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Comparative Study of Dynamic Responses & Speed Control of Switched Reluctance Motor Using Fuzzy & PI Controller

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Abstract— This paper presents the comparative study of dynamic responses and speed control of switched reluctance motor using Fuzzy Logic Controller and PI controller. The Switched Reluctance Motor is an electric motor which runs by reluctance torque. These motors usually run at very high speed of 50,000 rpm which is to be controlled for industrial use. The fuzzy logic controller is utilized to control the SRM speed without losing its system performance. The effectiveness of the fuzzy logic controller is then compared with that of the conventional PI controller. The simulation is performed in MATLAB/Simulink software.

Index Terms— Fuzzy logic controller (FLC), Proportional, Integrator controller (PI), Switched reluctance motor (SRM), Direct torque control (DTC) Inverter, speed control.

1 INTRODUCTION

In advances of power electronics and high-tech control techniques, as well as the development of high speed microcontrollers with powerful computation capability, switched reluctance motor (SRM) drives are used in various applications which requiring high performance, such as servomotor drives, electric vehicle propulsion, jet engine starter–generators, etc. SRM has already inherently feature numerous merits like simple and rugged structure, being maintenance free, high torque–inertia ratio, fault-tolerance robustness and reliability, high efficiency over a wide range of speeds, the capability to run in abominable circumstances, etc. [1], [2]. The requirements for variable-speed SRM drives include good dynamic and steady-state responses, minimum torque ripple, low-speed oscillation, and robustness. However, due to the heavy nonlinearity of the electromagnetic property and the coupling relationships among flux linkage, torque, and rotor position, it is not easy for an SRM to get satisfactory control characteristics. Therefore, new structure designs [3], [4], high performance magnetic cores [5], adaptive control techniques [6] in the innovation and improvement of various SRMs have been presented progressively in recent years. At present, the proportional, integral, and/or derivative controllers have a proven control performance for many industrial drives [7]. Based on the exact mathematical model and system operator's experience, the PI, PD, or PID controller could compensate system variations very efficiently via the appropriate tuning of its dominant parameters. However, the performance may significantly deteriorate when the operating condition is altered or when the parameters drift. When the exact analytical model of the controlled system is uncertain or difficult to be characterized, intelligent control techniques such as fuzzy logic control (FLC), neural network control, or genetic algorithm may allow better performance. Intelligent control approaches try to imitate and learn the experience of the human expert to get satisfactory performance for the controlled plant [8]. One of the most powerful tools which can translate linguistic control rules into practical operation mechanism is the FLC. The FLC has been found particularly suitable for controller design when the plant is difficult to model mathematically due to its complexity, nonlinearity, and/or imprecision. Hence, the FLC is widely applied in a considerable variety of engineering fields today because of its adaptability and effectiveness [9]. It has been shown that fuzzy control can reduce hardware and cost and provide better performance than the classical PI, PD, or PID controllers [10]–[12]. The FLC architecture approximates the way of expert operation intuitiveness; this makes it attractive and easy to incorporate heuristic rules that reflect the experience of human experts into the controller [13]. Recently, fuzzy control theory has been widely studied, and various types of fuzzy controllers have also been proposed for the SRM to improve the drive performance further [9]. In these research works, the main techniques utilized to enhance the self-adaptability and performance of the FLC are scaling factor (SF) tuning, rule base modification, inference mechanism improvement, and membership function redefinition and shifting. Among these techniques, SF tuning is the most used approach, and it has a significant impact on the performance of an FLC. A new self-tuning fuzzy PI controller with a condi-

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tional integral is proposed for the doubly salient permanent-magnet motor drive [9]. The initial parameters and scaling gains of the controller are optimized by the genetic algorithm to minimize overshoot, settling time, and rising time. In addition, an integral function with conditional operation strategy is introduced to the controller to decrease the steady state error and avoid the excessive overshoot that results from integral accumulation. This fuzzy controller, which is used in the outer loop, takes the speed error and change of error as the input signals to generate an equivalent control term. It can produce smooth torque and improve the system performance. Precise control of SRM model is not easy using conventional method (like PI or PID controls) as its flux linkage, inductance, and torque possess mutual coupling with rotor position and phase current. Hence, analytical or computer-based experimental determinations are often required to characterize the magnetization curves of the SRM. When the analytical model of the controlled system is vague or difficult to model, intelligent control techniques such as Fuzzy Logic Controller (FLC) gives better performance. Basically FLC is a control strategy better suited for non-linear and time varying objects. The advantages of FLC are robust, in-sensitive to parameters changes, etc., which is applicable to SRM drive control. This paper proposes a tuned fuzzy logic speed controller for SRM. The proposed FLC uses the speed error and change in speed error as input and generate an equivalent control term, which improves system performance in steady state.

