Indonesian Journal of Electrical Engineering and Computer Science
Vol. 31, No. 2, August 2023, pp. 647~657
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v31.i2.pp647-657

Speed control of switched reluctance motors based on fuzzy logic controller and MATLAB/Simulink

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Article Info

Article history:

Received Sep 19, 2022
Revised Mar 19, 2023
Accepted Apr 2, 2023

Keywords:

Fuzzy logic
Proportional-integral-derivative controller
Speed control
SRM modeling
Switched reluctance motor

ABSTRACT

Switched reluctance motors (SRM) becomes increasingly popular due to its simple structure and dependability. It seems to have a two-pole configuration. A stator had also centralized coils along each pole, whereas a rotor has an iron core only. As a result, the switched reluctance motor is anticipated to be a low-cost, incredibly robust variable-speed machine. Because the switched reluctance motor is only made up of laminated coils, its performance is heavily reliant on the magnetic properties of the core material. Vibration, torque ripple, and low torque for each unit volume are some of their drawbacks. Typically, a standard proportional-integral-derivative (PID) controller is designed to regulate the Switched Reluctance Motor's speed. Furthermore, the PID controller could also regulate and control SRM when the load changes abruptly. A fuzzy logic controller (FLC) is utilized within this article to regulate the speed of the SRM drive. The MATLAB/Simulink platform is used to analyze the behavior of SRM with FLC. To demonstrate FLC's superiority, its results have been compared to that of a typical PID controller.

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1. INTRODUCTION

Switching reluctance motors are simple and sturdy structures, low cost, high-speed capability, and lack PMs. So, it's a new and competitive option to permanent magnet motors. Switched reluctance motor (SRM) devices have a bright future in electric traction systems and are widely used in numerous industrial applications, including pumps and fans. Although non-magnetic SRM devices are more common, permanent magnet motors are still necessary for electrical transmission systems. To address the problems of excessive torque ripples, high noise, and low torque density in SRMs, extensive research was conducted. In-wheel traction motors work best with the SRM axial flow system because it has a larger torque density than radial flow systems [1].

A SRM has salient poles on both its stator and rotor. Without any coils or permanent magnets in the rotor, it is referred to as a double salient pole machine. Stator poles in SRM are larger than the rotor poles. SRM has a low inertia and good performance due to its winding-less rotor. It is also less expensive and more efficient. SRM is utilized in industrial applications because of these characteristics; however, it has large ripples with torque and non-linear magnetism. Such shortcomings restrict the SRM's usage in numerous applications that require the motor's smooth feedback. Traditional control approaches are insufficient to govern the speed of SRM due to its non-linear magnetic structure. As a result, non-linear controllers are needed [2].

Chen *et al*. [3] suggest using just two current sensors for the motor drive of a four-phase SRM. The use of a half-bridge circuit that is not symmetric in which only one current sensor is used to sense each of the two winding currents enables the SRM drive that is being proposed to provide additional charging and discharging functions without the need for additional selectors, current sensors, or circuit components. Watthewaduge *et al*. [4] discusses in depth several electromagnetic modeling strategies for SRM. The work covers interpolation and curve fitting methods as well as analytical models based on Maxwell's equations. The finite element method (FEM) and boundary element method (BEM) are two examples of numerical approaches. Additionally, the magnetic equivalent circuit (MEC) technique is covered.

To enhance SRM's performance, the best way to design multilayer switched reluctance motors for electric vehicles was the focus of [5]. To achieve more perfect driving performance in switching reluctance machines, many scholars are increasingly favoring advanced control mechanisms for improving the effectiveness of speed response of switching reluctance machines driving systems that will typically be realized in two primary methods. The first step is creating sliding mode, intelligent controllers which include fuzzy control. The fast terminal slip mode control (FTSMC) approach is used in [6] to present a novel impedance switching motor speed control SRM scheme. By utilizing the fuzzy logic compensator in conjunction with the suggested FTSMC, the signal function gain value is significantly boosted. Both in the frequency and time domains, the suggested method is contrasted with conventional sliding and proportional-integral (SMC) control methods.

Wang *et al*. [7] evaluate the use of a torque sensor-less directional torque control (DTC) SRM system and suggests a new Takagi-Sugeno-Kang (TSK) adaptive fuzzy slip mode controller (AFSC). Abdel-Fadil and Szamel [8] describe how fuzzy logic control (FLC) can be used in electric vehicle (EV) applications to reduce the motor starting frequency ripple SRM during phase conduction. To keep the current value of the motor following the signal of reference with the least amount of current ripple, the FLC current control is applied to the SRM. This will lessen the torque ripple. A FLC is developed in [9], [10] to regulate the SRM drive's speed. The FLC's performance is compared to that of a typical PI controller to demonstrate its superiority. A novel method of controlling a linear switched reluctance motor (LSRM) is presented in [11].

