 x_4 - b_1 x_5 - \hat{\theta}_5^T S_5(x) - \frac{L}{2} z_5 + \dot{\alpha}_3\right) \quad (13)$$

In Equation (13), $k_5 > 0$, is the DP of the controller. Substituting the CL u_d yields as in Equation (14).

$$\dot{V}_5 = \dot{V}_4 + z_5 \dot{z}_5 - \frac{\dot{L}}{2L^2}\tilde{\theta}_5^T\tilde{\theta}_5 - \frac{1}{L}\tilde{\theta}_5^T\hat{\theta}_5 \quad (14)$$

The final result is obtained as in Equation (15).

$$\begin{cases} V_n \leq -A_0 V + \dfrac{B_0}{L} \\ A_0 = \min\begin{Bmatrix} 2k_1, 2k_2, 2k_3, 2k_4, 2k_5 - m_1, \\ 1 - m_2, 1 - m_3, -m_4, -m_5 \end{Bmatrix} \\ B_0 = \dfrac{m_1}{2}\theta_1^T\theta_1 + \dfrac{m_2+1}{2}\theta_2^T\theta_2 + \dfrac{m_3+1}{2}\theta_3^T\theta_3 \\ + \dfrac{m_4+1}{2}\theta_4^T\theta_4 + \dfrac{m_5+1}{2}\theta_5^T\theta_5 \\ + \dfrac{\varepsilon_1^{*2} + \varepsilon_2^{*2} + \varepsilon_3^{*2} + \varepsilon_4^{*2} + \varepsilon_5^{*2}}{2} \end{cases} \quad (15)$$

Through the rotational speed error as well as the rotational speed error change adaptive adjustment dynamically changes the y size, which affects the value of i, thus changing the control output. The fuzzy system module and the back stepping module make up the two primary components of the fuzzy adaptive BSC. Fig. 5 depicts the block diagram of the controller structure.