This paper organized as follows:

In this paper, section 2 describes SRM model, section 3 describes block diagram of SRM speed control, section 4 describes PI controller, The introduction to Fuzzy controller is presented in section 5 & section 6 depicts the simulation and results and the optimum values are presented and conclusions are given in the last section.

2 SWITCHED RELUCTANCE MOTOR MODEL

The per phase equivalent circuit of the SRM (neglecting mu-tual inductances) was given as

$$v = Ri + L(\theta, i)\frac{di}{dt} + i\frac{dL(\theta, i)}{dt} \qquad (2.1)$$

where, v= applied phase voltage to the phase,

R= a resistance per phase,

Ri = resistive voltage drop

From the above (2.1) nonlinear equation , the motoring torque can be obtained only when the phase current is switched on during the rising period of phase inductance. From the Fig.1 it is observed that, the saturation effects are maximum at $\theta_m = 0^0$ and minimum at higher angles as rotor approaches unaligned position.

3 SPEED CONTROL OF SRM

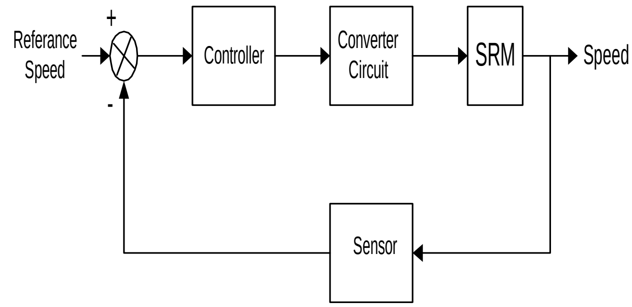

Fig. 1 shows the basic closed loop feedback control system for SRM. Here the position of rotor is sensed by the rotor position sensor and it provides its corresponding output to the error detector. Error detector compares reference speed and actual speed to generate error signal which is given to controller block. The controller either fuzzy or PI gives control signal to the converter according to the error signal. The converter thus controls the motor speed by exciting the corresponding windings [10].

4 PI CONTROLLER

A PI Controller (proportional-integral controller) is a specific case of the PID controller in which the derivative of the error is not used. It is a generic closed loop mechanism mostly used in industrial control systems. It generally calculates an "error" value which is the difference between a measured process variable and a desired set point and is denoted as Δ. The PI controller attempts to minimize the error by adjusting the process control inputs. The PI Controller contains proportional term (P) and integral term (I). Here P depends on the present error and I depend on the accumulation of past errors [11].

4.1 Proportional term:

The proportional term produces an output value which is proportional to the current value of error. The proportional response can be adjusted by multiplying the error by a constant is called the proportional gain.

The proportional term is given by:

$$P_{out} = K_p\Delta \qquad (4.1)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances.

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4.2 INTEGRAL TERM:

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output.

The integral term is given by:

$$I_{out} = K_i \int \Delta \, dt \quad (4.2)$$

The integral term accelerates the movement of the process towards set-point and eliminates the residual steady-state error that occurs with a pure proportional controller. However, since the integral term responds to accumulated errors from the past, it can cause the present value to overshoot the set-point value

The overall controller output is given by:

$$K_p \Delta + K_i \int \Delta \, dt \quad (4.3)$$

Where, Δ is the error or deviation of actual speed from the reference speed.

5 FUZZY LOGIC CONTROLLER

5.1 Basic concept of process block diagram:

Fig. 2 shows the block diagram of a proposed FLC control scheme, used to design SRM, which can approximate relations between variables [23].

