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RESEARCH ARTICLE

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H-infinity robust control technique for controlling the speed of switched reluctance motor

Abstract The switched reluctance motor (SRM) is applied in various industrial applications due to its profitable advantages. However, the robustness speed of SRM is one of the major drawbacks, which greatly affects the performance of motor. Thus, the aim of this paper is to control the speed of SRM using *H*-infinity control strategy. This *H*-infinity control technique is stronger against robustness. In the proposed speed controller, the rotor position of the SRM is applied to the controller. The speed variation of the rotor is determined from the reference speed and applied to the controller as input. Then, the speed variation and the corresponding sensitivity function are determined. The sensitivity function determination is based on the input weight of the controller. The weight adjustment process is repeated until a stable speed condition is achieved. Then, the output of the proposed control technique is compared with the existing control technique and the robustness is analyzed. Here, the existing control techniques considered are proportional-integral (PI) controller and fuzzy logic controller (FLC)-based PI gain tuning. The proposed control strategy is simulated in MATLAB working platform and the control performance is analyzed.

Keywords switched reluctance motor (SRM), speed control technique, *H*-infinity control, robust

1 Introduction

Over the past decades, the switched reluctance motors (SRMs) have been the focus of several researches [1–3]. The SRM is a doubly salient device, in which a torque is created by the tendency of the rotor to move to a position where the inductance of the excited windings is increased [4]. The smooth production of electromagnetic torque is an enviable characteristic of any motor [5]. The benefits of SRM are low manufacturing cost, excellent reliability, fault tolerance, wide range of operational speeds and torque, and fast dynamic responses [6,7]. The SRM is convenient to numerous applications because of its simplicity and low-price [8]. The higher torque ripple, vibration, and acoustic noise are the major drawbacks that heavily disturbing the performance of SRM during high-speed application [9]. Thus, an exact knowledge of the rotor position is necessary for achieving an enhanced performance of the SRM drive [10]. Due to the simple motor structure and power converter requirements, SRM drives have been found to be competitive with conventional AC and DC drives [11,12]. An excellent electromagnetic operation of an SRM can be achieved only by the appropriate excitation control, but this is quite complex to attain only from experiments [13].

Moreover, during speed control, the SRM has undergone some troubles due to its nonlinear characteristics. For example, the function of flux correlation based on phase current and rotor position represents the key characteristic of the SRM, but it is tricky to depict such a relationship due to the effects of magnetic saturation and double saliency of the construction [14]. The SRM is a powerful, reliable and almost maintenance free device for variable speed application [15]. The nonlinear methods, namely, sliding mode, artificial neural network (ANN), fuzzy logic, and gain tuning proportional-integral (PI) controllers are often utilized for SRM control [16]. The traditional control techniques are incompetent in providing superior damping performance [17]. Robust *H*-infinity control can give a perfect control to linear systems and high robustness to stabilize in unfavorable operating conditions, such as parameter change, high disturbance environment actuator saturation, and model uncertainty [18,19]. The *H*-infinity control theory makes it possible to apply multivariable control with frequency domain design technique and to obtain efficient stable control systems [20].

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The SRM controlling problem is one of the mixed sensitivity control problems. In this paper, an *H*-infinity control technique is proposed for controlling the rotor speed of SRM. The function of the proposed control technique is to identify the position of the rotor. The rotor position variation is identified from the speed performance of the motor. The speed of the motor is compared with the reference speed and the actual speed of the rotor is determined. Based on the rotor position, the controller weight is adjusted. By satisfying the control strategy condition, the rotor speed of the motor is maintained as stable. From the controlled output, the torque, speed, and current characteristics are analyzed. The details of the problem statement and the proposed *H*-infinity controller-based speed control technique are described in Section 3. Before that, a summarized review about the recently available related researches is given in Section 2. Section 4 discusses and analyzes the results of the proposed *H*-infinity control technique and Section 5 concludes the paper.

2 Related research works: A brief review

Numerous related works that already existed in the literature are based on rotor control of SRM. Some of them are reviewed here. Karakas et al. [21] have proposed a dynamic model, where the flux current-rotor position and torque current-rotor position values of the SRM have been obtained. Here, the motor control speed has been achieved via self-tuning fuzzy PI controller with ANN tuning (NSTFPI). Finally, the performance of NSTFPI controller has been compared with the performance of fuzzy logic (FL) and fuzzy logic PI (FLPI) controllers with regard to rise time, settling time, overshoot, and steady-state error.

An application of adaptive neuro-fuzzy (ANFIS) control for SRM speed has been presented by Tahour et al. [22]. The ANFIS has the advantages of expert knowledge of the fuzzy inference system and the learning ability of neural networks. An adaptive neuro-fuzzy controller of the motor speed has been then designed and simulated. Simulation results have proved that the proposed ANFIS speed controller has achieved an enhanced dynamic performance of the motor, a perfect speed tracking with no overshoot, and a better rejection of load disturbance impact. Moreover, the results of applying the adaptive neuro-fuzzy controller to an SRM have given an excellent performance and high robustness than those obtained by the application of a traditional controller (PI).

