Abstract: This paper presents a new approach used for switched reluctance motors (SRM) speed control. Two nonlinear controller, one is variable structure with sliding mode controlled type (VSC) and the other is PI-like fuzzy controller (FLC), define a new control structure. The VSC acts mainly in a transient state which is increasing system stability limits. But, PI-like FLC controller acts in the steady state which is reducing the chattering phenomena in this state. The introduced controller applied to control the reference current of the hysteresis controller to improve the electromechanical torque to ensure a robust speed regulator. The results have been simulated through the matlab – simulink toolbox show that using the proposed controller in the speed loop gives a best and robust responses.

Keywords
Switched reluctance motor, variable structure control, sliding mode, and fuzzy based control.

1. Introduction

Switched Reluctance motors are fast becoming a popular attractive to induction motors in the variable speed drives market due to their advantages. SRM is simple and rugged in structure, has high energy density, and low rotor inertia. References [1, and 2] show the implementations of controllers used with SRM speed drive are complex and too difficult to implement. Since the 1960’s, with the advent of power electronics and high power semiconductor switches, control of the SRM become much easier and there has been a renewed interest in SRM drives.

In recent years sliding mode control, based on the theory of variable structure systems has attracted a lot of research on robust control of nonlinear systems for the last two decades. The main important advantages of sliding mode control, especially for application in the power electronics area, are high accuracy, fast dynamic response, good stability, simplicity of design implementation, and beside to its robustness or low sensitive to variation of system parameters and external disturbances. [3, and 4].

VSC with sliding mode is a high speed switching control law driving the system states from any initial state onto a user specified surface in state space called switching or sliding surface, and maintained the states on the surface for all subsequent time. As a result, the system dynamics, governed by the parameters, is described by that sliding surface which is allows stable [5].

Fuzzy logic control (FLC) is recently finding wide popularity in various applications that include managements, economics, medicines, and process control systems. The theory was introduced by Zadeh [6]. FLC have generated a good deal of interest in certain applications due to its advantages over the conventional controller like: not need accurate mathematical model, works with imprecise inputs, handles nonlinearty, and is more robust than conventional nonlinear controller. The application of fuzzy theory in power electronics is almost entirely new [7, and 8].

The switching action in VSC methodology causes a severe chattering in steady state which is undesirable in some dynamic systems. Several chattering reduction methods based on using a boundary layer in the sliding mode have been reported [3, 9, and 10]. Although there has been some research on the stability analysis of fuzzy control systems, fundamental problems, however, still exits in the control of complex systems using fuzzy logic controller like the huge amount of fuzzy rules for a high order system makes the analysis complex, and no general stability analysis tools applied to FLC [9].

This paper describes a new robust fuzzy variable structure controller for speed regulation of 6/4 switched reluctance motor. This novel method of control combines the best behaviors of both VSC and FLC. VSC mostly acts in a transient state, providing a fast dynamic response and enlarging the stability limits of the system, while the PI – like fuzzy acts mainly in steady state to reduce chattering. A supervisory fuzzy controller is used to weight the outputs obtained from both two nonlinear controllers to get the best control action, and overcome the problems mentioned in the last paragraph. The proposed controller structure gives a better performance, global stability, and also the robustness is assured.
2. Switched Reluctance Motor

2.1. Basic of operation

The 6/4 SRM is an electrical motor as shown in Fig. (1), which the stator windings on diametrically opposite pole are connected in series to form one phase since there are no windings or magnets on the rotor.

The torque is produced by the tendency of rotor to move to a position where the reluctance of the excited phase winding is minimum. During motor operation, each phase is excited when its inductance is increased, and unexcited when its inductance is decreased [11].

A good summary gives several possible configurations to energize a SRM from a converter found in [12]. With using the H bridge asymmetric type converter, each phase has two IGBTs and two diodes as shown in Fig. (1). When both IGBTs Q1, and Q2 are closed, the current passes through them from the DC supply to the phase winding causing the rotor movement. When they are open, the stored co-energy in the phase winding is returned back to the supply through the freewheeling diodes D1, and D2 [12].