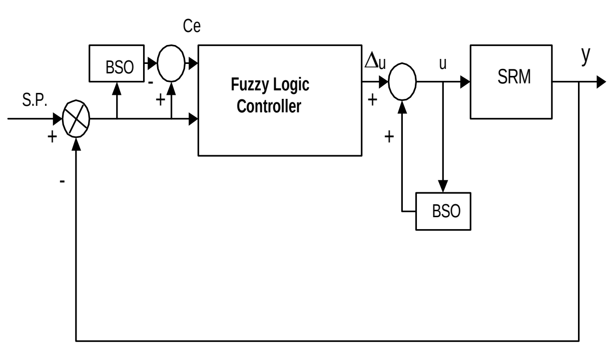

Fig. 2 Block diagram of FLC control scheme

The controller uses the speed error (e) and change in speed error (Ce) as inputs and the output is torque reference (Δu). The SRM output torque is compared with the set point (S. P.) value; output of the comparator is given to another comparator which takes another input from the back shift operator (BSO). The compared output between e and Ce is fed to the FLC which gives a tuned torque output (Δu). That tuned output is given to the third comparator which compares Δu and u. This torque reference is given to SRM. The input is divided into Membership Functions (MF) which is designed to allow the SRM to conduct over the entire positive torque. A triangular membership function is chosen for inputs and output. The control rules are shown in table 1.

5.2 FUZZY LOGIC CONTROL SYSTEM:

Fuzzy logic controllers are the one which is mainly used in system control for industries. This is mainly used when a non linear system is taken in to account. The fuzzy logic controller has the following main functions they are

- Fuzzification
- Inference Engine
- Rule base Design
- Defuzzification

A. Fuzzification:

Fuzzification is the process of converting real scalar value in to membership fuzzy set values. The fuzzification process is done using fuzzifiers. Different types of fuzzifiers are used according to the application

B. Inference Engine:

The fuzzy inference engine decides how to process rules using fuzzy input. The inputs for the fuzzy controller will be error and change in error. The control signals will vary according to error and change in error. Once the fuzzy controller receives input the rule base is evaluated.

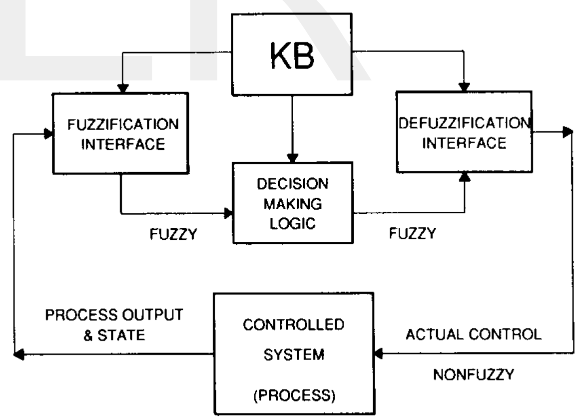

Fig. 3 Basic configuration of FLC controller

C. Rule Base Design:

Basically a rule base is a linguistic controller, which is designed using IF THEN statements. Here we have two input conditions and one output response. Based on that, rules are designed for proper control of the system. The Table 1. shows the rule base design for the speed control of Switched Reluctance motor.

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e/Ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	ZE
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NM	NS	ZE	PS	PS	PM
PS	NS	NS	PM	PS	PS	PM	PB
PM	NS	ZE	ZE	PM	PM	PB	PB
PB	ZE	ZE	PS	PB	PB	PB	PB

In developing the solution, few input points were selected and the centroid method for defuzzification was employed. More rules would result in a closer fit.

In this paper, three scaling factors were introduced to tune the controller: Ke, KCe, and αKu. The relationships between the scaling factors, input and output variables are as follows:

$$eK \mid tuned = K_e e(k) \quad (5.1)$$

$$CeK \mid tuned = KC_e C_e(k) \quad (5.2)$$

$$U(K) \mid tuned = (\alpha Ku)\Delta u \quad (5.3)$$

D. Defuzzification:

Defuzzification is the process of converting the degrees of membership of output linguistic variables with in their linguistic terms in to crisp values. There are number of defuzzification methods in use. The defuzzification method used in this paper is centroid method which will change the current of the controller accordingly.