A Type-2 Takati-Sugeno control algorithm is used to perform the motor approximation. The lower and upper membership functions describe the motor's uncertain parameters. A controller with an adaptive sliding mode is created by constructing a surface with an integral sliding mode, and the Lyapunov function is used to verify the sliding motion's dynamic stability. By controlling the pulse-width modulation (PWM) on/off duty cycle for each interrupt period, the current chopping controller designed in [12] reduces torque ripple more effectively using fuzzy logic rules. A switched reluctance motor's speed is controlled by the auto-tuning proportional-integral controller [13]. The programmable logic controller is responsible for carrying out the control algorithm. Fuzzy logic is used to figure out the gains on the proportional integral. MATLAB/Simulink software is used to execute fuzzy logic on a separate computer.

Adaptive control technique, and artificial neural network (ANN) [14]-[16] those advanced algorithms that necessitate complex processes and professional users during the design process, which limits their practical applications. Another type is optimization methods, such as the algorithm of ants colony, particle swarm optimization (PSO), or some optimal control techniques [17]-[20] that use the performance index for a given speed response as the optimal control purpose, establishes restriction situations, following that enhances the performance of given speed response. Even so, there is no assumption that the controlling function of the optimization techniques necessitates a significant amount of computing and processing of data, which places a larger market on the controller's arithmetic abilities in real applications.

In the world of engineering, fuzzy controllers are now popular. These are sophisticated and reliable controllers that accept input uncertainty. Fuzzy logic controllers are put to good use. When mathematical modeling isn't enough to fully represent the system. Under transitory situations, the fuzzy logic controller outperforms the PID controller [21], [22].

In this study, the fuzzy logic controller is used to enhance SRM speed with varying speeds and constant load situations. The sections of this paper are as shown in: The SRM modeling is reviewed in section 2. The implementation of FLC and SRM's speed control are the topics covered in section 3. The results are discussed in section 4. The final section provides the conclusion.

2. THE SRM MODELING

The rotor and stator of an SRM have prominent poles, making it a rotating electric machine. As a result, a machine is known as a "doublely significant machine." It consists of a magnetic rotor and a stator with dynamic winding. Torque is produced as a result of the rotor poles' propensity to align with excited poles to reduce the stator flux connections caused by an applied stator current. As a result, no permanent magnet is required. The electrical behavior of SRM is typically described by the motor phase equations. According to Faraday’s law, the flux linked in the SRM winding is related to the instantaneous voltage across the phase's terminals. Rotor position and phase current I influence the SRM phase-linked flux due to magnetic saturation effects and double salient construction. Single phase SRM equivalent circuit, consisting of stator resistance and inductance, is shown in Figure 1. Ignore the saturation magnetization impact, leakage flux, and mutual attraction inductance of phase windings while modeling SRM. SRM mathematical modeling is made up of many types of electrical equations [23], [24].

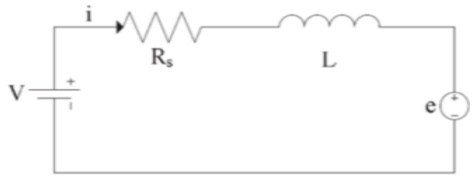


Figure 1. Circuit equivalent of SRM

A phase voltage equation is written as;

$$V = Ri + \frac{d\Phi(\theta,i)}{dt} \tag{1}$$

R stands for phase resistance and Φ represents flux linkage to every phase that is clearly expressed as;

$$\Phi = L(\theta, i) \tag{2}$$

L denotes the phase inductance, which fluctuates according to phase current and the rotor's position.
Using equations (1) as well as (2).

$$V = Ri + L(\theta, i)\frac{di}{dt} + \frac{dL(\theta,i)}{dt} i\omega_m \tag{3}$$

In which ω_m is the SRM's angular velocity.
The induced emf in the machine seems to be (4).

$$e = \frac{dL(\theta,i)}{dt} i\omega_m = i\omega_m K_b \tag{4}$$

The torque produced for each phase seems to be (5).

$$T_e(\theta, i) = \sum_{phase} \left(\frac{1}{2}\, i^2 \frac{dL(\theta,i)}{d\theta}\right) \tag{5}$$

