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Adaptive Fuzzy Logic Speed Control of SRM in Hysteresis Current Control Mode

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ABSTRACT

The "switched reluctance motor" SRM can be operated in many modes based on the desired application that employs such kinds of motor. The SRM speed in each mode can be controlled. Thus, it's better to select the fast response speed control method with the lowest torque ripples and speed variations. The aim of the current research is to enhance the SRM speed control by that works in "hysteresis current control" HCC mode. The SRM speed is regulated by a "fuzzy logic controller" FLC. The role of the speed control signal by FLC is compared with the SRM position sensor to produce a reference current signal. This signal is fed to a hysteresis band to control the speed of the motor. This method of speed is referred to as HFLC. In this paper, another approach is made by replacing the hysteresis band with a hyperbolic tan function for more smooth in system control. This method is called TanHFLC. The results showed that the speed control in TanHFLC is faster by 6.2 %, and current and torque ripples are less by 10.9% and 20.8%, respectively. This work is simulated by the "MATLAB Simulink" software successfully at several operating conditions.

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1. INTRODUCTION

In the last two decades, "switched reluctance motors" SRMs have gained good interest in many industrial and electric drive fields than the normal 3-phase induction motors. The reason is due to its high efficiency and wide range of speed controllability, and reliability. There is no excitation necessary to rotate the SRM. Also, it can work at high speeds up to 50000 R.P.M without any need to change its poles [1-4]. Usually, SRMs are not supplied directly by mains electricity, they need a special driver circuit that normally converts a DC supply voltage into a controllable voltage at the desired switching time to excite their stator windings [5-7]. Depending on types of rotation, speed, and torque ripple reduction, SRMs may be operated in many modes such as "Single pulse" SP mode, "pulse width modulation" PWM mode, "hysteresis current control" HCC mode, "Sensor less" SL mode, …etc [8-10]. For high-speed control, SP is recommended; for low/medium voltage, PWM mode is preferred; for instantaneous current regulation, HCC mode is used, and for Cost-sensitive applications, SL mode is used. For many years, numerous researchers have used these modes of operation, with different types of controllers used to regulate the speed of the SRMs. A. Prasad K.M., et.al. [11] had used a Fuzzy Sliding Mode Controller to regulate the speed of SRM to associate the robustness of the "sliding mode control" SMC with the intelligence of a "fuzzy inference system". The results are compared with a PI controller. S. Wang et al. [12] had proposes a novel Adaptive controller based called "Takagi-Sugeno-Kang" TSK which is also Fuzzy SMC. To make a sensor less "direct torque control" DTC. SMC is utilized for external disturbances reduction with fast response, the TSK parameters are modified online for other error reduction after the SMC function. For applications of electric vehicles, a minimization of current ripples by a "Fuzzy logic controller" FLC for SRM is made in [13]. The motor is operated in HCC mode. The reduction in current ripples minimizes torque ripple as well. The SRM speed is controlled by a PI controller to make a reference current signal depending on the reference speed value. This control method is used for 6/4 SRM. A novel speed controller by Fuzzy SMC for 12/8-pole SRM is made by M. Divandari et al. [14]. Their used method is called fast terminal SMC. The results are compared with PI and normal SMC controllers in the frequency and time domains. Another novel speed controller is made based on the double-thread controller with adjusted multi-oscillatory regulation to reduce speed ripples of 8/6 SRM [15]. This method is constructed on shaping the phase current online. Their work is made under various speed values. Also, the overall cascade speed regulator with linear controllers is provided. S. O. Madbouly [16] had used an FLC inside a speed regulation loop of a DTC. This control is used for a 3-phase “synchronous reluctance motor” SynRM to enhance its performance at variable speed values. The FLC uses error and change or error in speed comparison between the SynRM actual and reference speed. The FLC makes the required torque signal hysteresis comparison inside the DTC loop. Y. Boumaalif et al. [17] had addressed SRM speed control issues by focusing on torque ripple minimization through reference current shape optimization. They proposed a two-stage optimization. The 1st is by using “particle swarm optimization” PSO in offline mode to estimate the SRM parameters of the reference current. The 2nd stage is refining in real time to estimate the “extremum seeking” ES method. Most of the previous works which are mentioned in the literature use FLC with some methods to reduce the ripples that are accompanied by the SRM current and torque. In this paper, another approach is used where the motor is working in hysteresis current control mode and its speed is regulated by FLC and the discontinuous nature of hysteresis band can be replaced by hyperbolic Tan function to reduce the current and torque ripples with faster response. The main sections of this paper are arranged as an introduction, system architecture, the control system, simulation results, and conclusions.