6 SIMULATION AND RESULTS

The simulink models designed for the speed control of Switched Reluctance Motor using PI and Fuzzy Logic Controller is shown Fig. 4, Fig. 6 in section A & B respectively.

A.Simulink model and results of PI controller:

In this section fig 4 shows simulink model for speed control of switched reluctance motor with PI controller. In fig 4 a) shows the closed loop simulink model of PI controller in which controller removes the speed error between reference and output which is fed to process i.e here switched reluctance motor. system gives better response using PI controller.fig 4 b) shows block of PI controller in which values of K_p& K_i is chosen in such a way that these values should be suitable for motor so that system gives good response ,here values of K_p is 7.18 & K_i is 245.

In fig 5 shows the results in which SRM using PI controller and with different speed of motor shows the response of system. Here for comparison at two values of speed 25 & 55 considered

B. Simulink model of Fuzzy controller:

In this section fig 6 shows the simulink model for speed control of switched reluctance motor with fuzzy logic controller. In fig 6 a) shows the closed loop simulink model of fuzzy controller and here controller uses rule base design for the speed control of Switched Reluctance Motor.fig 6 b) shows fuzzy controller block in which using 49 rules SRM motor gives good response.

Fig 7 shows the results in which SRM using fuzzy controller and here two values of speed 25 and 55 considered.both controller gives smooth responses at different speed of motor.but fuzzy controller is modified controller so we prepared the comparison table for minute observation.

Table 2 shows the comparison of both controller PI & Fuzzy then we can obsereved at different speed of motor what is the rise time and settling time for respective controller.

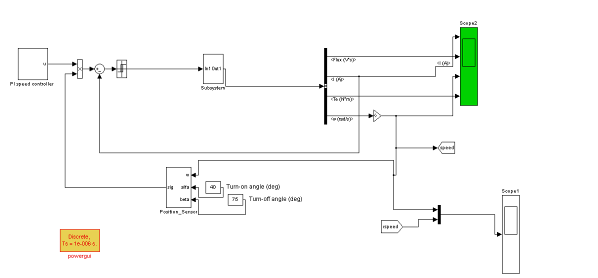

Fig a: Simulink diagram of PI controller

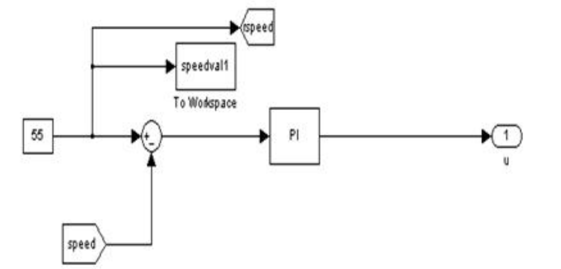

Fig b: PI controller Block

Fig 4 : Simulink model for speed control of switched reluctance motor using PI controller

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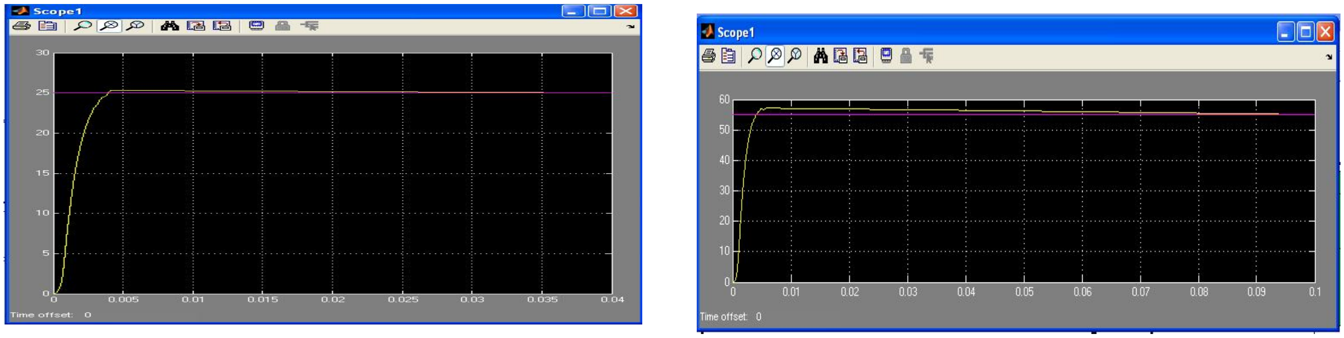

