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A Novel Hybrid Backstepping and Fuzzy Control for Three Phase Induction Motor Drivers

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ABSTRACT

High-performance control using three-phase Induction Motors (IM) is increasingly required in industrial applications. However, due to the nonlinear structure and the continuous impact of issues such as load disturbances and motor parameter variations, traditional control techniques cannot achieve the desired high-performance drive system. In this paper, a new hybrid control scheme combining Backstepping (BS) with fuzzy logic (FL) control for the outer speed control loop to enhancing Field Oriented Control (FOC) vector control performance of the SPIM drives, is proposed. Different from the BS control strategies that have been proposed in the control of IM drive systems before, this paper proposes to use FL control theory to continuously update the coefficients appearing in the virtual control vectors extracted from the traditional BS control technique according to the input error of the system. This contributes to improving the performance of the drive system, enhancing the stability and adaptability of the drive system. Lyapunov stability theory is used to design the drive system to ensure the stability of the overall system. The proposed speed control strategy is validated through Matlab-Simulink. The simulation results show that: first, the proposed control strategy provides fast speed response, and the convergence capability of the drive system remains in an optimal state during transient modes without causing overshoot. Second, the drive system operates stably over the long term under load disturbances.

1. Introduction

Today, the induction motor have been widely used in many high performance industrial applications and are gradually replacing traditional DC motor drive systems. This is achieved thanks to the superior advantages of IM over DC motors, such as: a simple and robust structure, low production cost, minimal maintenance requirements, high efficiency and reliability [1].

With the increasing demands for performance, response time, steady-state error, in the control of IM, various control techniques have been developed based on modern vector control strategies. Among them, direct torque control (DTC) is a simple control strategy that allows control of both flux and torque components. In addition to some advantages such as fast response, less dependence on motor parameters, DTC also has the advantage of simple design, does not require conversion between coordinate systems or current control loops [2]. However, DTC faces some significant disadvantages, such as flux and torque ripple, high switching frequency, generating mechanical noise and vibration in the motor and poor control performance at low speeds [3]-[5]. In contrast to the DTC control strategy, FOC invented in 1972 [6], provides fast torque response, wide speed control range and high performance over a wide range of load variations. These benefits are achieved by decoupling the control of torque and flux. Problems such as flux and torque ripple, mechanical noise and vibration in the motor, as well as poor control performance at low speeds, do not occur in this control method. In addition to these remarkable advantages, FOC still has some disadvantages such as high sensitivity to changes in machine parameters, relatively complex control design due to the need to convert between coordinate systems, and the use of many control variables [7]-[8]. Therefore, when applying traditional PID control methods with fixed coefficients to FOC, it often fails to meet the control quality required for high-performance drives [9].

With remarkable advancements in the fields of power electronics, microcontrollers, and machine language, various control techniques have been implemented for IM drive systems such as: Linear output feedback control [10]-[12], Sliding mode (SM) [13]-[24], Backstepping control [25]-[36], Fuzzy Logic control [37]-[42], Neural networks (NN) control [43]-[46], predictive control [47], Hamiltonian control [48]-[51], Hybrid controllers [52]-[57], etc. In the proposed control techniques, Backstepping control has received significant research attention due to its systematic and recursive design methodology for nonlinear feedback control. It has the ability to decompose the high-order global system into a series of first-order subsystems. Each control signal generated by a subsystem will serve as a reference for the next system until the final command appears [58]. The BS method has produced very interesting results which have been discussed in [59], [60]. However, when applying classical BS techniques to IM drive systems, the performance is only modest, especially when there are changes in uncertain nonlinear components in the system. Some researchers have chosen to design external disturbance observers to solve this problem [59]. A simpler and more effective approach to improving the ability to eliminate external disturbances using a pure integrator has been proposed. However, in practical control systems, saturation blocks are essential in the control structure of IM drive systems. The use of integrators with limited devices can lead to a phenomenon known as windup [60]. This phenomenon means that the information generated by the controller does not accurately match the actual command for the drive system. During transient modes, the effect of the integrator can continue to increase even when the control signal exceeds its limit value. As a result, it becomes challenging to quickly weaken the actual control signal before the system fully stabilizes. During saturation, the dynamic response can cause significant overshoot, accompanied by strong oscillations and excessive inrush current, which is detrimental to the motor and its power supply.