2. System architecture

The 6/4 SRM has 3-phase windings in its stator. The stator has six poles. The rotor has four poles. The stator and rotor poles are salient in shape. When the stator windings are excited, a magnetic force are induced in the rotor side. Its magnetic reluctance may align the stator pole. To let the SRM rotate at the desired direction, the stator windings are excited in a consecutive manner which is made by the 3-phase electric drive of the motor as shown in fig. (1).

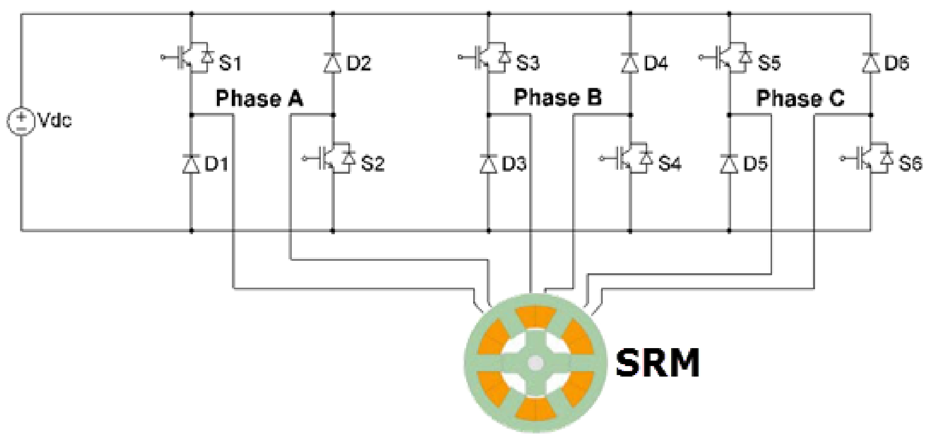

Figure (1) 3-phase 6/4 SRM with its electric drive

The 3-phse driver is asymmetric H bridge circuit. If the switches S1 and S2 are ON at the same time, the coil of phase A will be excited. These switches are turned ON when the rotor pole position is aligned with the stator pole. When the rotor is rotated at some angle, the Switches S1 and S2 are turned OFF and the diodes D1 and D2 will be forward biased. The same manner is happened for coils of B phase and C phase [18-19]. The phase voltage of the SRM is given by:

$$V = R.i + \frac{d\varphi\ (i,\theta)}{dt} \qquad (1)$$

It can be expanded to be:

$$V = R.i + \frac{\partial\varphi}{\partial i}\frac{di}{dt} + \frac{\partial\varphi}{\partial\theta}\,\omega \qquad (2)$$

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where ω is the rotor speed, $R$is phase resistance, $\theta$is the rotor angle, i represents the instantaneous current, and φ is the flux linkage. The instantaneous per phase mechanical torque T_k is given by:

$$T_k = \frac{1}{2} i_k^2 \frac{dL_k(\theta)}{d\,\theta} \qquad (3)$$

L_k represents nonlinear inductance with respect to rotor position. The phase inductance L that varies with rotor position is calculated by:

$$L(\theta) = \begin{cases} L_{min} + \left(\frac{L_{max}-L_{min}}{\theta_{aligened}-\theta_{unaligned}}\right)\theta \\ L_{max} \\ L_{max} + \left(\frac{L_{max}-L_{min}}{\theta_{aligened}-\theta_{unaligned}}\right)\theta \end{cases} \qquad (4)$$

where the 1st part is at the occurrence of rising slop, the 2nd part is at the aligned position, and the 3rd part is at falling slop. The dynamic model of the SRM can be represented by the following state-space equations:

$$\frac{di_k}{dt} = \frac{V_k - R.i_k - \frac{\partial\varphi_k}{\partial\theta}}{\frac{\partial\varphi_k}{\partial i_k}} \qquad (5)$$

$$\frac{d\omega}{dt} = \frac{T_{total} - T_{load} - B_{\omega}}{J} \qquad (6)$$

$$\frac{d\theta}{dt}\ \omega \qquad (7)$$

where J is the rotor inertia, B represents friction coefficient, and T_{load} is the load torque. The mechanical power is given by:

$$P_{mech} = T_{total} \,.\, \omega \qquad (8)$$

3. The control system

The control system is divided into two sections: the 1st section is about FLC speed controller and the 2nd section is for HCC.

3.1 FLC speed controller

Normally, the control systems depend on complex mathematical models. Conversely, FLC employs language variables and approximate reasoning to manage intricate and unpredictable systems. It is based on the mathematical structure that deals with uncertainty and imprecision. Many membership functions can be used with different degrees of being false or true [20-21]. In the present paper, the FLC used contains 2 inputs repressed by the speed error ER and change or error CER, but it has only a single output. For each input or output form, there are five membership functions named as (NB, NS, ZE, PS, and PB) where the letter N is for negative, the letter P for positive, the letter B is for big, S is for small, and ZE for zero. The universe of discourse range of ER is $-5\ to + 5$, for CER is $-2.5\ to + 2.5$ and for the output is $0\ to + 100$. fig. (2) represents all the ports of the FFLC concerning their membership functions. Table (1) represents the 25 rules between the two inputs and the membership function of the resulted output.

3.2 Hysteresis current control HCC

HCC is considered one of the modes used to operate the SRM. As presented in Fig. (3), the FLC generates a signal which is multiplied another signal that is obtained from the rotor position sensor. This multiplication performs a reference current signal. This reference is compared with the actual derived current by the SRM. The result of this comparison makes the error signal that is fed to the hysteresis band to perform the HCC. The state of switching is varied according to the motor current value, either less than or greater than the reference current by the hysteresis band. [22-24]. In this paper this method is named as HFLC.

Table (1) The proposed FLC rules

ER / CER	**NL**	**NS**	**ZE**	**PS**	**PL**
NL	NL	NL	NL	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PL	PL	PL