The mechanical equation was substituted with equation (5), which is written as;

$$T_e - T_l = J_m \frac{d\omega_m}{dt} + B_m \omega_m \tag{6}$$

in which Bm denotes the friction coefficient, J_m denotes the moment of inertia, and Tl denotes the load torque.
Since unipolar drives are typically utilized in SRM, the motor phase's current is usually positive. Therefore, from (6) the dΦ/dθ sign has a direct connection to the torque sign. To put it another way, to produce a positive torque, the amplitude of the stator flux must rise relative to the rotor's position, whereas to produce a negative torque, the stator flux change must fall relative to the rotor's motion. A flux acceleration can be described by a value of dΦ/dθ that is positive, while a flux deceleration can be described by a value of dΦ/dθ that is negative [25].

3. SWITCHING RELUCTANCE MOTOR SPEED CONTROL

The essential block diagram for SRM speed control is given in Figure 2. This control technique communicates the difference for both the reference and exact speeds to the speed control system. Here the reference currents are generated by a reference current according to the position of the rotor. A variation between both the reference and real current is fed into the Hysteresis current controller as an input. This controller sends control signals to the non-symmetric inverter, which is provided to the machine [26]-[28].

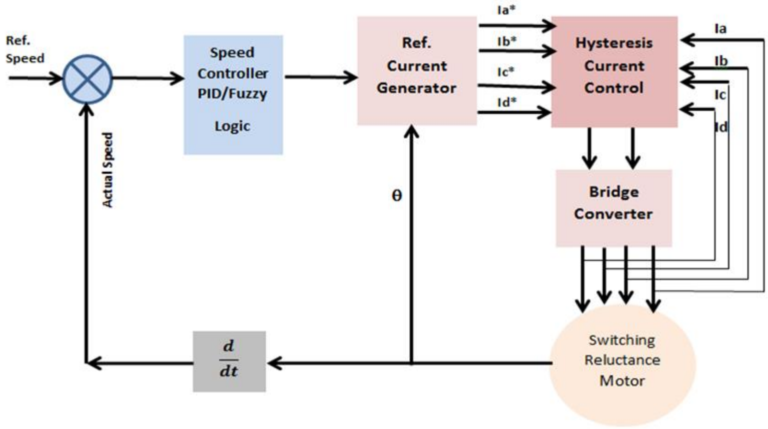


Figure 2. SRM drive control system

The fundamental advantage of using an (FLC) is that the system's mathematical model is not required. FLC layout is primarily derived from professional knowledge. In comparison to conventional methods, the fuzzy logic technique provides a solution that is easier, faster, as well as more dependable. There are three major blocks in the FLC. The first one is the block of fuzzification, which converts crisp inputs (real-world input data) to linguistic variables so that the physical input data can utilize the rule basis via membership functions. Rule-base is the next block, and it compares fuzzy inputs before the controller uses the membership functions of each input to make a decision. The third one will be the block of defuzzification, which converts back the fluffy results of the standard base to fresh ones and chooses participation capabilities to the alternative control yields from the standard base. Figure 3 depicts the fundamental FLC configuration.

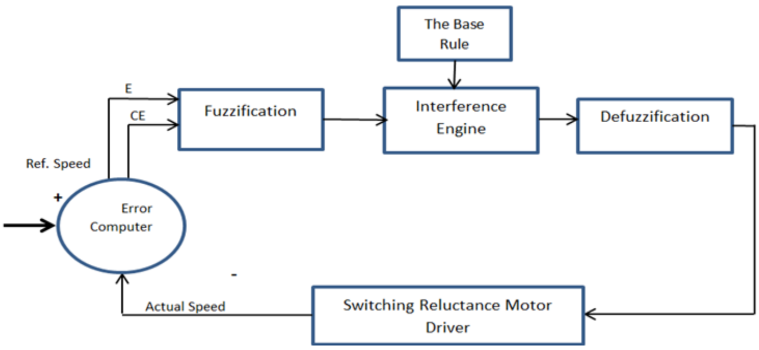


Figure 3. FLC's fundamental structure

Before programming the FLC, the following steps must be completed: First, classify and label the inputs along with their ranges and limits. The outputs are categorized, labeled, and assigned a range or limit in the second step. Thirdly, create a function representing the degree of membership for each input and output. Then, select the best rule-based structure for the system and decide how the action will be carried out. Finally, defuzzify the output and combine the rules.FLC receives two parameters in this speed control method: speed error (E) and the change in the error of speed (CE). FLC's result is written by (7).