However, under the assumption of linear magnetism, the inductance against rotor position profile can be approximated in trapezoidal manner over one rotor pole pitch as shown in Fig. (2.a) The inductance profile of the first phase can be expressed as

\[ L_i(\theta) = \begin{cases} 
L_u & \theta_s > \theta > 0 \\
L_u + K\theta & \theta_s > 0 > \theta_s \\
L_u - K(\theta - \beta_1 - \beta_s) & \theta_s > 0 > \theta_s \\
L_u & \theta_s > 0 > \theta_s 
\end{cases} \]  

(1)

Where \( K \) is the slope of the profile in zone of increasing inductance, \( \theta \) is the rotor position, \( \theta_s \) to \( \theta_s \) are described in Fig. (2) and \( \beta_1 \) and \( \beta_s \) are rotor and stator pole arcs and \( L_u \) and \( L_a \) are unaligned and aligned inductance respectively.

And the other phases inductances are shifted by \( \theta_s = 2\pi\left(\frac{1}{N_r} - \frac{1}{N_s}\right) \) from each others where \( N_r \) and \( N_s \) are number of rotor and stator poles respectively.

The chopping current strategy is used in the introduced work. Since this strategy is so called a hysteresis current regulator in which the power transistor are switched off and on according to whether the phase motor current is greater or less than a reference current. The error is used directly to control the states of the power transistor as shown in Fig. (2) [11].

The system dynamics of SRM drives can be modeled as:

2.1. Electrical system

\[ \frac{d\varphi_n}{dt} = -R_n i_n(t) + v_n(t) \]  

(2)

\[ \varphi_n(\theta, i_n) = L_n(\theta) i_n(t) \]  

(3)

\[ T_t = \frac{1}{2} \sum_{n=1}^{q} \int_{\theta_s}^{\theta_s + (q-n-1)\theta_s} \frac{dL_n}{d\theta} \left[ \theta + (q-n-1)\theta_s \right] \]  

(4)

Where \( i_n \), \( R_n \), \( L_n \), \( v_n \), and \( \varphi_n \) are \( n \) phase current, resistance, inductance, voltage, and flux linkage respectively. \( T_t \) is total electromagnetic torque, and \( q \) is Number of motor phases

2.2. Mechanical system

\[ \frac{d\omega}{dt} = \frac{1}{J} \left( T_t - T_i - f\omega \right) \]  

(5)
Where $\omega$ is angular rotor speed, $T_f$ is load torque, $f$ is viscous fraction coefficient and $J$ is the inertia constant respectively.

Then the state equations of SRM are

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -f/J \\ 0 & -a/J \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b/J \end{bmatrix} u$$

(6)

Where $a = f/J$, $b = 1/J$, $x_1 = \omega_d - \omega$ is speed error, $\omega_d$ is desired reference speed and $x_2 = d\omega / dt$.

### 3. Control System

The structure of the control system is shown in Fig. (3). The output of the proposed controller is the desired torque or current component of the stator winding, which compensates the load applied to the motor.

![Fig. (3) Structure of the proposed control.](image)

To obtain the control law, the VSC and PI-like fuzzy controllers are separately designed to obtain especially good characteristics in the state, where each one provides the dominating control action. Afterwards, they are adjusted to achieve satisfactory features when they are combined. The error and its change between the reference and rotor speeds are the inputs for both controllers. The control action are combined by means of a weighting factor ($\gamma$), which is the output of a supervisory fuzzy logic system operated at a higher hierarchical control level. The final action $i_{ref}$ is built as follows:

$$U_{vc} = \Delta i_{ref,vc}$$

(7.a)

$$U_{fi} = \Delta i_{ref,fi}$$

(7.b)

$$U = \Delta i_{ref} = (1-\gamma) U_{vc} + \gamma U_{fi}$$

(7.c)

$$i_{ref} = \frac{1}{r} \int_0^t U \, dt$$

(7.d)

Where $\Delta i_{ref,vc}$ is the VSC output, $\Delta i_{ref,fi}$ is the PI-like fuzzy output, $U$ represents the global control action of supervisory fuzzy controller before the integration, and $r$ is the control action integration constant.

### 3.1. Variable structure controller.

The main problem related to the high gain inherent in VSC systems is the large chattering due to the sliding mode switching control law. This phenomenon causes a finite time delays in control computations, this beside to the limitations of the physical actuators which are unable to switch current at an infinitely fast rate. Although chattering is especially noticeable in the steady state, it also exists when the system is approaching to that state. Thus, an integral compensation can be inserted to decrease chattering and enable smooth the output signal of the controller [5].

$$\dot{x}_1 = \frac{1}{\tau} \int_0^t U \, dt$$

(8)

Where $\sigma$ is the sliding line, and its slope is $\lambda$.