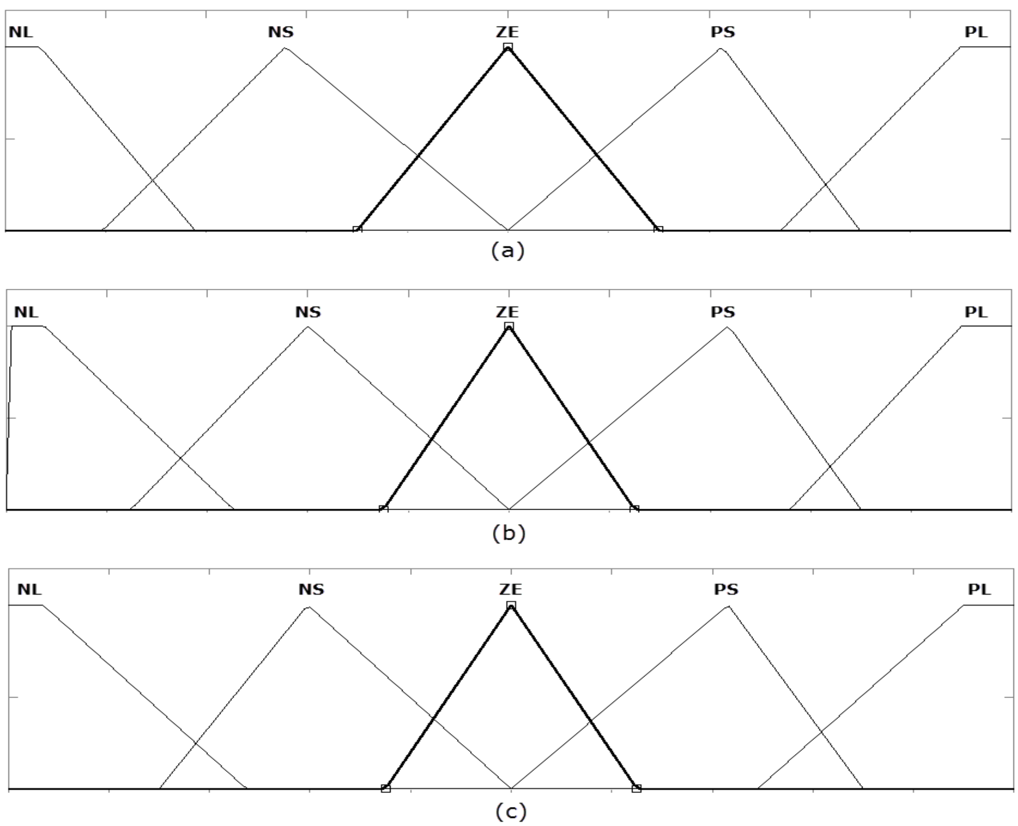

Figure (2) FLC membership function: (a) ER (b) CER and (c) Output

The hysteresis band controller has a discontinuous non-smooth manner. Its output switches sharply between two states like ±1 or ON/OFF status. This may cause an issues in systems steady-state stability. Another approach is used in this paper is to enhance the response of the SRM and eliminate the issues that are generated through using of the hysteresis band is by replacing it by hyperbolic Tan or TanhHFLC. For switching action, the hyperbolic Tan (tanh) function can be approximated as:

$$u(x) = \tanh(\alpha.(x_{ref} - x) \qquad (9)$$

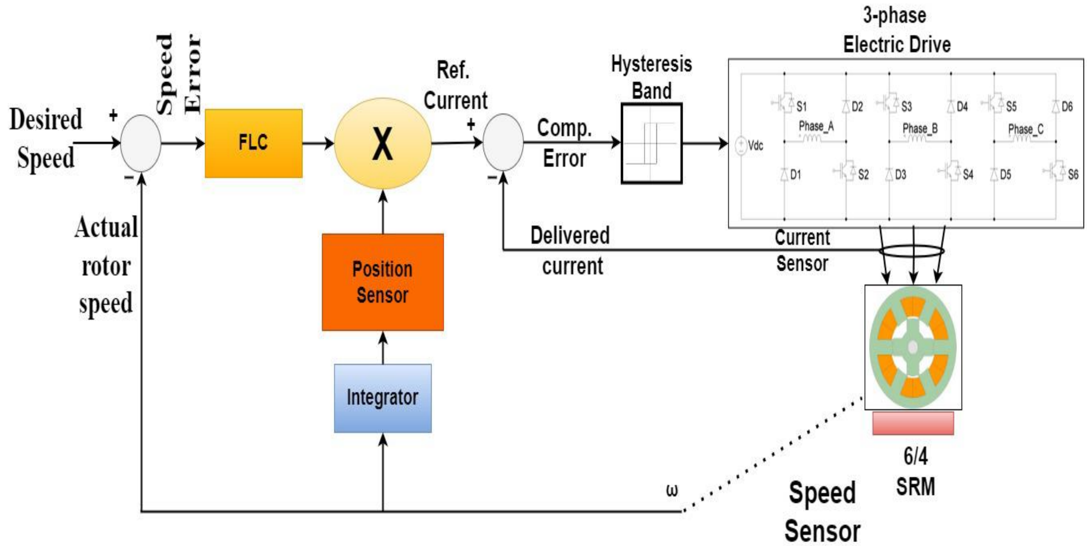

Figure (3) Functional block diagram of SRM HCC

Where: x is the actual signal, x_{ref} is the reference signal, α represents gain parameter (controlling of system transition), $u(x)$ is the output control signal which can be scaled for analog control or PWM [25-26].