$$x\,(i) = f\,(E\,(i) - CE\,(i)) \tag{7}$$

Fuzzification, rule base, and defuzzification are the three primary steps in the design of an FLC. Fuzzification is the process by which crisp inputs are turned into linguistic variables. Positive big (PG), positive medium (PM), positive small (PP), zero (EZ), negative small (NP), negative medium (NM), and negative big (NG) are the seven membership functions. FLC's rule base generates the necessary output in aspects of semantic variables. The amount of current error and the change in the error signals are represented by the inputs linguistic variables, while the amount of modulated index is represented by the output linguistic variables. The variables' values are chosen based on the way the variables act which was spotted in simulations, and the membership functions were defined offline. One of three rules—AND (∩), OR (∪), or NOT (~)—can be used to perform the fundamental operations on a fuzzy set required for evaluating among two inputs (X and Y). According to (8) demonstrates the use of the AND-intersection. Table 1 contains a list of the basis of the rules (decision-making logic) utilized with this paper. It is important to note that this table is diagonally symmetric regarding the membership function medium (M). Outlining the rules given in Table 1.

$$\mu\ X \cap Y = \min\ [\mu\ X\ (Z), \mu\ Y\ (Z)] \tag{8}$$

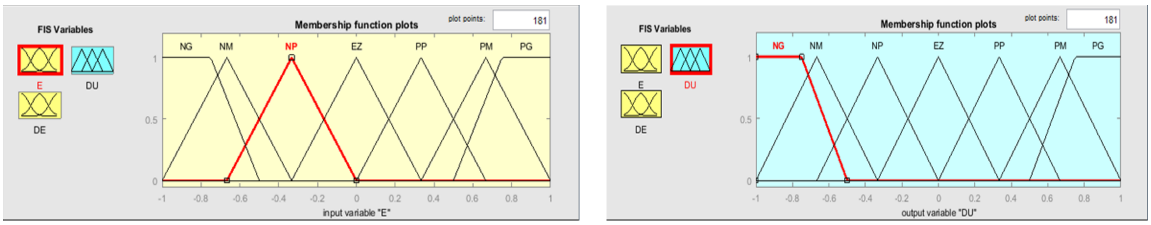
Figure 4 illustrates the membership function of the input whereas Figure 4(a) shows the error membership functions and the error change membership function for the speed of the motor shown in Figure 4(b). The last step in the process of FLC layout is defuzzification, which is the process of converting lingual variables into precise results. The required output in a linguistic variable is generated by the rules of fuzzy logic; it is necessary to convert these variables into precise output (a real number). In this study, the defuzzification membership functions are depicted in Figure 5, and this step is called defuzzification. For membership defuzzification, there are three options: the center of area (COA), the Bisector, or the middle of maximum as the most widely used method, the center area is used for defuzzification in this study, as shown in (9):

$$U(k) = \frac{\sum_{j=1}^{k} \mu(nj)\omega j}{\sum_{i=1}^{k} \mu(nj)} \tag{9}$$

where (nj) represents the membership function of a jth fuzzy set of the input variable nj, (ωj) indicates the jth fuzzy output, and (k) represents the total number of fuzzy membership functions [8], [29]-[31].

Table 1. The FLC rules table

E	CE						
	NG	NM	NP	EZ	PP	PM	PG
NG	NG	NG	NG	NG	NM	NP	EZ
NM	NG	NG	NG	NM	NP	EZ	PP
NP	NG	NG	NM	NP	EZ	PP	PM
EZ	NG	NM	NP	EZ	PP	PM	PG
PP	NM	NP	EZ	PP	PM	PG	PG
PM	NP	EZ	PP	PM	PG	PG	PG
PG	EZ	PP	PM	PG	PG	PG	PG



(a) (b)

Figure 4. The membership functions of the input; (a) the membership functions of Error and (b) the membership functions of error change

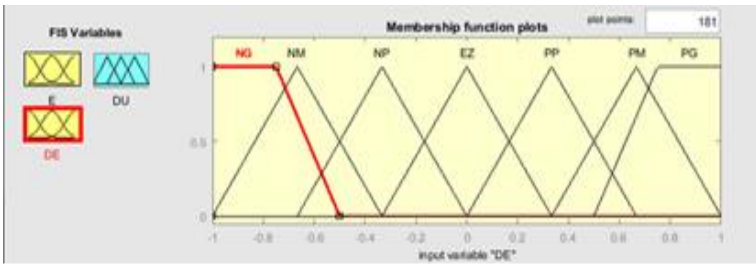


Figure 5. The membership functions of a reference current

4. RESULTS AND ANALYSIS

The modeling results are generated using MATLAB/Simulink to demonstrate FLC's superiority in SRM speed control. Figure 6 shows an SRM MATLAB/Simulink diagram for speed regulation [32]. Table 2 displays the switched reluctance motor driving parameters. There are two main parts to the simulation testing: The first part involves a PID controller to provide the SRM's speed and use the speed error as a reference current signal for the controller. The second part is to apply the FLC to the SRM and compare the results.