As well, Tahour et al. [23] have presented an application of sliding mode control for SRM speed. The sliding mode approach finds its stronger justification in the exploitation of an efficient control law to model uncertainties. A sliding mode controller of the motor speed has been then designed and tested.

Kamala Kannan et al. [24] have studied the control of SRM by a tuned fuzzy logic controller. Here, the structure hierarchy and the computational complexity of the controller have been simplified by minimizing the number of fuzzy sets in the membership function (MF) without reducing the efficiency of the system. By the development of a knowledge/rule base with scaling factors, the tuning of fuzzy logic controller has been carried out. A complete simulation, applied to the nonlinear model of SRM has been studied by means of MATLAB and an enhanced performance has been revealed through the simulation results.

The problem of position control in SRM drives has been investigated by Srivastava et al. [25]. They have utilized an advanced proportional-integral (PI) and proportional-differential (PD) controllers for the speed and position control, respectively. Here, the parameters of the controllers were online fine tuned based on the load torque and rotor speed in order to achieve a high dynamic performance and accurate position control. Also, a low-pass filter has been integrated in the position controller for enhancing the set-point tracking of the drive performance. The proposed four-quadrant control technique was based on the average torque control method. The turn-on and turn-off angles have been determined via simple formulas and the proposed regulator has the potential to maintain the torque ripple at a satisfactory level over a wide speed range. This was significant because the motor torque ripple greatly affects the accuracy of position control.

Rafiq et al. [26] have presented a performance comparison of PI controller with sliding window controller for speed control of SRM. Also, a robust controller has been proposed for high performance speed control and tracking problem of SRM. The proposed scheme was based on higher order sliding mode (HOSM) method. The proposed controller has assured that the motor speed converges to the desired speed considerably faster than other traditional techniques. The simulation results have shown the efficiency of the proposed controller. Moreover, the strength of the proposed controller to parametric variations has also been validated via simulation studies.

Wang et al. [27] have intended to simplify the structure hierarchy and computational complexity of the controller by minimizing the number of fuzzy sets in the MF without reducing the efficiency and stability of the system. For the proposed controller, the output scaling factor has been changed incessantly by a gain updating factor, whose value has been derived from the fuzzy logic reasoning with the error and change of error of the plant as the input variables. The rule base has been generated based on the practical comprehension and knowledge of the SRM's basic dynamic performance, operating mode, and experimental experience. Different aspects of the design considerations about the membership function, rule base, and gain tuning strategy have been described in detail.

3 Problem formulation and proposed methodology

From the review of the recent research works, it is clear that during the time of high-speed operations in certain application, the SRM reaches an uncontrollable speed. Thus, the continuity operation of SRM gets affected that leads to internal damage. Due to this internal damage, the torque and speed characteristics are affected. To control the speed of SRM, different control techniques are presented in the literature. Those control techniques are broadly classified into linear and nonlinear control techniques. The nonlinear control techniques are sliding mode, artificial neural network (ANN), fuzzy logic and gain tuning PI controllers. The sliding mode control technique is applicable only for bounded disturbance; hence it is not suitable in unbounded region. In ANN-based technique, a huge training data set is needed for controlling the speed of SRM. To generate such training data set, a survey about the SRM control is required, which is one of the complex processes. The fuzzy system can be operated without data set, but its straightforward characteristics lead to poor performance in nonlinear controlling problems. Finally, the PI controller tuning process is a closed-loop controlling process. Thus, the control process is repeated for regulating the speed variation of SRM. If a sudden disturbance is happened during the time of controlling process, the overshoot of PI controller is varied to an undesirable range as well as the sensitivity of controller gains is affected. Hence, to overcome all these problems, an *H*-infinity control technique is proposed for controlling the speed of SRM. The *H*-infinity controller is performed based on the robustness of the control system. The description of the proposed controller is given in the following subsections.

3.1 Behavior model of SRM

The motor behavior model is used for analyzing the magnetizing characteristics of the system by the related parameters. In SRM, the parameters are the flux linkage, the inductance, the torque possess highly coupling and nonlinear with the variation of rotor position and phase current [27]. The variation in rotor position behavior is occurred due to the uncertainties such as noise, load variation, and more. Here, three-phase 6/4-pole SRM is taken for analyzing the behavior model and the characteristics. Figure 1 shows the cross section profile of a three-phase 6/4-pole SRM and its equivalent circuit of one phase winding. The equivalent circuit can be represented by a resistance R in series with an inductance $L(i,\theta)$, which is a function of rotor position θ and excitation current i. The cross section and the equivalent circuit of three-phase 6/4-pole SRM is described as follows.