To improve the quality of the IM drive system using the Backstepping technique without increasing system complexity, this paper proposes a Backstepping technique with coefficients adaptively adjusted through fuzzy logic control. This stable and easily implementable control technique combines the option of adaptively transforming coefficients into the speed controller by applying fuzzy control theory to ensure optimal design for control signals. By using this method, the control process becomes adaptive, and the speed will be well-controlled, eliminating overshoot and optimizing transient modes. Lyapunov stability theory is also employed in this paper to design virtual control vectors, ensuring that the system consistently operates stably. The effectiveness of this proposed control structure is verified by simulation using MATLAB/ Simulink.

In the next section, a brief description of Field-Oriented Control (FOC) is provided. The improved FOC technique for the IM drive system is presented in Section 3. Subsequently, Section 4 discusses the research results obtained through MATLAB-Simulink software. Finally, Section 5 summarizes the contributions of the paper and includes a discussion.

2. Mathematical Model of IM Controlled by Indirect Field Oriented Technique

Field-Oriented Control is the most widely used strategy in industrial applications. The implementation of vector control simplifies the dynamic equations of IM by eliminating certain nonlinear elements. The simplified model provided by FOC is highly convenient for control applications. The fundamental idea of vector control is to make the dynamic performance of the IM drive system resemble that of a separately excited DC motor drive. This is achieved by aligning the axes of the synchronous rotating coordinate system so that the d-axis is aligned with the rotor flux space vector. In this configuration, IM control is performed in the synchronous reference frame, where alternating quantities appear as DC quantities under steady-state conditions. When the rotor flux is perfectly aligned along the d-axis, the quadrature flux component ψ_{rq} is eliminated. As a result:

- The direct current component i_{sd} can be controlled to maintain a constant rotor flux amplitude.
- The electromagnetic torque equation directly depends on the quadrature current component (i_{sq}).

In this case we obtain as follows: $\psi_{rq} = 0; \psi_{rd} = \psi_{rd}$. The model motor dynamics is described by the following space vector differential equations:

$$\begin{cases} \dfrac{d\omega_r}{dt} = \dfrac{3}{2}P\dfrac{\delta\sigma L_s}{J}(\psi_{rd}i_{sq}) - \dfrac{T_L}{J} - B'_{\omega_r} \\ \dfrac{d\psi_{rd}}{dt} = \dfrac{L_m}{\tau_r}i_{sd} - \dfrac{1}{\tau_r}\psi_{rd} \\ L_s\dfrac{di_{sq}}{dt} = -ai_{sq} + L_s\omega_e i_{sd} + b\omega_e\psi_{rd} + cu_{sq} \\ L_s\dfrac{di_{sd}}{dt} = -ai_{sd} + L_s\omega_e i_{sq} + bR_r\psi_{rd} + cu_{sd} \end{cases} \quad (1)$$

where $\sigma = 1 - \frac{L_m^2}{L_s L_r}; \delta = \frac{L_m}{\sigma L_s L_r}; a = \frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_r^2}; b = \frac{L_m^2 R_r}{\sigma L_r^2}; c = \frac{1}{\sigma}; \tau_r = \frac{L_r}{R_r}; B' = \frac{B}{J}$

$u_{sd}, u_{sq}, i_{sd}, i_{sq}$: The components of stator voltage and stator current, respectively; ψ_{rd}, ψ_{rq}: Rotor flux components; T_L, T_e: Electromagnetic and load torque; *d-q*; *D-Q*: Synchronous and stationary axis reference frame quantities, respectively; ω_r: the angular velocity (mechanical speed), $\omega_r = (2/P)\omega_{re}$; $\omega_{re}, \omega_{sl}, \omega_e$: the electrical speed respectively Rotor and slip angular and synchronous angular velocity; L_s, L_r: Stator and rotor inductances; L_m: Mutual inductance ; R_s, R_r: Stator and rotor resistances; *J*: the inertia of motor and load; σ: Total linkage coefficient; *P*: Number of pole pairs; *B*: Friction coefficient; τ_r: Rotor time constant. The new expression of the electromagnetic torque and the slip frequency are given by:

$$T_e = \frac{3}{2}n_p\frac{L_m}{L_r}\psi_{rd}i_{sq} \quad (2)$$

$$\omega_{sl} = \frac{L_m}{L_r}\psi_{rd}i_{sq} \quad (3)$$

3. Novel Hybrid Backstepping and Fuzzy Logic Control (BSFL) Design for the Vector Control of IM Drive

In this section, an improved Backstepping Control technique is proposed for three-phase IM drive systems. The BS method is a systematic and recursive approach to designing nonlinear control laws. The core idea of this control method is to transform the system into a cascade of first-order subsystems. The virtual control vectors are established based on Lyapunov stability theory [61] to ensure the convergence of the system to its equilibrium state. This approach allows for the synthesis of robust control laws that can withstand disturbances and parametric uncertainties. The robustness and stability of the control system are enhanced by: first, incorporating integral components that track the system's errors into the control design; and second, continuously updating the coefficients in the virtual control vectors during operation using fuzzy logic control techniques.

By employing this method, the control process becomes more adaptive, allowing for precise adjustment of the motor speed to follow a predetermined desired trajectory. This effectively eliminates most overshoot phenomena that typically occur during startup, reversal, or in response to external load disturbances. The proposed strategy not only improves responsiveness and enhances stability but also contributes to extending the lifespan of the motor and related components by minimizing mechanical stress during speed transitions. The following tracking errors are defined:

$$\varepsilon_\omega = (\omega_r^* - \omega_r) + k_\omega \int_0^{t\int} (\omega_r^* - \omega_r)dt \tag{4}$$

To ensure the stability of the outer loops, the virtual inputs isq are used. The dynamics of the tracking errors are given by:

$$\frac{d\varepsilon_\omega}{dt} = \frac{d\omega_r^*}{dt} - \left[\frac{3}{2}P\frac{\delta\sigma L_s}{J}(\psi_{rd} i_{sq}) - \frac{T_L}{J} - B'_{\omega_r}\right] + k_\omega(\omega_r^* - \omega_r) \tag{5}$$

The Lyapunov function is selected as

$$V = \frac{1}{2}\varepsilon_\omega^2 \tag{6}$$

its derivative can obtain:

$$\frac{dV}{dt} = \varepsilon_\omega \frac{d\varepsilon_\omega}{dt} = \varepsilon_\omega [\frac{d\omega_r^*}{dt} - k_t\,\psi_{rd}\,i_{sq} + \frac{T_L}{J} + B'\omega_r + k_\omega(\omega_r^* - \omega_r)] \tag{7}$$

Where: $k_t = \frac{3}{2}P\frac{\delta\sigma L_s}{J}$

To satisfy $\frac{dV}{dt} < 0$, Then

$$[\frac{d\omega_r^*}{dt} - k_t\,\psi_{rd}\,i_{sq} + \frac{T_L}{J} + B'\omega_r + k_\omega(\omega_r^* - \omega_r)] = -k_{BS}\varepsilon_\omega \tag{8}$$

From (8) BS control laws are designed as follows:

$$i_{sq} = \frac{1}{k_t\,\psi_{rd}}\left\{\frac{d\omega_r^*}{dt} + k_{BS}\varepsilon_\omega + \frac{T_L}{J} + B'\omega_r + k_\omega(\omega_r^* - \omega_r)\right\} \tag{9}$$

where k_{BS} and k_ω is positive constant that is continuously updated using fuzzy logic control techniques. Substituting (8) into (7), the derivative of the Lyapunov function can obtain as:

$$\frac{dV}{dt} = -k_{BS}\varepsilon_\omega^2 < 0 \tag{10}$$

The use of coefficients in the speed controller allows the controller to adapt across various operating regions and maintain robustness against external disturbances. However, traditional integral BS techniques may lead to issues overshoot in transient regimes because of the integral term [61]. However, a proportional integral is required in steady state compensate foruncertain nonlinearity including applied load torque values. During the overtaking, strong vibrations can appear together with an overcurrent. This is closely related to the selection of coefficients in the BS technique. This behavior can destabilize the overall system or even damage the control setup. The key point here is how to select appropriate coefficients to respect the maximum torque and current intensity, while generating control vectors capable of providing fast response, reducing overshoot, and ensuring robustness against external disturbances. The proposed solution is to use FL control to adaptively select coefficients that align with the speed error input to the controller. The FL control rules are designed as shown in Table 1. The coefficients k_{BS} and k_ω are updated according to the FL technique illustrated in Fig. 1. The FL control rule is presented in Fig. 2. The following tracking errors are defined:

$$\text{er\_}speed = |\omega_r^* - \omega_r| \tag{11}$$

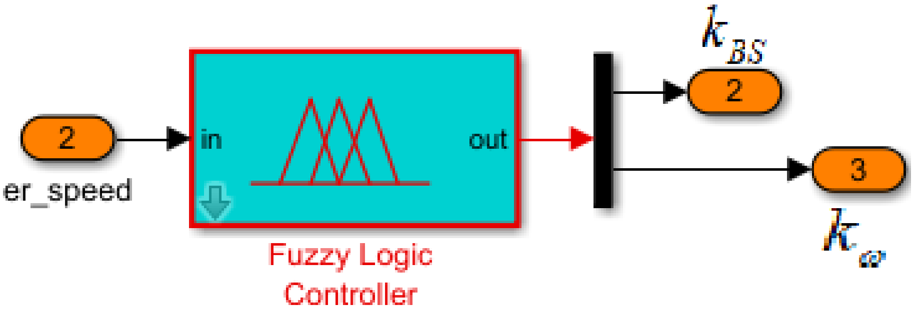


Fig. 1. Fuzzy logic controller updated coeficients

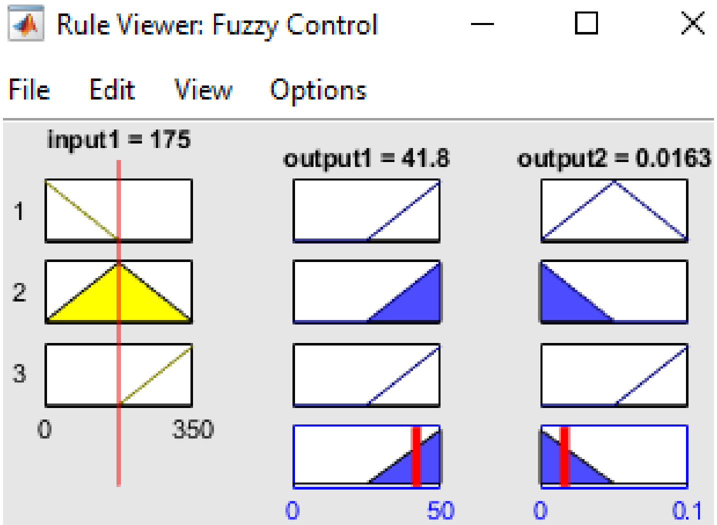


Fig. 2. The fuzzy logic control rule

Table 1. Includes the defined rules

er_speed	k_{BS}	k_ω
Positive Small	Positive Big	Positive Small
Positive Medium	Positive Medium	Positive Medium
Positive Big	Positive Small	Positive Big

The proposed BSFL scheme is illustrated in Fig. 3 where $Zn = [\psi_{rd}; T_L]$. The BSFL consists of a backstepping controller, a fuzzy logic adaptive law.

4. Simulink and Discussion

The vector control for IFOC induction motor drive system is simulated by using MATLAB software. The block diagram of system is shown in Fig. 4. The proposed BSFL technique is compared to the classical control using a PI controller and traditional BS controller, to show the effectiveness of the proposed BSFL algorithm. IM parameters: 400V, 50 Hz, 2 pole, 2950 rpm. Rs = 1.97Ω, Rr = 1.96Ω, Ls = 0.0154 H, Lr = 0.0154 H, Lm = 0.3585H, Ji = 0.00242 kg.m2.