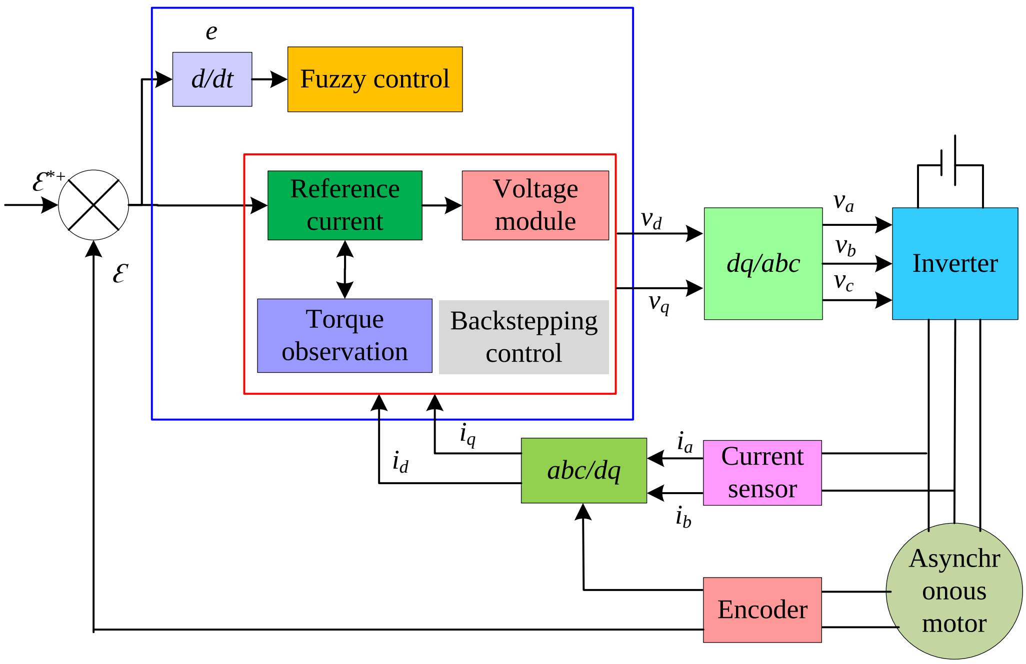


Figure 5: Controller structure diagram

For the convenience of experimentation and verification, relevant hypotheses and limitations were set up in the study. Firstly, it is essential to make reasonable assumptions about the system during the modelling process. This may entail the exclusion of certain secondary factors, the assumption of parameter variation within a defined range, and so forth. Secondly, there are control assumptions. In the controller design process, it is assumed that the system state is measurable or observable, and the CI is limited. Finally, due to limitations in computing resources and time, the model needs to be simplified or approximated using algorithms.

3 Results

To validate the FATCNS-based method suggested in the study, the experiment analyzes the corresponding DPs, verifies the advantages and feasibility of the method, and provides a reference for the effective control of NC.

3.1 Experimental design for performance validation of the FATCNS approach

The study conducts MATLAB simulation experiments, through the experimental results verifies that the fuzzy adaptive control method used in ACM can effectively track, showing the dynamic performance of the motor changes in the process of TC. Some of the specific parameters is shown in Table 2. The experimental platform has 8GB of memory, the system is OSXE | Capitan system, the experimental software is Matlab, and the 2.9GHz Intel i5 processor is used.

Table 2: The specific parameters involved in the experiment

Variables and parameters	Specific values and expressions	Variables and parameters	Specific values and expressions
J	0.0586Kg·m2	k_4	80
R_s	0.1	k_5	35
n_p	1	m_1	0.4
L_s	0.0699H	m_2	0.35
L_r	0.0699H	m_3	0.3
L_m	0.068H	m_4	0.4
T_L	1.5Nm: 0≤t≦5; 3Nm: 5<t	m_5	0.35
k_1	100	y_d	0.25sin(2t)
k_2	80	x_d	1
k_3	60	/	/

The experimental conditions include setting the initial state or conditions of the system to simulate different start-up situations, designing input signals to test the response characteristics of the system, and adding appropriate disturbance or noise signals to the system according to actual needs to evaluate the robustness of the controller.

3.2 Analysis of FATCNS results

In the motor parameter setting, the d-axis and q-axis inductances are adjusted to 0.5Lg and 1.5L, respectively. The speed response curves of the asynchronous motor in the traditional BSC and the fuzzy adaptive BSC are displayed in Fig. 6, where the rotor rotational inertia is 1.1J and the controller parameters remain the same. The speed of fuzzy adaptive BSC goes from decreasing to increasing before 0.55s and stabilizes at 150 rads around 0.65s, while the traditional BSC method stabilizes at 148 rads. Although it tends to stabilize at 0.55s, but it does not reach the reference speed. Therefore, the fuzzy adaptive BSC has stronger stability and robustness compared with the traditional BSC.

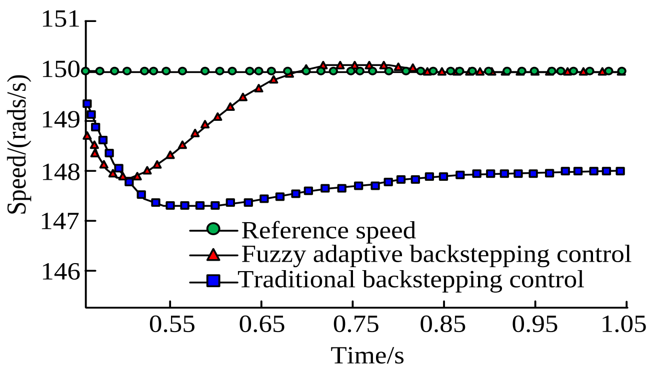
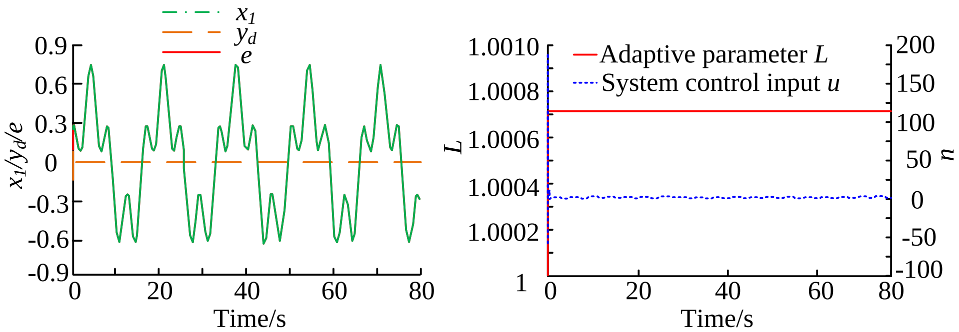