From the equivalent circuit, the magnetic coupling effect between two phases is taken into account and the dynamic behavior of the m-phase SRM is analyzed. The voltage equation of SRM in each phase is determined as

$$v_r = Ri_r + \frac{\mathrm{d}\lambda_r(\theta,i_r)}{\mathrm{d}t} + \frac{\mathrm{d}\lambda_l}{\mathrm{d}t}, \tag{1}$$

where v_r is the rth phase winding voltage, i_r is the rth phase current, λ_r is the linking flux, R is the resistance of phase winding, and λ_l is the leaky linking flux. In Eq. (1), the coupling between the adjacent winding is neglected. Thus, the equation is expressed as

$$v_r = Ri_r + \frac{\mathrm{d}\lambda_r(\theta,i_r)}{\mathrm{d}i_r} \times \frac{\mathrm{d}i_r}{\mathrm{d}t} + \frac{\mathrm{d}\lambda_r(\theta,i_r)}{\mathrm{d}\theta} \times \frac{\mathrm{d}\theta}{\mathrm{d}t} + \frac{\mathrm{d}\lambda_l}{\mathrm{d}t}, \tag{2}$$

i.e.,

$$v_r = Ri_r + L_{inc}\frac{\mathrm{d}i_r}{\mathrm{d}t}C_{back}\omega + L_f\frac{\mathrm{d}\lambda_r}{\mathrm{d}t}, \tag{3}$$

where L_{inc} is the increasing inductance, C_{back} is the back EMF coefficient, and L_f is the flux leakage. The L_{inc} and C_{back} depend on the phase current and rotor angular position. The torque is produced by the SRM and the co-energy is obtained by the following equation:

$$T(i,\theta) = \sum_{k=1}^{n}\left(\frac{\partial W}{\partial \theta}\right)_{i_j=etc}, \tag{4}$$

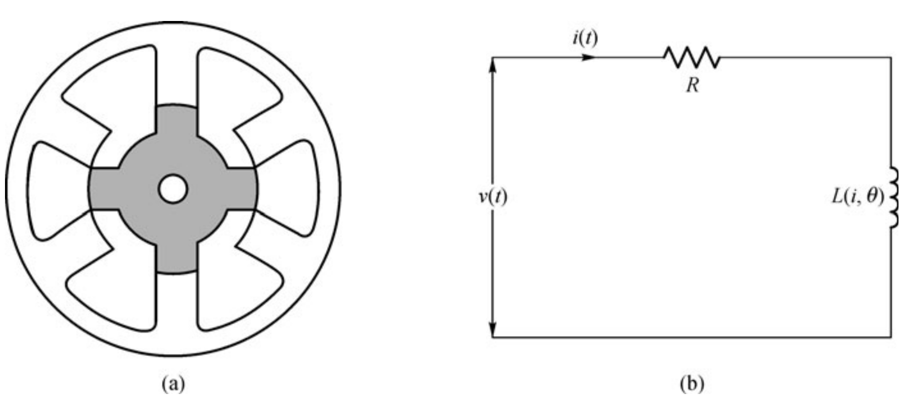

Fig. 1 (a) Cross section and (b) equivalent circuit of 6/4-pole SRM

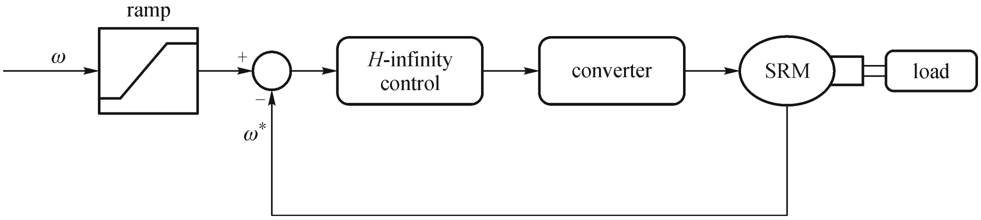

Fig. 2 Proposed SRM drive system

$$W(i_r,\theta) = \int_0^{i_r} \lambda_r(i_r,\theta). \tag{5}$$

The mechanical equation of the SRM is described as

$$\omega = \frac{\mathrm{d}\theta}{\mathrm{d}t}, \tag{6}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{J}\Big(T(i,\theta) - T_L - B\omega\Big). \tag{7}$$

In Eqs. (6) and (7), ω is the angular velocity, T_L is the load torque, B is the friction coefficient, and J is the moment of inertia. The speed of SRM is the part of the angular velocity. Thus, the angular velocity control value is the control speed of the motor and other velocity depending on the parameters. Here, the angular velocity is controlled by the *H*-infinity controller. Through the control value of angular velocity, the friction of the system is reduced. The block diagram of drive system is shown in Fig. 2.

3.2 Robust control formulation for SRM

H-infinity is one of the robust control techniques, used to synthesize controllers for achieving robust performance. To use *H*-infinity method, a control designer first expresses the control problem as a mathematical optimization problem and then finds the controller that solves this problem. The *H*-infinity control technique is readily applicable to solve problem involving multivariable systems [28]. Also, using the *H*-infinity control, the nonlinear constraints are handled well. In the proposed SRM speed control, the *H*-infinity control structure is based on a standard feedback structure. It consists of a plant *P*, a controller *K*, reference speed ω_r, commanded input, i.e., manipulated variable u, output z, and error speed e. To include some performance objectives in the system model, the standard feedback structure is modified by adding weighting functions. The weight function measures the components in different metrics. The standard feedback *H*-infinity control structure configuration is shown in Figs. 3(a) and 3(b).