In this section, the author uses Matlab-Simulink software to test the effectiveness of the proposed improved BS algorithm. Fig. 5 examines the dynamic response of the IM motor operating at different speed ranges to evaluate the dynamic performance of the proposed algorithm (The motor starts and operates at a rated speed of 295 rad/s, then reverses direction to -295 rad/s, reverses again back to +295 rad/s, and finally decelerates to operate at a low-speed range of +5 rad/s. A rated load of 7 N.m is applied at time t=0.2s and maintained throughout the survey period). The survey results are compared with traditional PI and BS algorithms. The results presented in Fig. 5 show that the algorithm proposed in this paper provides a good dynamic response, without overshoot issues. The speed is stable and consistently tracks the set speed.

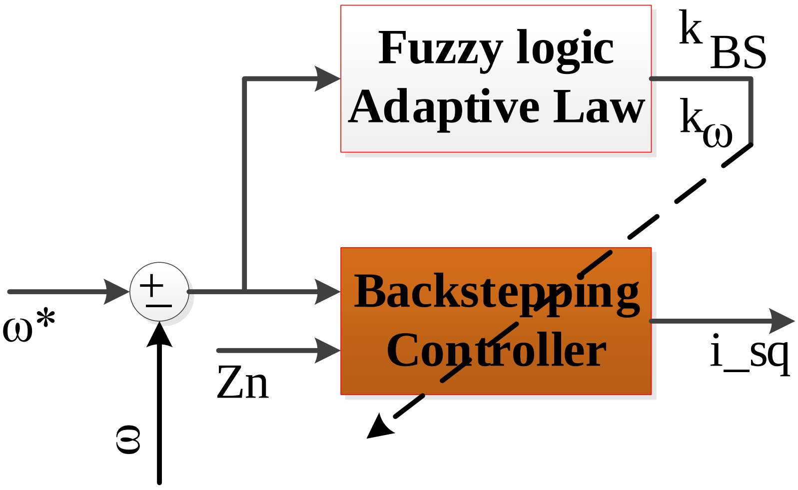


Fig. 3. Structure of the proposed BSFL

In Fig. 6, the author continues to present the survey results with a continuously varying load from 0 to 7 N.m and back to 0 at two speed ranges (the rated speed range and the low-speed range near 0). The simulation results show that despite the continuous load changes, the motor still provides a good response, with low error and consistently follows the given reference speed.

Fig. 7 shows the survey results on the robustness and stability characteristics of the proposed algorithm. The survey was conducted at a medium speed range (150 rad/s) with the rotor resistance Rr increased by 200%. The simulation results indicate that, with the proposed algorithm, the motor operates stably and is almost unaffected by the changes in Rr.