Figure 6: Speed response curves of asynchronous motors in traditional BSC and fuzzy adaptive BSC

To confirm that the research proposed approach tracking is effective, experiments are run on the second order system. Fig. 7(a) shows x_1, the tracking target y_d and the system TE e. The Fig. 7(b) shows the adaptive parameter L and the system CI u. In Fig. 7(a), x can immediately track on the tracking target y_d, and it can react quickly to keep the TE within the accuracy. Moreover, the tracking effect is very stable and the error is small. In Fig. 7(b), the CI u is able to respond quickly with a smooth input. It may oscillate more at the beginning, but since the parameter L is adjusted at the beginning, the system stabilizes quickly with good control. The adaptive parameter L is quickly adjusted at the beginning of tracking and suddenly increases, directly making the TE less than the control accuracy requirement. At the back L does not continue to change, this is because at the beginning of the system the error is immediately controlled within the accuracy range. When the derivative of L is 0, L does not change anymore and remains unchanged, the TE is also always controlled within the accuracy range. The adaptive parameter L ensures that the system quickly tracks up the tracked target to meet the requirement of control accuracy.

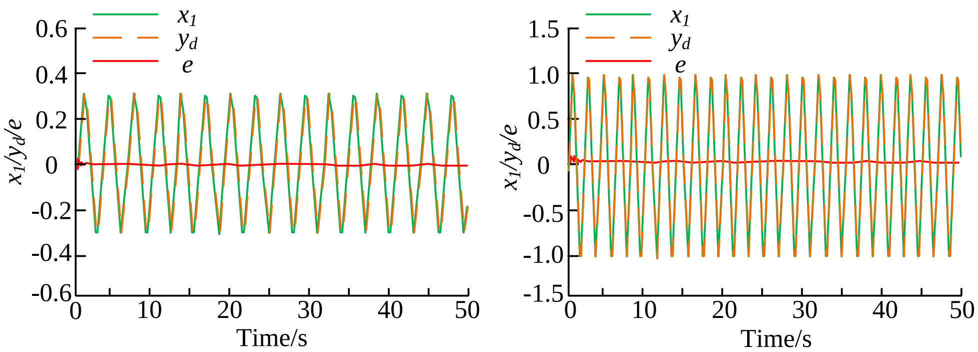


(a) x_1 and tracking target y_d, as well as system tracking error e

(b) System control input u and adaptive parameter L

Figure 7: Research proposes method tracking effectiveness parameter analysis

Fig. 8 displays the results of the simulation. Fig. 8(a) shows x_1, tracking target y_d and system TE e for the asynchronous motor. Fig. 8(b) shows x_1, tracking target y_d and system TE e for the synchronous motor. In Fig. 8(a), x_1 does not have a very large error when tracking at the beginning, and it stays within a small range. It is able to track the target function y_d very quickly. Even if the load torque changes (LTC) at t=5, it still maintains a small tracking The TE e is still small even when the LTC at t=5. Since the LTC, L starts to make small adjustments to achieve the TE e within a certain accuracy range. In Fig. 8(b), x_1 can track the target function y_d very quickly, at this time, because the parameter L is constantly being adjusted. Therefore, the TE e will be further reduced until the TE e is realized to be within the required accuracy and the tracking effect is very stable.