The general formula for the above system is illustrated as below:

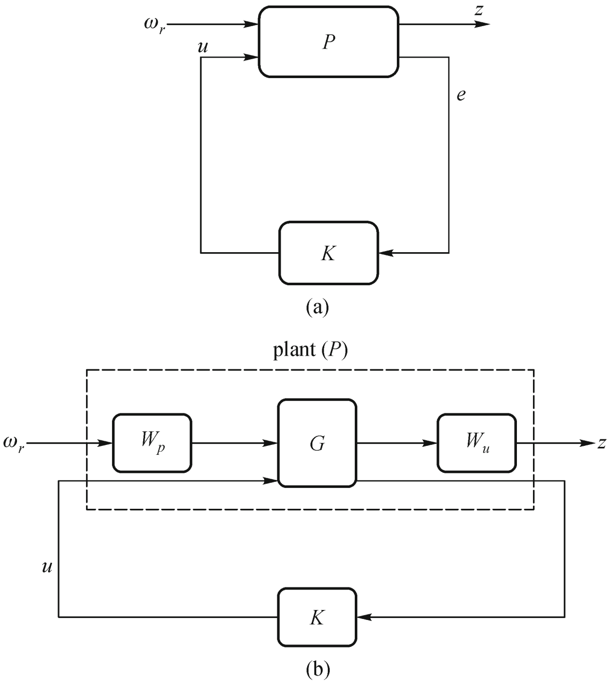

Fig. 3 *H*-infinity feedback control structure configuration

$$\begin{bmatrix} z \\ v \end{bmatrix} = P(s)\begin{bmatrix} \omega \\ u \end{bmatrix}. \tag{8}$$

The value of $P(s)$ is system function of SRM, which is given as

$$P(s) = \frac{1/R_m}{(L/R_m)s + 1}. \tag{9}$$

The condition for satisfying the closed-loop system is

$$\|T_{zw}(s)\|_\infty \leqslant \gamma, \tag{10}$$

where $T_{zw}(s)$ is the closed-loop transfer function matrix from ω to z. The weight of the matrix is adjusted to control the output of the motor. The weight adjustment process is repeated till the SRM speed reaches a stable condition that was described in Eq. (10). The output of the system is represented in frequency domain. The input and output weight of the system are W_p and W_u. Usually, the *H*-infinity control problem is solved by using Riccati equations. Here, the control problem is considered as the mixed sensitive problem. The closed-loop stable speed condition of SRM is described as

$$\|T_{zw}\|_\infty = \left\| \begin{matrix} -W_pGS & -W_pS \\ -W_uT & -W_uKS \end{matrix} \right\|_\infty \leqslant \gamma, \tag{11}$$

where GS, S, T and KS are the pre-specified templates of all the closed-loop transfer function of SRM. Then, W_p and W_u are the weight function. The sensitive weight function W_p and W_u are defined as follows. The inverse of the weighting function $W_p(\mathrm{j}\omega)$ is used to impose a performance specification in terms of the sensitivity function S:

$$W_p(\mathrm{j}\omega) = \frac{\mathrm{j}\omega/M_s + \omega_b}{\mathrm{j}\omega + \omega_b A_s}. \tag{12}$$

The control output u is weighted according to the SRM limitations:

$$W_u(\mathrm{j}\omega) = \frac{\mathrm{j}\omega + \omega_{bc}/M_u}{\mathrm{j}\omega\varepsilon + \omega_{bc}}. \tag{13}$$

Then, using the sensitive function, i.e., Eqs. (12) and (13), the sensitivity of the reluctance motor is maintained. Thus, the steady-state error of the system is reduced and the controller gain is ensured. The purpose for ensuring the controller gain is to make the speed of the SRM in stable range at any speed variation. The speed variation is compensated by reducing the uncertainty of the system by means of adding weight. The weight matrix of the system is defined based on the rated speed of SRM. Once the weight function is defined, the speed output of the SRM is applied to the *H*-infinity controller. The *H*-infinity control strategy is compared with the actual speed of the motor from the reference speed. According to the speed variation, the weight is added and the motor speed is regulated. The updation of weight is performed by the Riccati equation, which is used to analyze the inequalities of the weight matrix for the requirements.

4 Results and discussion

The proposed *H*-infinity robust controller-based SRM rotor position speed control technique is simulated in MATLAB working platform (version 7.12). From the simulated model, the rotor speed control performance of the proposed control technique is analyzed. Then, the speed control characteristics of the *H*-infinity control technique are compared with the existing speed control technique such as PI controller and fuzzy controller. After that, the torque, flux, and transfer function of the SRM are described. The Simulink model of the proposed control system is illustrated in Fig. 4. Then, the simulation model of the *H*-infinity controller is shown in Fig. 5.