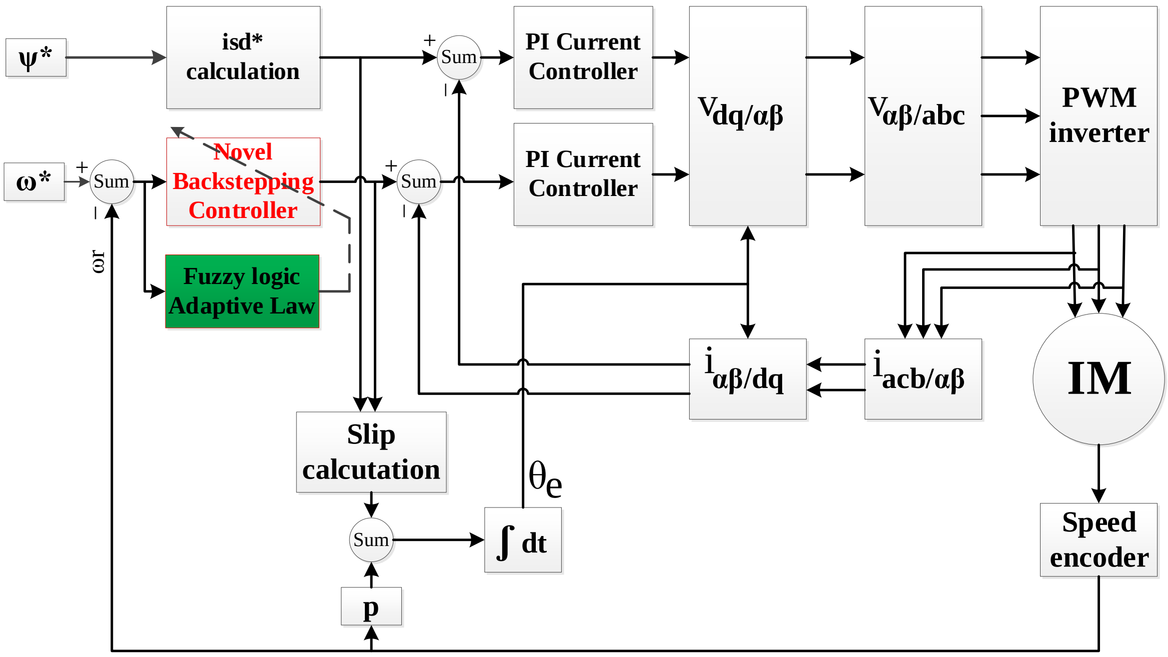
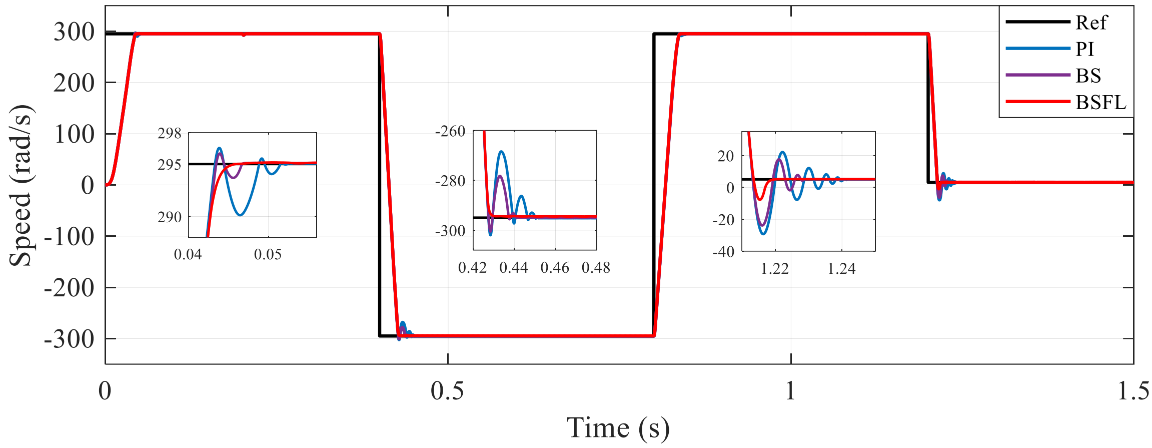
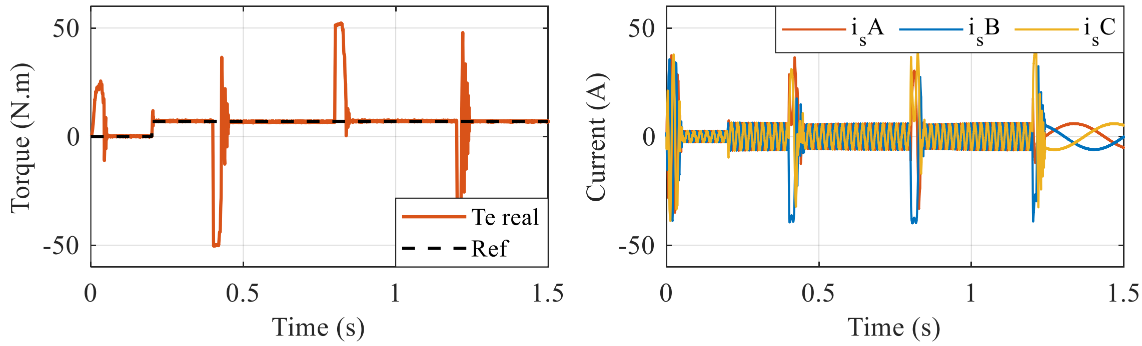