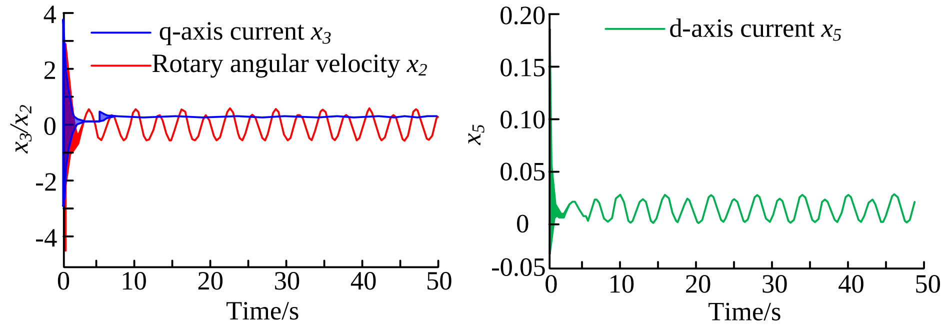


(a) Asynchronous motor system

(b) Synchronous motor system

Figure 8: x_1 and tracking target y_d, as well as system TE e

Fig. 9(a)-(b) show the rotor angular velocity x_2, q-axis current x_3 and d-axis current x_5 of the asynchronous motor system. The variation of the rotor angular velocity x_2 initially oscillates sharply, but the system gradually stabilizes as the parameter L is adjusted. It can be concluded that the q-axis current x_3 varies smoothly with the constant change in input voltage and the d-axis current x_5 varies smoothly with the change in input voltage.

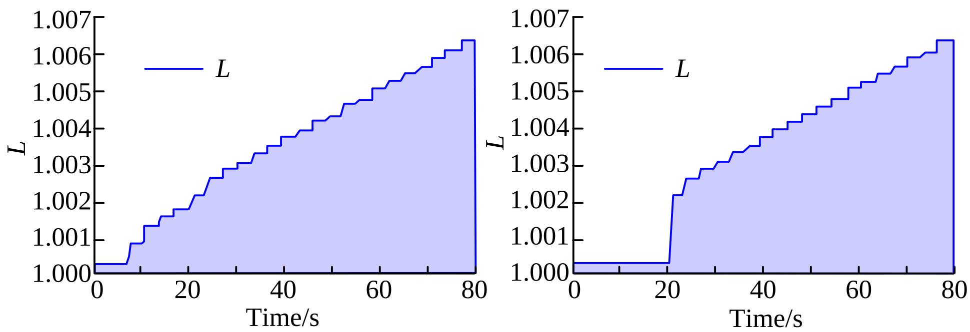


(a) Rotary angular velocity x_2 and q-axis current x_3

(b) d-axis current x_5

Figure 9: Rotor angular velocity x_2, q-axis current x_3, and d-axis current x_5 of an asynchronous motor system

Fig. 10(a) displays the change of adaptive parameter *L* for asynchronous motor. Fig. 10(b) shows the variation of adaptive parameter *L* for synchronous motor. In Fig. 10(a), the adaptive parameter *L* is constantly fine-tuned when the mistake exceeds the precision of the control. Because of the definition of *L*, it can also be noticed from the figure that *L* has an increasing trend to achieve the control accuracy. In Fig. 10(b), the adaptive parameter *L* is constantly undergoing minor adjustments over time, with an increasing trend, to achieve the requirement that the TE is less than the control accuracy.