- **Simulink model description**

The proposed control system contains a current-controlled 60-kW 6/4 SRM drive. The SRM is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two insulated gate bipolar transistors (IGBTs) and two free-wheeling diodes. Here, DC supply voltage of 240 V is used. The converter turn-on and turn-off angles are kept constant at 45° and 75°, respectively, over the speed ranges. The reference current is 200 A and the hysteresis band is chosen as 10 A. The

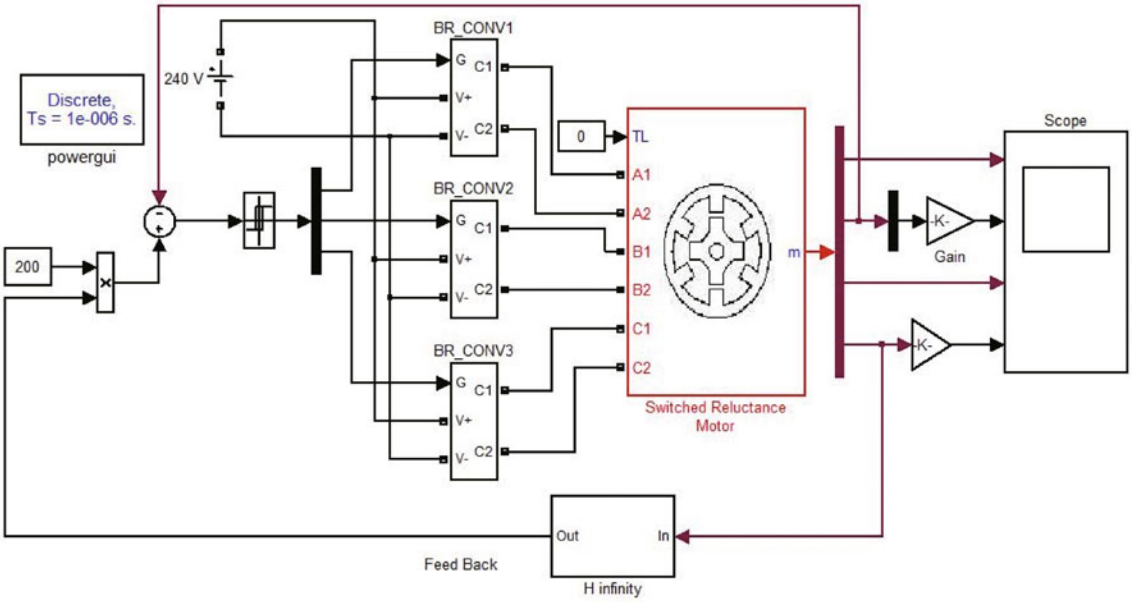

Fig. 4 Simulink model of the proposed control system

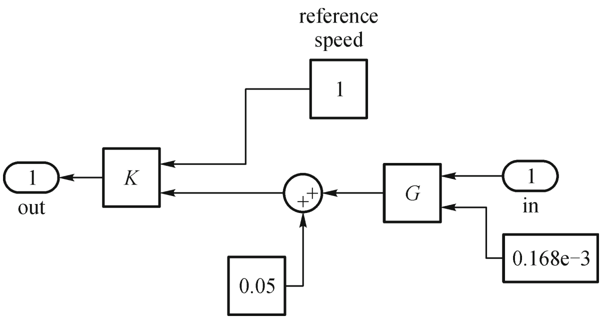

Fig. 5 Simulink model of *H*-infinity controller

desired speed of the SRM is settled as above 3000 rpm. Then, the SRM transfer function model is derived in terms of resistance (R_m) and inductance (L). The derived model is described as

$$P(s)=\frac{20}{0.0034s+1}. \tag{14}$$

From the above derived model, the rotor angular speed, torque, and voltage characteristics are obtained. The obtained characteristics are illustrated below. The rotor angular speed of SRM, torque, flux, voltage, current, and transfer function model are shown in Figs. 6–11, respectively.

Then, the rotor speed characteristics of the *H*-infinity controller are compared with the discrete PI controller and Mamdani fuzzy controller. The Simulink model of PI and fuzzy controllers are illustrated in Figs. 12 and 13. The speed of SRM without using the speed controller is illustrated in Fig. 14. Then, the performance of the proposed *H*-infinity controller is described. The comparison performance of *H*-infinity controller and without speed controller is illustrated in Fig. 15. The comparison performance of *H*-infinity controller and PI controller is illustrated in Fig. 16. Then, the comparison performance of *H*-infinity controller and fuzzy controller is shown in Fig. 17.