4 Simulation Results

In this section, the simulated results of the proposed speed control method for the SRM is presented. The 1.5 kW SRM specifications are listed in table 2. The entire system is simulated by "MATLAB SIMULINK R2020a".

Table 2. Parameters of the SRM motor

Parameter	Value
Rated Power	1500 W
Input voltage	60 V
Stator resistance	0.026 Ω
Inertia	0.0072 J(kg.m2)
Stator/rotor Poles	6/4
Rated speed	4000 R.P.M
Saturated aligned Inductance	0.94 mH

The 1st simulation results are obtained when the system is set to work at startup and reach the desired rated speed as shown in fig. (4). There two speed controller are used and their results are compared. In fig. (4), it can be seen that the speed control at TanhHFLC is faster to reach the desired speed than the case when the HFLC is used by 6.4 %. Fig. (5) shows the 3-phase of the motor input current and the electromagnetic torque T_e. The superior characteristics of the TanhHFLC can also be noted than the HFLC speed control method. In TanhHFLC, the T_e and the input

current are less by 20.8% and 10.9% respectively. In TanhHFLC, the Te is 3.6 N.m, and the input current per-phase is 53A, and in HFLC, the T_e is 4.55 N.m , and the input current per-phase is 59.5A.
In the case of the motor speed change, the desired speed of the SRM is varied from 2000 R.P.M. to 3500 R.P.M. as shown in fig. (6). Before the simulation time exceeds 0.5 s, the desired speed is at 2000 R.P.M., and the motor is working at either the TanhHFLC or HFLC methods at the same speed.