Table 2. The parameter of SRM

Type	8/6
Rs	3.1Ω
Jm	0.0089 Kg.m.m
Friction	1e-2 Nms
Speed and position	[zero,zero]
Unaligned inductance	5.9e-3 H
Aligned inductance	23.60 e-3H
Saturated aligned inductance	0.150 e-3 H
Max. current	10 A
Max. Flux Linkage	0.4860 (V s)

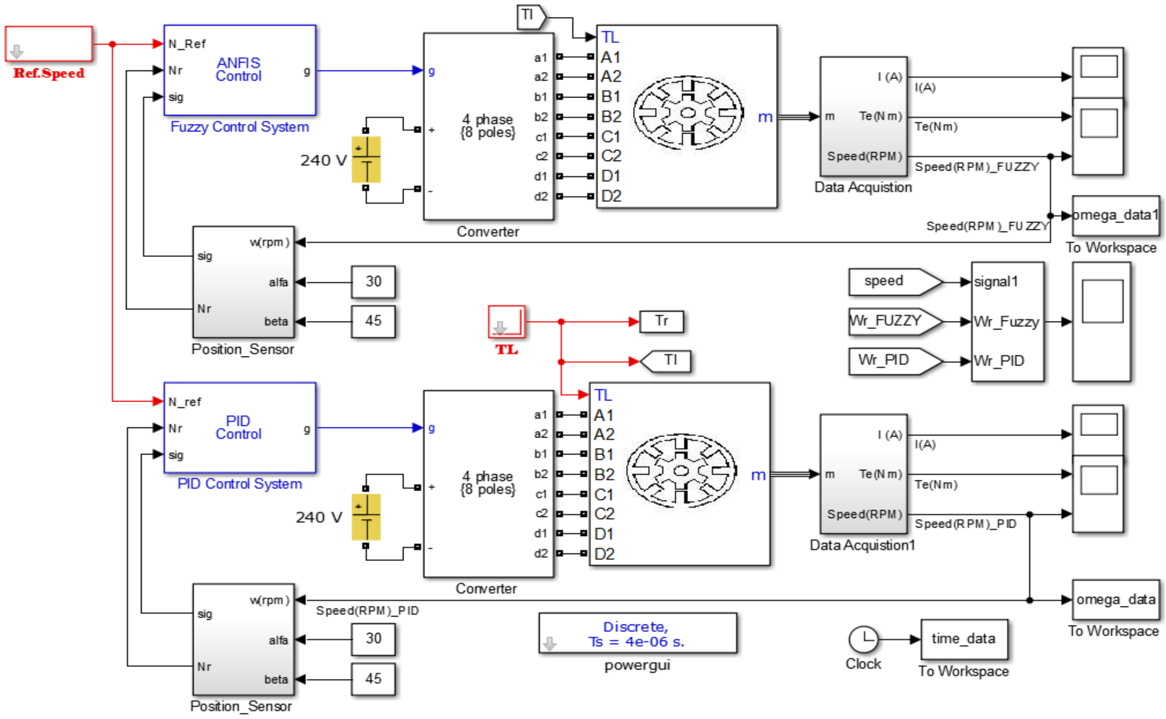
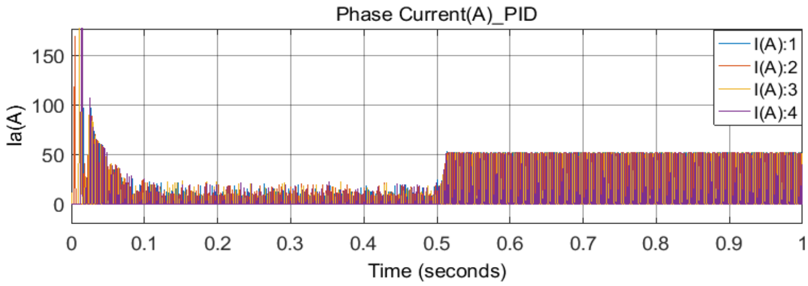