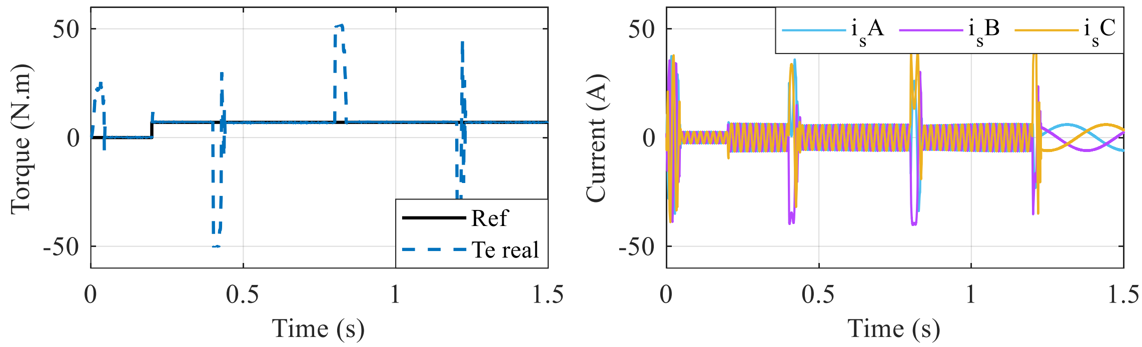
Fig. 4. The vector control of IM drive using BSFL control



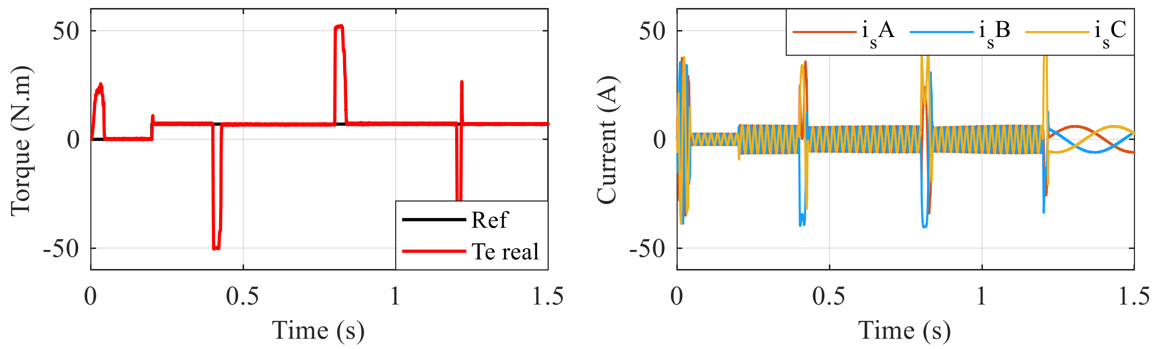
The dynamics performance of IM drive with PI, BS and BSFL controller