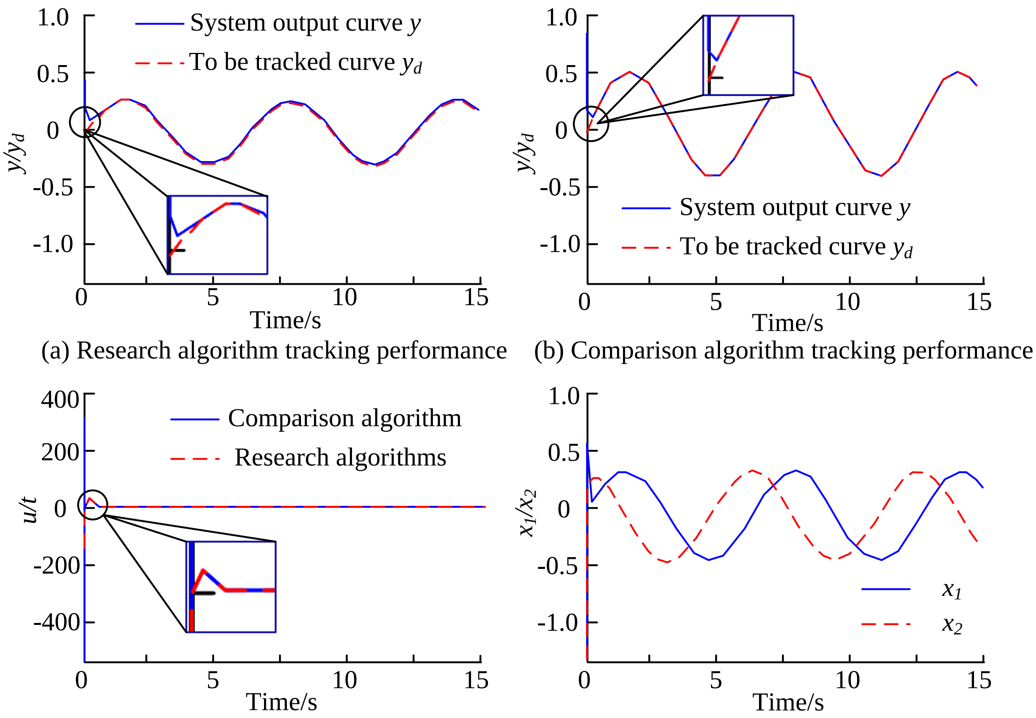


(a) Asynchronous motor

(b) Synchronous machine

Figure 10: Changes in adaptive parameter *L* for different motors

In Matlab simulation, the controller DPs k=13, α=1/3, β=4/3 are taken. The initial state of the system is taken as x_1 (0) =0.5, *u*(0)=0 and x_2 (0)=-0.3. Figs. 11(a)-11(b) show the tracking performance curves of the research-designed control algorithm in comparison with the tracking performance curves of the comparison control algorithm. Fig. 11(c) shows the comparison between the CI *u* of the research algorithm and the CI *u* of the comparison algorithm, and Fig. 11(d) shows the response curve of the research system state x_1 and x_2. According to the simulation results in Figs. 11(a)-(b), for the same system equation, the research proposed control algorithm has more accurate tracking effect compared to the comparison algorithm. In Fig. 11(c), the CI *u* of the comparison algorithm has much higher pulse than the research CI when the system is just started. Thus, it is possible to deduce that every signal inside the CLS is well-bounded and monitored.

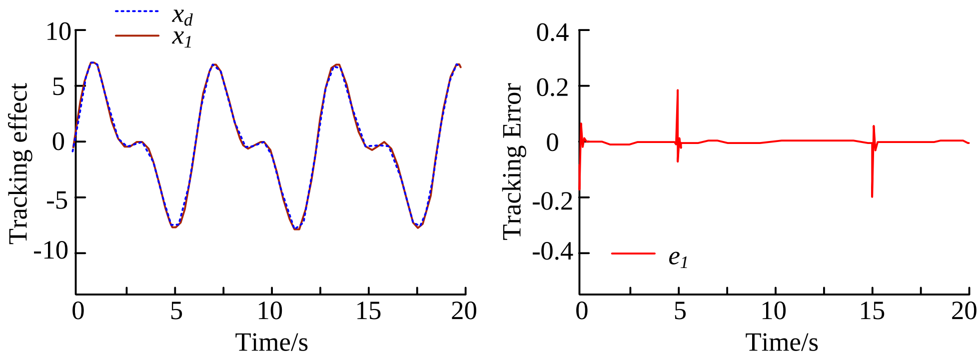


(a) Research algorithm tracking performance (b) Comparison algorithm tracking performance