Figure 6. The MATLAB/Simulink speed control model for SRM

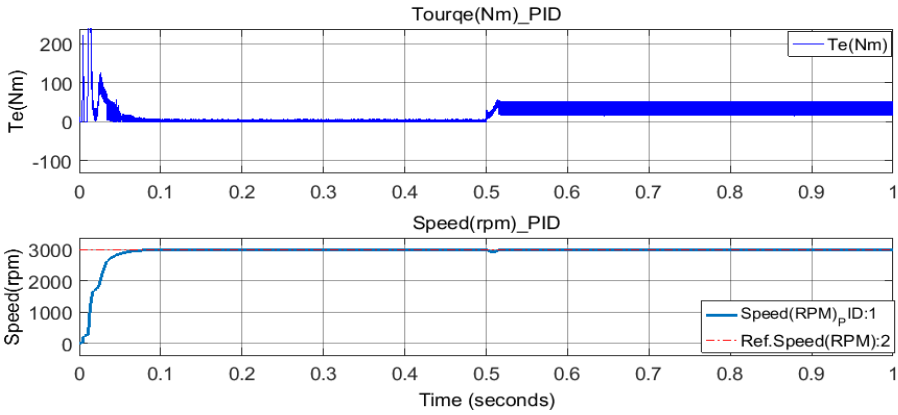
MATLAB/Simulink is used to build the simulation model for 8/6 SRM. It uses a 240 V DC supply power. The turn-on and turn-off angles of the converter are maintained throughout the speed ranges at 30° and 45°, respectively. Practical turn-on and turn-off angle ranges depend on the inductance profile, which in turn depends on the geometry of the configuration and poles of a certain SRM. Turning on and off the windings' angle of phase controls the torque waveforms. The development of positive, negative, high, or low electromagnetic torque by SRM depends significantly on these two switching angles. To boost the electromagnetic torque to its maximum or reduce torque ripples, as a function of phase current and rotor speed, the optimal turn-on and turn-off were discovered. Online calculations can be made to find the turn-on and turn-off angles that balance efficiency and torque ripple requirements [33].

The SRM is put through speed tests at 2,000 and 3,000 rpm, with a 0.5-second shift in load torque from 0 to 30 Nm. The primary duties of a PID speed controller are to create the reference current to supply the necessary torque and to maintain the real speed as closely as feasible to the reference speed under two load circumstances.

Input control variables for the PID and FLC current control systems both utilized the reference current produced by the speed control loop. The sample time is kept constant in two control approaches (Ts=4 μs) to ensure the efficacy of the suggested control strategies. Figure 7 depicts the performance of an SRM drive with a conventional PID controller. Figure 7(a) depicts the phase current of the A phase. During the phase conduction period in PID, it is observed that the current ripples. Figure 7(b) depicts the SRM's speed and torque response. SRM achieves its reference speed with a longer settling period, due to the current ripples, the torque ripples during the phase conduction interval may be observed in Figure 7(b). FLC is the ideal solution for managing the speed of the SRM drive since it overcomes the disadvantages associated with standard PID controllers.



(a)



(b)

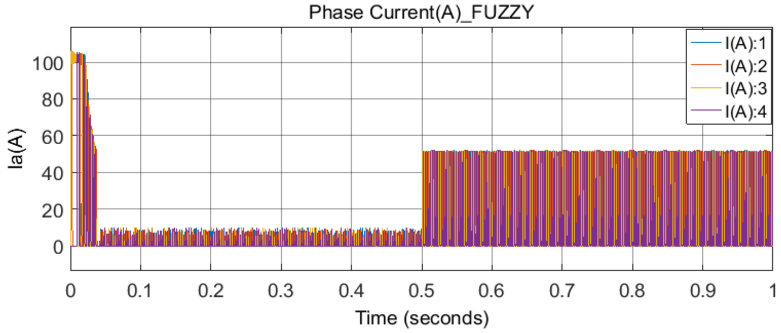
Figure 7. SRM PID controller results of at 0N.m to 30 N.m with 3,000 r.p.m (a) the phase A current and (b) The SRM's torque and speed response

Figure 8 depicts the result of switched reluctance motor drive when it is running at 3,000 rpm and a load torque of 30 Nm using the suggested FLC. The waveform of phase A current is shown in Figure 8(a). Figure 8(b) depicts the SRM load torque and the speed waveform of SRM with FLC. It can be shown in Figure 8(b) that the SRM's speed response has improved with a shorter settling time.