(a) Torque and Current with PI Controller



(b) Torque and Current with BS Controller



(c) Torque and Current with BSFL Controller

Fig. 5. The dynamics performance of IM drive with PI, BS and BSFL controller

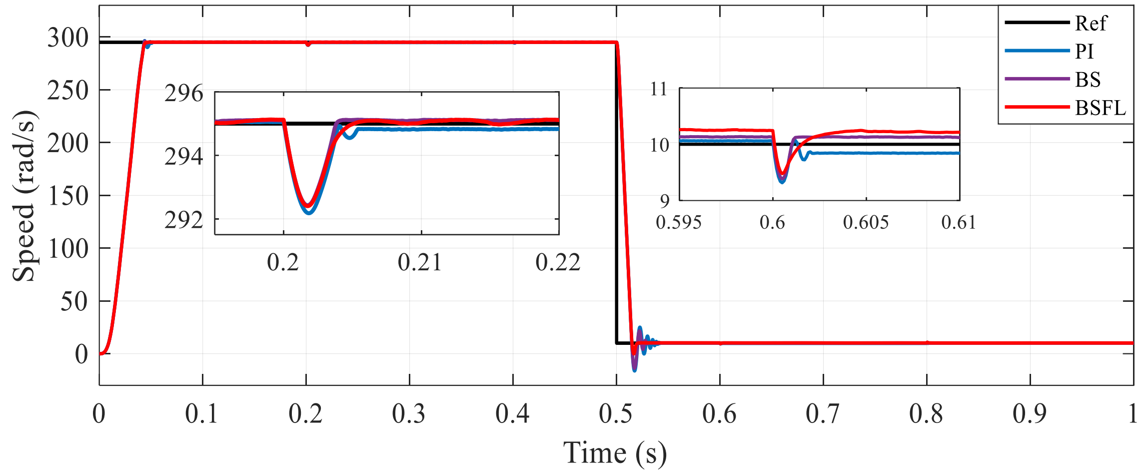


Fig. 6. Performance of SPIM drive on the load disturbance

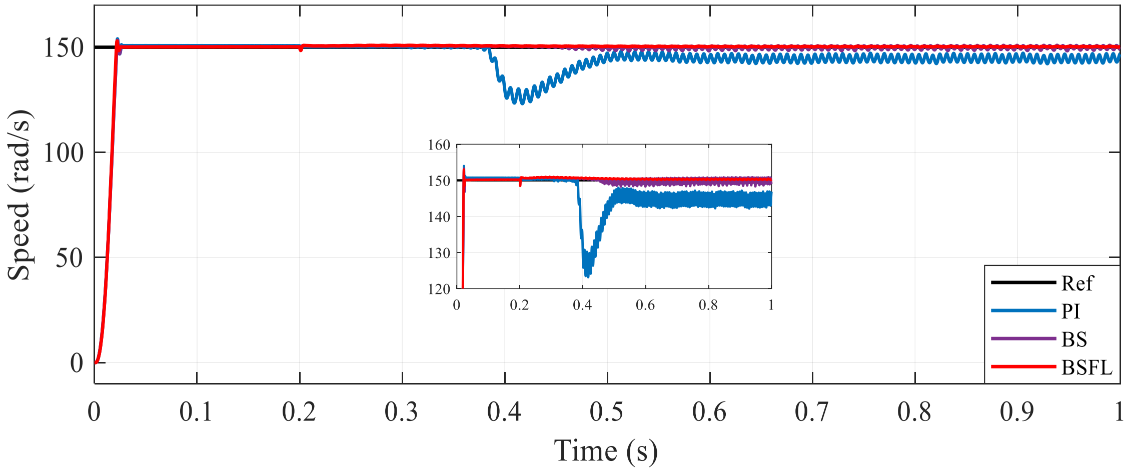


Fig. 7. Performance of SPIM drive with Rr increased by 200%

5. Conclusion

This paper introduces a new nonlinear control structure that combines Backstepping and fuzzy logic control for three-phase induction motors (SPIM). The controller design is based on Lyapunov stability theory with the Backstepping (BS) technique, where adaptive coefficients are controlled using fuzzy logic techniques to enhance the performance and robustness of the drive system, providing excellent static and dynamic performance for the IM drive system. This method allows precise adjustment of reference speed values, quick current and torque responses. The proposed new control technique delivers good speed response and eliminates overshoot during transient periods. With adaptive coefficients, the technique ensures stable operation across all speed ranges and improves resistance to load disturbances and changes in IM parameters. The simulation results and discussions in Section 4 have confirmed the good dynamic characteristics and robustness of the proposed control algorithm.

However, besides the notable advantages mentioned above, implementing the BS controller updated via FL requires microcontrollers with high processing speeds and robust configurations to continuously update the controller coefficients. Additionally, the design of fuzzy control rules heavily relies on expert knowledge to create fuzzification rules and select appropriate parameter ranges for FL. These are considered limitations of the proposed BSFL technique in this paper and are issues that require serious consideration and resolution in the future. The survey results demonstrate that this strategy is highly promising for industrial applications involving high-power systems and those demanding high control quality, reliability, and fault tolerance. It is particularly suitable for propulsion systems in electric vehicles and marine applications. In the future, the authors plan to develop hardware for real-world testing of the proposed control technique in practical systems, such as electric vehicle propulsion systems. Initially, small-scale power experiments will be conducted in laboratory settings, followed by testing on actual electric vehicle models.

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