If the VSC output can be designed as the same manner described in [13],

$$U_{vc} = \psi_1 x_1 + \psi_2 \dot{x}_1 + d \sigma$$

(9)

Where $\psi_1$ and $\psi_2$ are variable gains, which is selected by sliding conditions. $d$ is a dither gain to eliminate steady state offset error due to load disturbance to provide system robustness.

To satisfy the existence condition of the sliding mode controller the following condition must be satisfied:

$$\lim_{\sigma \to 0} \sigma \dot{\sigma} \leq 0$$

(10)

By checking the sign of $\sigma \dot{\sigma}$, giving the condition of the sliding mode as:

$$\psi_1 = \begin{cases} \alpha_1 & \text{if } x_1 \sigma > 0 \\ -\beta_1 & \text{if } x_1 \sigma < 0 \end{cases}$$

(11.a)

$$\psi_2 = \begin{cases} \alpha_2 & \text{if } \dot{x}_1 \sigma > 0 \\ -\beta_2 & \text{if } \dot{x}_1 \sigma < 0 \end{cases}$$

(11.b)

The conditions in inequalities (11) are applied for selecting the values of $\alpha_1, \alpha_2, \beta_1, \beta_2,$ and $d$ which are real constant values to give the VSC gains described in eqn. (9).

### 3.2. PI – like Fuzzy controller

The principal drawback associated with FLC systems is the difficulty stating system stability, especially with using nonlinear control systems. FLC system provides a smooth performance when reaching a steady state case.

Fuzzy logic can be considered a special class of symbolic controller. The three main features of this
controller are fuzzification (for the numeric to symbolic inference), rule evaluation (for the decision making), and defuzzification (for symbolic to numeric inference).

### 3.2.2. Fuzzification

FLC uses linguistic variable instead of numerical variable. In a closed loop control system, error between reference and output can be labeled as zero (Z), positive small (PS), and negative small (NS), etc. In real world, measured quantities are real numbers (crisp). The process of converting a numerical variable (real numbers) into a linguistic variable (fuzzy numbers) is called fuzzification. Fig. (5) and, Fig. (6) shows the membership function used in fuzzification stage.

The output of the fuzzy controller is a fuzzy set of output variable using fuzzy sets. The rule base contains a collection of fuzzy conditional statements, such as:

If error is NB and change of error is PB then the output is Z

Finally, crisp output is obtained by defuzzification stage is needed. Defuzzification can be performed by two algorithms, one is center of gravity (COG) and the other is the mean of maximum (MOM). The output membership function is shown in Fig. (7). The MAX-MIN composition is chosen as fuzzy inference method. Table 1 describes the rule table of fuzzy controller.

### 3.3. Defuzzification

The output of the fuzzy controller is a fuzzy set of control so it is necessary to convert this fuzzy sets to numerical values, i.e. reverse to fuzzification stage, so a defuzzification stage is needed. Definition of symbols are: very large (VL), large (L), medium (M), small (S) and zero (Z). When an error and its derivative w.r.t. time in absolute value are small, the PI-like fuzzy controller must be dominant and γ approaches to 1. In opposite case, sliding mode controller is dominant and γ approaches to zero

\[
\Delta u = \sum_{j=1}^{m} \left[ \mu_j \cdot \Delta u_j \right] / \mu_j
\]

Where \( m \) is the number of quantization level of the output \( \Delta u_j \) is the amount of control output at the quantization level j, and \( \mu_j \) is represent output membership value.

### 3.3. Fuzzy supervisory system

A fuzzy supervisory system is used to calculate the γ value. The control region is divided by means of a fuzzy inference machine, which acts at the highest hierarchical level of control [14]. The objective of the supervisory is to change the γ value described in eqn. (7). Fig. (8) shows the structure of membership functions and their rules data base are described in table 2 for the proposed hierarchical control law. The membership functions are triangular ones and output function are singletons. Definition of symbols are: very large (VL), large (L), medium (M), small (S) and zero (Z). When an error and its derivative w.r.t. time in absolute value are small, the PI-like fuzzy controller must be dominant and γ approaches to 1. In opposite case, sliding mode controller is dominant and γ approaches to zero

\[
\gamma = \frac{1}{1 + \frac{\text{Abs}(E) / \text{Abs}(CE)}{\text{VL}}} \cdot \frac{\text{Abs}(E) / \text{Abs}(CE)}{\text{VL}}
\]

Table 1 The rule data base for PI-like fuzzy controller.