(c) Control input u (d) Response curves for states x_1 and x_2

Figure 11: Comparison of tracking performance curves, control inputs, and system state x_1 and x_2 response curves between research control algorithms and comparative algorithms

To verify the robustness of the control algorithm proposed by the research, step disturbance signals with amplitudes of 20 and -20 are applied at 5s and 15s, respectively. From the tracking effect in Figure 12, it can be concluded that when the CLS is disturbed by disturbance signals, the controller can quickly restore the original state of the CLS and has strong robustness.



(a) Tracking effect (b) Tracking Error

Figure 12: Tracking effect after applying disturbance interference

The research requires statistical analysis of the tracking application effect of tracking algorithms. Three optimized sensors are applied to motors, and their sensitivity is compared and analyzed. The results are shown in Figure 13. The research method was applied to motor 2. The sensitivity index represents the sensitivity of the system to changes in input parameters, with values closer to 1. It indicates a higher sensitivity of the system to changes in input parameters. In different system monitoring, compared to other motors, the system sensitivity detected by motor sensors based on NC FATC method is higher.

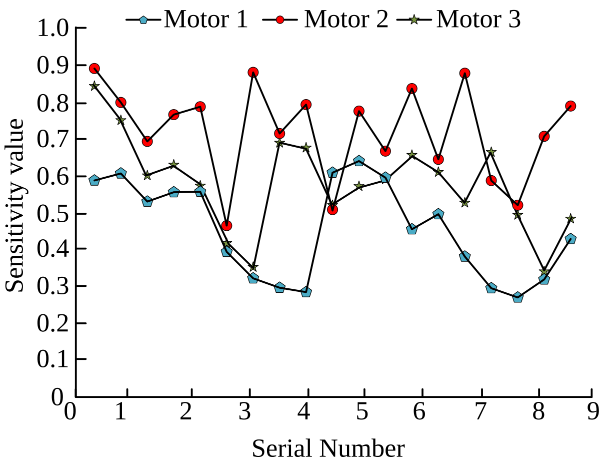


Figure 13: Sensitivity comparison of three algorithms

4 Discussion and conclusion

Due to its simple structure and easy control, ACM is widely used in aerospace field and military equipment. Concern and attention to the development of electric motors is of great strategic significance for the improvement of China's core competitiveness and China's economic construction. Thus, investigating cutting-edge control technology to enhance the motor's control performance is a useful area of study. The study suggests the FATC method for nonlinear ACM systems, which is based on back stepping and FL, in order to enhance the TC performance of this NC. According to simulation studies, the fuzzy adaptive BSC was more robust and stable than the conventional BSC. In the case of changes in x_1, tracking target y_d and system TE e of the asynchronous motor, x could immediately track on the tracking target y_d and could react quickly to keep the TE within the accuracy range. In addition, its tracking effect was stable and the error was very small. The variation of the adaptive parameter L for different motors indicated that the adaptive parameter L was constantly fine-tuned when the error was larger than the control accuracy. L showed an increasing trend, which could show the feasibility and superiority of the proposed algorithm of the study to achieve the control accuracy. Nevertheless, the study is excessively reliant on the control parameters of the motor, and the system uncertainty is considerable. Consequently, it is imperative to pursue alternative control methods that can circumvent the physical model of the motor in future research. This will facilitate the realization of nonlinear control with enhanced performance.

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