Fig 5 : Results at speed 25 & 55 respectively

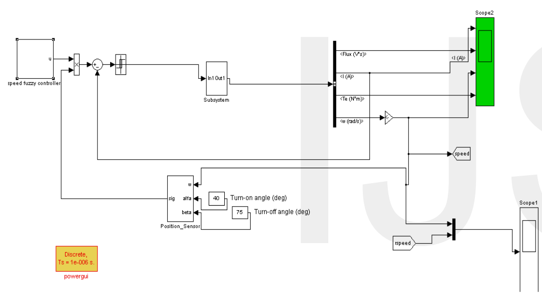

Fig a: Simulink diagram of Fuzzy controller

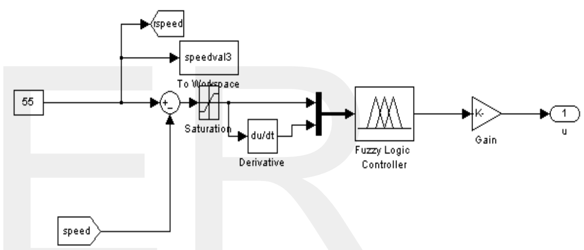

Fig b: Fuzzy controller Block

Fig 6 : Simulink model for speed control of switched reluctance motor using FLC

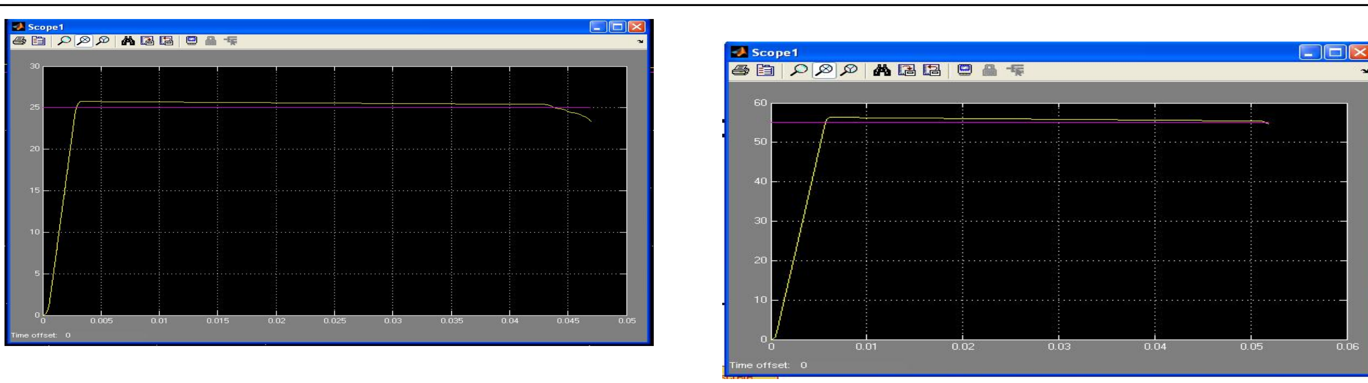

Fig 7 : Results at speed 25 & 55 respectively

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Table 2: comparison of PI & Fuzzy controller at different speed

controller	Speed	Rise time	Settling time
Pi	25	5e-3	0.03
fuzzy		2.9e-3	0.044
Pi	55	4e-3	0.1
fuzzy		5.7e-3	0.052
Pi	75	0.0197	1.35
fuzzy		0.0376	0.055
Pi	100	0.0195	1.1
fuzzy		0.114	0.12

7 CONCLUSION

The dynamic performances of SRM are predicted and the model is simulated using MATLAB/Simulink environment. The speed control for SRM using Fuzzy logic controller has been design and implemented using both PI and Fuzzy Logic speed Controller. From the simulation results it can be concluded that the Fuzzy Logic Controller provides a better performance in term of overshoot limitation and fast response.

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