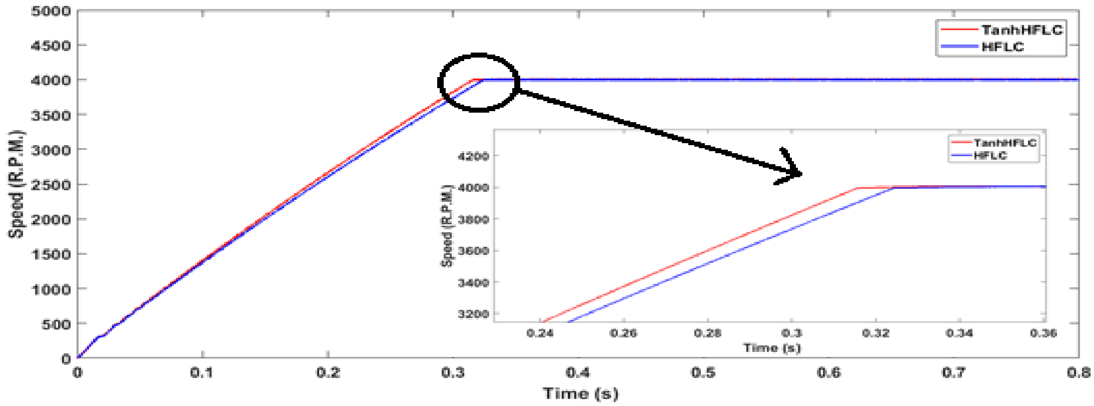

Figure (4) Speed of the SRM during system startup

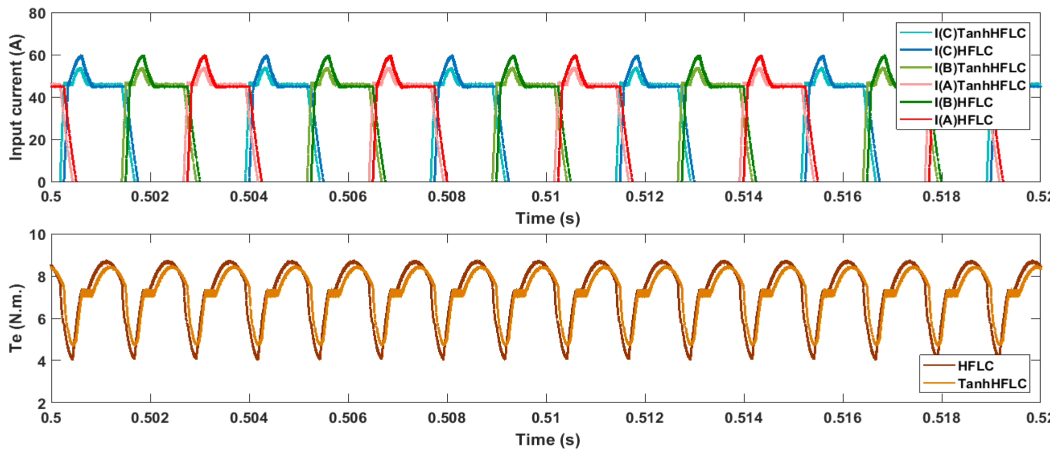

Figure (5) Input current and T_e

After the simulation time exceeds 0.5 s, the desired SRM speed is changed to be 3500 R.P.M. for a transient time of 128 ms. It can be seen that the TanhHFLC performs better for sudden speed changes than the HFLC speed control method. In both cases, if the TanhHFLC or HFLC is used, the proposed FLC makes a fast response for the SRM, and for better performance, the TanhHFLC gives better performance than the HFLC speed control of the SRM.

5 Conclusions

In the present paper, a speed controller for the SRM motor is designed by FLC when the motor is working in hysteresis mode. With the FLC, there are two approaches made, which are TanhHFLC and HFLC. From the simulation results, it can be concluded that the speed control of the SRM when the TanhHFLC is applied, the motor performance is better with faster response than in the case where the HFLC is used. During the employment of the TanhHFLC method, the SRM, the T_e, and the input current are reduced by 20.8% and 10.9%, respectively. Also, the speed response is faster by 6% than the utilization of the HFLC. This means the TanhHFLC can be used to regulate the speed of the SRM for many electric vehicles and industrial applications.

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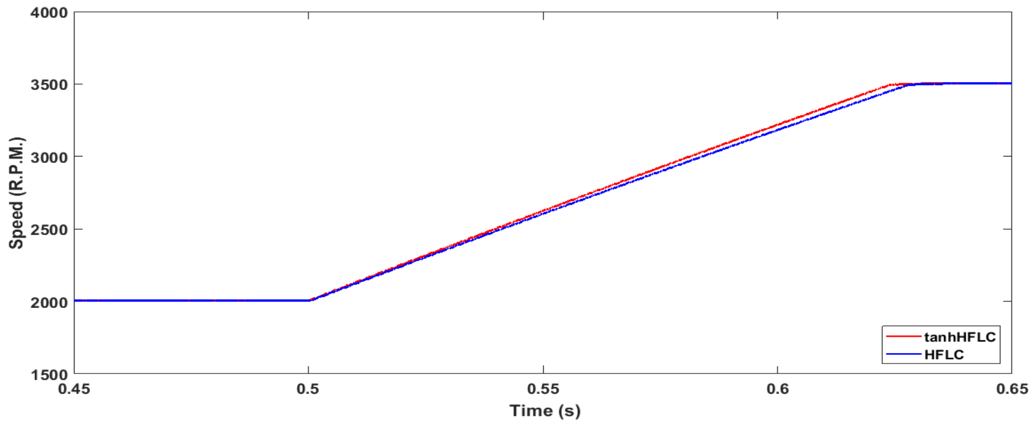

Fig. (6) speed change from (2000 to 3500) R.P.M.

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