<table>
<thead>
<tr>
<th>Input</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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<tr>
<td>ECE</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
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<td>NS</td>
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<td>NM</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>NS</td>
<td>NM</td>
<td>NS</td>
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<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
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<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

Table 2 The rule data base for supervisory fuzzy controller.

<table>
<thead>
<tr>
<th>Abs(E)/Abs(CE)</th>
<th>Z</th>
<th>M</th>
<th>L</th>
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</thead>
<tbody>
<tr>
<td>Z</td>
<td>VL</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>M</td>
<td>S</td>
<td>S</td>
<td>Z</td>
</tr>
<tr>
<td>L</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
</tr>
</tbody>
</table>

### 4. Simulation results

In order to verify the control strategy as discussed above, the simulation study of total system, as shown in Fig. (9), was implemented using matlab / simulink soft

![Fig. (5) Linguistic rules for speed error.](image1)

![Fig. (6) Linguistic rules for change of speed error.](image2)

![Fig. (7) Linguistic rules for change of reference current.](image3)

![Fig. (8) Memberships of the supervisory fuzzy control](image4)

![Fig. (9) Implementation using Matlab / Simulink software](image5)
ware packages using the parameters of a typical three phase 6/4 pole SRM drive stated in appendix listed in section 6.

**Fig. (9)** Closed loop of SRM using proposed FVSC controller.

**Fig (10) speed response with reference speed 1000 rpm.**

**Fig (11) a. Phase1 instantnuos torque.**
**b. Developd instantnuos motor torque.**

**Fig (12) Instantnuos 3phases steady state current**

In order to verify the proposed controller strategy, the drive has been simulated under different working conditions. The drive response to a speed reference step is 1000 rpm, with the motor full loaded (0.5 Nm.). **Fig. (10)** shows the speed response under the proposed controller and the motor speed traces the reference without any overshoot and with minimum ripples, also the settling time in the transient state is 0.2 sec. **Fig. (11)** shows the traces of the instantaneous torque developed by phase 1 **Fig. (11-a)** and the motor **Fig. (11-b).** The resultant demonstrate the reduction in the torque ripples by using the proposed controller because the currents, of the motor phases, are almost flat topped as shown in **Fig. (12).** Since the hysteresis current controller flatten each phase current to obtain a constant torque and the controller effort output is shown in **Fig. (13 a, and b).** The corresponding phase 1 excitation voltage and
inductances profile of the three phases are shown in Fig. (14) and Fig. (15), respectively.

The proposed controller was simulated with changing the speed reference step from 1000 rpm. At time equal one second to 700 rpm, and is raised again to 1000 rpm. At time equal two second with a full load motor operation as shown in Fig. (16). It is observed that the speed response gives a good tracking for the reference one and when steady state is reached, the torque chattering of the proposed controller is reduced as shown in Fig. (17 a, and b)

5. Conclusions

A new type of fuzzy inference based hierarchical controller is presented. The proposed control structure combines a variable structure controller and PI-like fuzzy logic controller. The control action is weighted between two basic nonlinear controller by a fuzzy inference machine.

The dynamic response of the proposed FVSC when applied to 6/4 SRM speed regulator gives a good performances. The overshoot in transient state is ignored, also in steady state torque chattering is decreased. So the proposed controller gives a good smoothing speed tracking with minimizing its ripples to guarantee a robust command control action

6. Appendix

System parameters of SRM 3 phase 6/4 pole drive

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Stator pole arc</td>
<td>40 deg.</td>
</tr>
<tr>
<td>Rotor pole arc</td>
<td>45 deg.</td>
</tr>
<tr>
<td>DC voltage</td>
<td>220 V.</td>
</tr>
<tr>
<td>Rated current</td>
<td>2 Amp.</td>
</tr>
<tr>
<td>Rated torque</td>
<td>0.5 N.m.</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>17 Ohm.</td>
</tr>
<tr>
<td>Aligned inductance</td>
<td>0.605 H.</td>
</tr>
<tr>
<td>Unaligned inductance</td>
<td>0.155 H.</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>0.0013 Kg.m²</td>
</tr>
<tr>
<td>Viscous friction coefficient</td>
<td>0.0183 N.m.sec²</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1000 rpm.</td>
</tr>
</tbody>
</table>

7. References