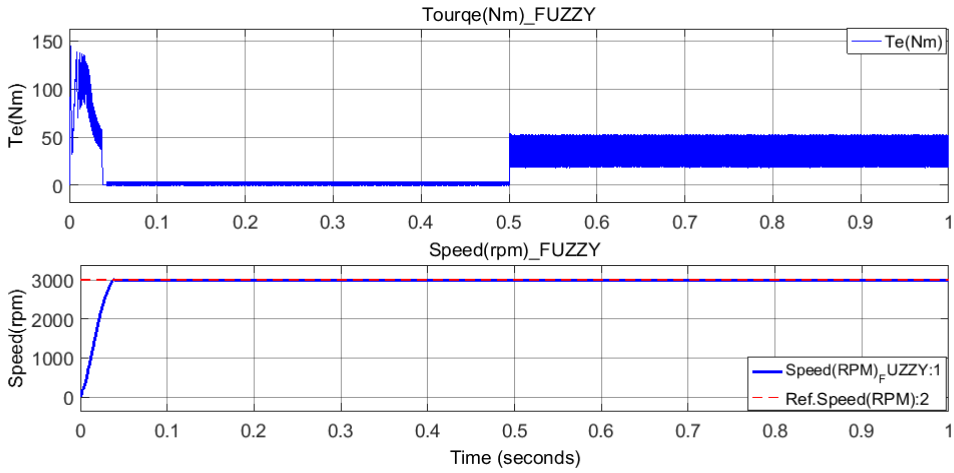
The results of Figure 8 demonstrate that, in addition to having a fixed switching frequency, the suggested current control method has numerous advantages over the traditional method. It also lets permits a low value of current ripples (ΔI) for the phase's current to follow the reference current signal. Due to the direct impact of phase current on motor torque, adopting fuzzy logic current management also helps to lessen the motor torque ripples.

Figure 9 illustrates the planned FLC's and PID's speed responses. An external load of 30 N was supplied to the SRM at t = 0.5 s to study the consequences of a sudden shift in motor load. Figure 9 illustrates the speed responses under sudden load variations at a reference speed of 2,000 rpm. The proposed control system allowed the motor speed to achieve the intended value more quickly and with less chattering. The results obtained under various moving part weights demonstrate the suggested controller's good performance.

According to the resultsas shown in Figure 9, the rising time utilizing the FLC is 0.0168 seconds when speed is applied to 2,000 rpm, however, the settling time was measured at 0.0213 seconds. The simulation results of the SRM drive with the suggested and PID controller with TL=0-30 N and speed at 3,000 rpm are shown in Figure 10. The rising time of the suggested controller is 0.0261 seconds, and the settling time is measured to be 0.0361 seconds when speed is applied at 3,000 rpm.



(a)



(b)

Figure 8. SRM (FLC) results at 30 N.m with 3,000 rpm, (a) the phase current of A phase and (b) the response of torque and the speed for (SRM)

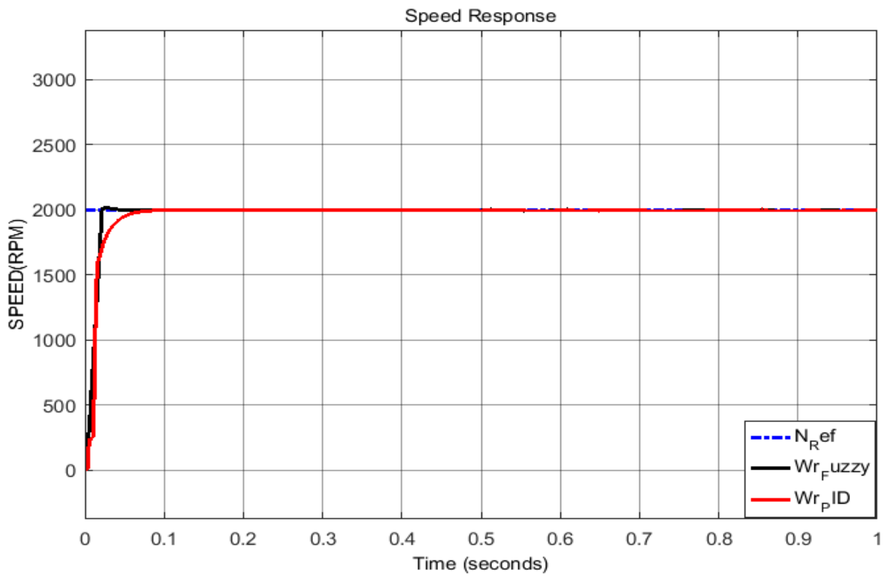


Figure 9. The comparison of the performance of the FLC to PID controller at 2,000 rpm