Then, from the speed comparison performance, the rotor speed control performance accuracy and controlling time are analyzed. In Fig. 15, the rotor speed of SRM is smoothly controlled by *H*-infinity controller. However, the rotor speed of SRM is oscillated when the speed is controlled without using any control technique. In Fig. 16, the PI controller has smoothly controlled the rotor speed, but it is inefficient in achieving the desired rotor speed. Thus, the performance of the SRM would be affected. In

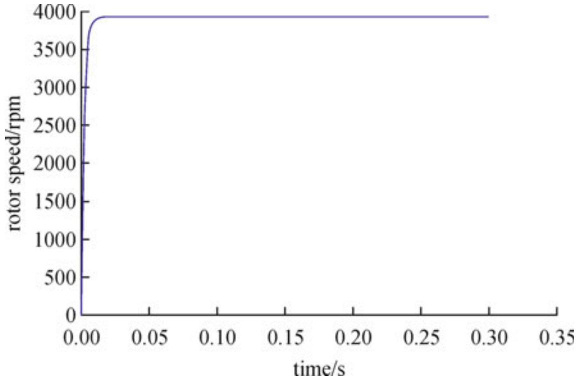

Fig. 6 Performance of SRM rotor speed

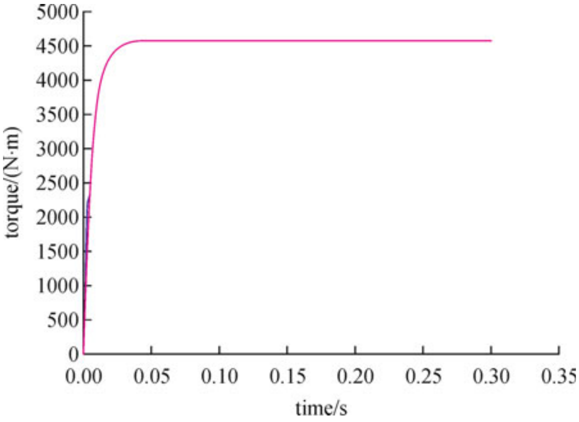

Fig. 7 Performance of SRM torque

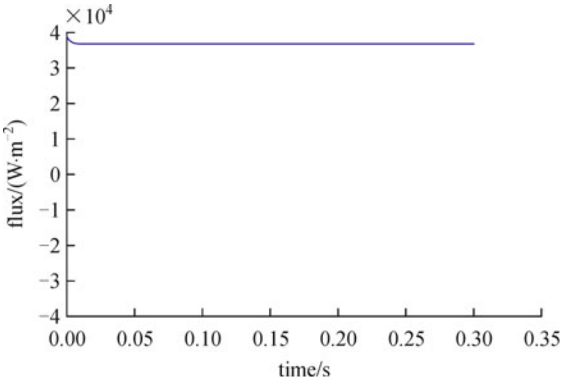

Fig. 8 Performance of rotor flux

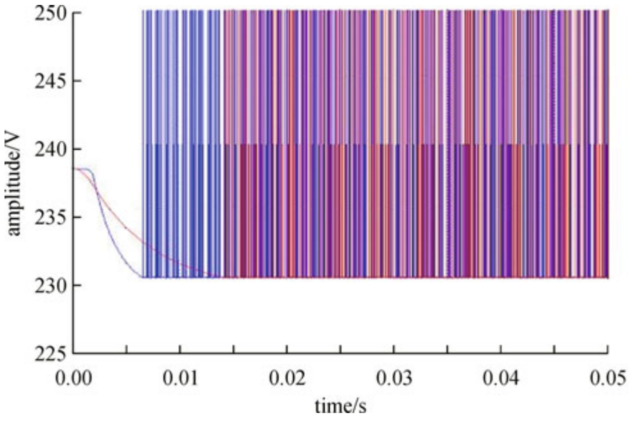

Fig. 9 Performance of motor output voltage

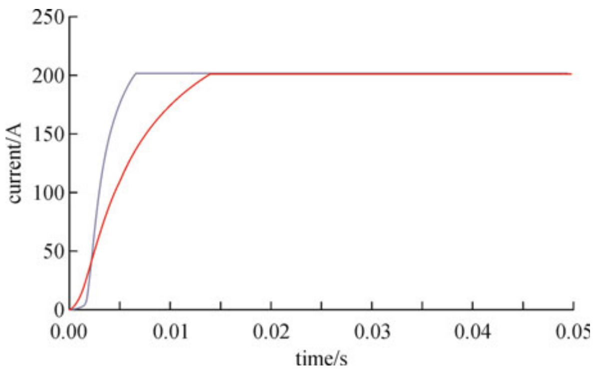

Fig. 10 Performance of motor output current

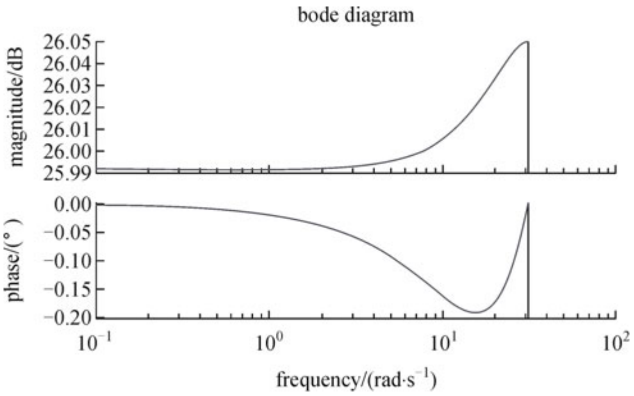

Fig. 11 Performance of SRM transfer function model

Fig. 17, the fuzzy control technique has taken more time for achieving desired rotor speed. Among the control techniques, the proposed *H*-infinity control technique has controlled the rotor speed robustly and the control action response is quick compared to PI and fuzzy controllers. The speed control action time performance of the *H*-infinity, PI, and fuzzy controllers are described as follows.