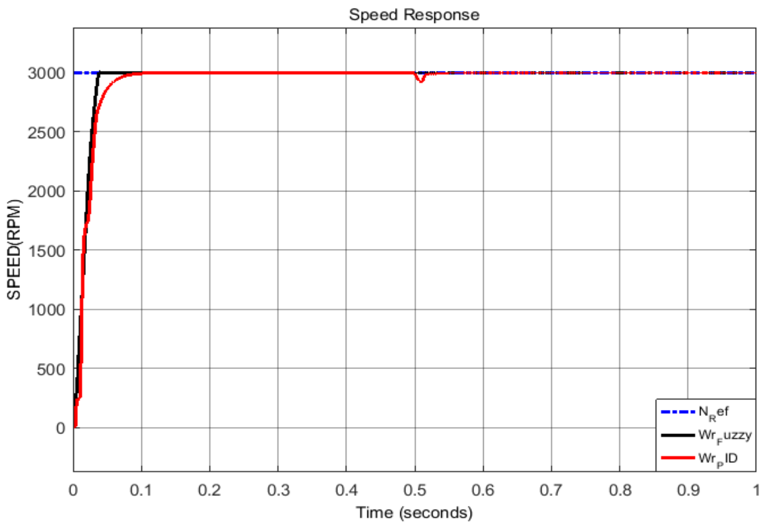


Figure 10. The comparison of the performance of the FLC to PID controller at 3,000 rpm

The simulation output mentioned above demonstrates that the suggested controller with PID controller has a settling time that is less than that of the proposed controller under no load conditions. The integral value reduces overshoot, and faster commutation makes it easier to manage the production of negative torque, which reduces torque ripple for the suggested controller. The rise time and settling time of the SRM motor drive are the foundation for the effectiveness of speed response measurements. The settling time is the amount of time that has transpired between the application of an ideal instantaneous step input and the moment at which the output entered and remained within a predefined error limit. The comparison made with the Modified SRM controller and PID controller is shown in Table 3.

Table 3. PID and FLC evaluation at a different speed

Measurements	2,000 rpm, (0-30) N.m		3,000 rpm, (0-30) N.m	
	PID	Fuzzy	PID	Fuzzy
Rise time (s)	0.0224	0.0168	0.0269	0.0261
Settled time (s)	0.0530	0.0213	0.5122	0.0361
Overshoot	0.2879	1.0836	0.0046	0.2025

Table 3 compares the speed responses of the FLC and the PID controller in terms of performance. For experimental purposes, reference speeds of 2,000 rpm and 3,000 rpm were used. The table shows that the suggested controller reduces the rise time by 5.6% when speed is applied at 2,000 rpm as compared to the PID controller and by 0.8% when speed is applied at 3,000 rpm. As a result, the proposed controller offers the superior performance of rising time relative to reference speed in terms of rpm. Table 3 displays the FLC and PID controller settling time measurements. The suggested controller reduces the settling time by 31.7% when applied at 2,000 rpm and by 47.61% when applied at 3,000 rpm. It follows that the proposed controller performs better than the PID controller.

5. CONCLUSION

The purpose of this study was to regulate SRM's speed. The MATLAB/Simulink environment was used to design the utilized controller algorithms. The speed-control technique for switched reluctance motor drives is called switched reluctance motor drives and has been controlled by using the fuzzy control method. In this way, it has the upsides of two techniques, i.e., quick and limited time combination of the following blunder during load aggravation is ensured even though jabbering impacts are dispensed with, as uncovered in the outcomes. Simulation has shown that the proposed method works well for a wide range of speeds under loaded conditions. The simulation data for two conventional control strategies—fuzzy control and proportional-integral-differential—have also been extracted for comparison. According to the data, the suggested controller ensures that, even when loaded, the reference speed will eventually converge in a finite amount of time. Under loaded conditions, the proportional-integral-differential control approach has a slower rise time in the time domain than the proposed fuzzy control. Additionally, the proposed fuzzy control outperforms the other control methods in both torque-load disturbance and speed ripple resistance due to its smaller speed-drop magnitude. In conclusion, the results show that under load, the proposed fuzzy control method tracks the reference speed more quickly and has a lower speed ripple than the proportional-integral-differential method. The switched reluctance motor drive is assumed to function normally by the authors. This study demonstrates that process control can benefit from the use of artificial intelligence techniques. Under various loads, the reference speed is maintained without causing an overshoot. The ant colony optimization (ACO) and genetic algoritma (GA) can be improved in the future by changing them so that new and updated research can focus on the disadvantages of each technique to produce a better solution by making it easier to find the best solution and reducing its limitations.

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