The fuzzy control technique has taken 4.3038 s extra time compared to *H*-infinity controller. Similarly, compared to PI controller, the *H*-infinity control has taken 0.0609 s less for making robust speed system. Hence, the *H*-infinity control strategy is more efficient for creating robust system than the PI and fuzzy controllers. Then, the SRM rotor speed control action of the *H*-infinity control technique is compared with the PI and fuzzy controllers, which are shown in Fig. 18. From the above performance analysis, the *H*-infinity controller has achieved a remarkable level in reducing the robustness.

5 Conclusion

In this paper, the rotor speed of SRM was controlled by a robust *H*-infinity control technique. The proposed control technique was simulated and the output performance was analyzed. Then, the output performance was compared with the conventional speed control technique. From the comparison results, it was found that the proposed control technique was more sensible and accurate for controlling the speed of SRM. The existing control techniques used for comparison were PI controller, fuzzy controller, and without using any control technique. Controlling the speed of rotor without using any controller was more difficult and more time was taken for achieving the stable speed. Whereas, the speed of SRM controlled by PI controller was better than without using the controller, but here the stability and accuracy were affected. Also, the fuzzy-based PI controller gain tuning has not performed well compared to proposed control technique. Moreover, the speed control efficiency of the *H*-infinity controller was

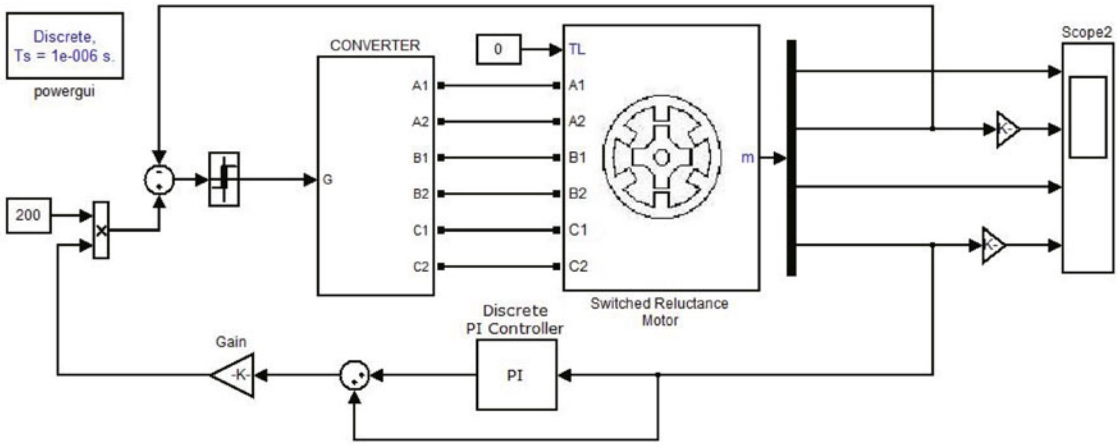

Fig. 12 Discrete PI controller-based SRM control model

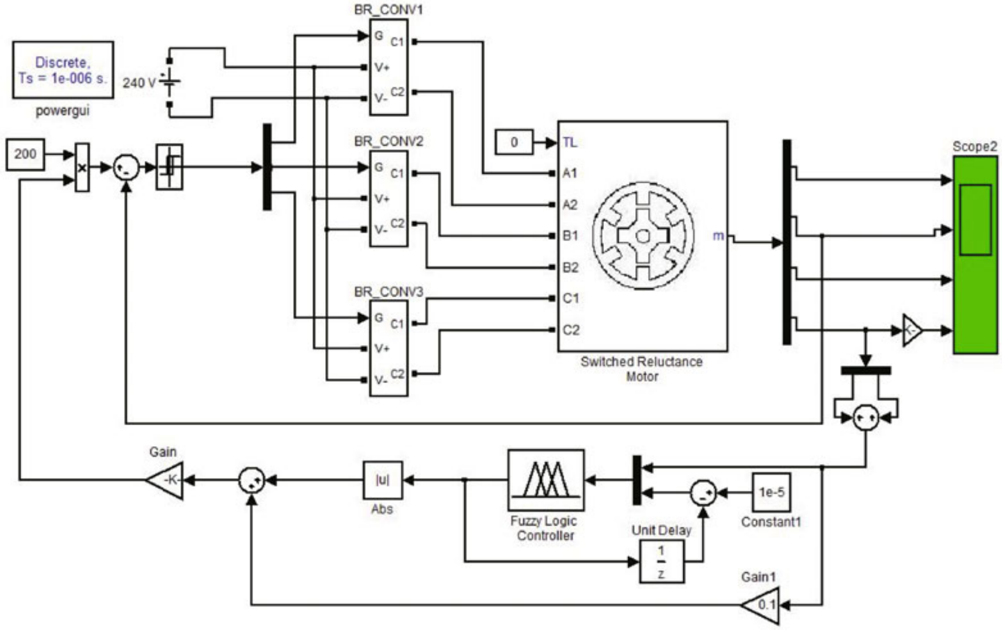

Fig. 13 Mamdani fuzzy controller-based SRM control model

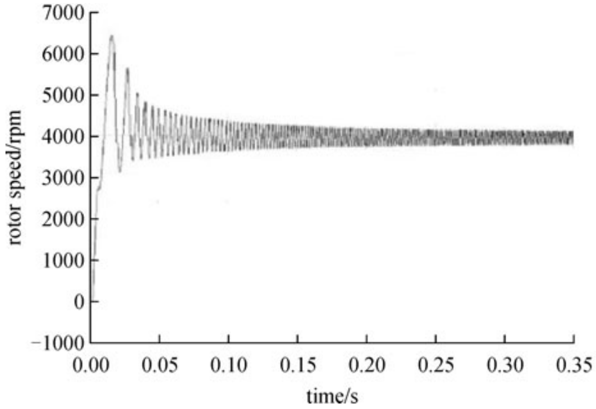

Fig. 14 Performance of rotor speed without speed controller

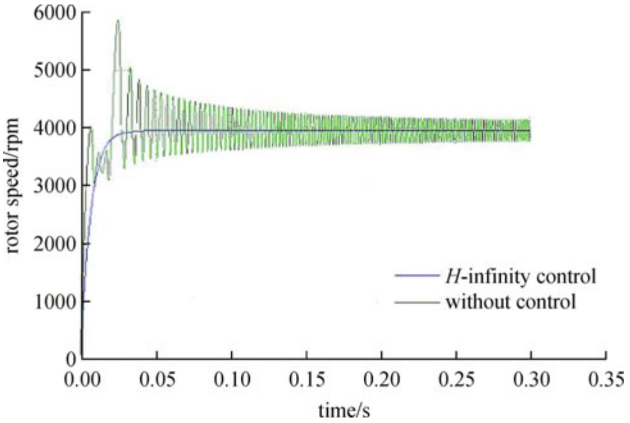

Fig. 15 Rotor speed comparison of *H*-infinity control and without control

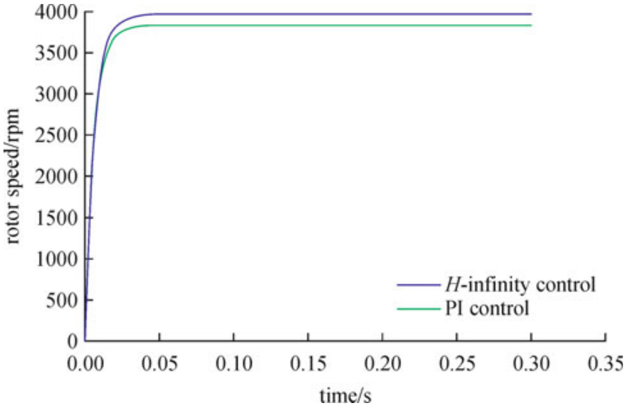

Fig. 16 Rotor speed comparison of *H*-infinity control and PI control

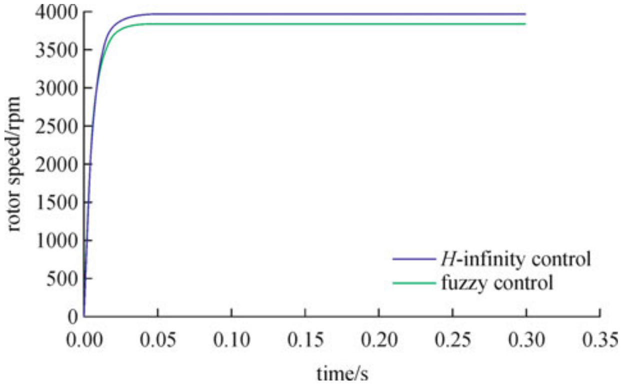

Fig. 17 Rotor speed comparison of *H*-infinity control and fuzzy control

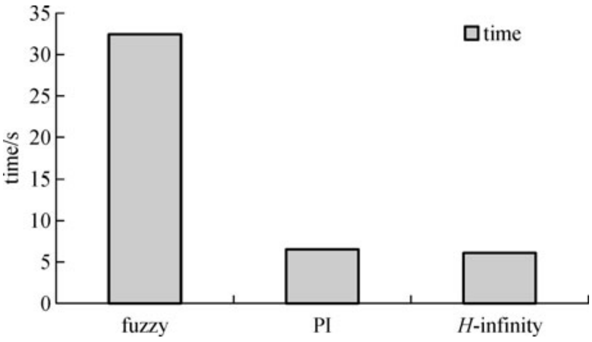

Fig. 18 Performance of speed control action in time

high and steady than the PI and fuzzy-based controllers. Overall, the proposed *H*-infinity control technique has achieved a remarkable level in controlling the rotor speed of SRM.

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