Fuzzy Controller of Switched Reluctance Motor

Ahmed TAHOUR, Hamza ABID, Abdel Ghani AISSAOUI and Mohamed ABID

Abstract- Fuzzy logic or fuzzy set theory is recently getting increasing emphasis in process control applications. This paper presents an application of fuzzy logic control (FLC) for switched reluctance motor (SRM) speed. The (FLC) technique finds its stronger justification in the utilization of a robust control law to model uncertainties. A fuzzy logic controller of the motor speed is then designed and simulated. Digital simulation results shows that the designed fuzzy speed controller realises a good dynamic behaviour of the motor, a perfect speed tracking with no overshoot and a good rejection of impact loads disturbance. The results of applying the fuzzy logic controller to a SRM give best performances and high robustness than those obtained by the application of a conventional controller (PI).

Keywords: switched reluctance motor, PI, fuzzy logic, speed control.

1. Introduction

Switched reluctance motors (SRMs) can be applied in many industrial applications due to their cost advantages and ruggedness. The switched reluctance motor is simple to construct. It is not only features a salient pole stator with concentrated coils, which allows earlier winding and shorter end turns than other types of motors, but also features a salient pole rotor, which has no conductors or magnets and is thus the simplest of all electric machine rotors. Simplicity makes the SRM inexpensive and reliable, and together with its high speed capacity and high torque to inertia ratio, makes it a superior choice in different applications.

However, the motor is highly nonlinear and operates in saturation to maximize the output torque. Moreover, the motor torque is a nonlinear function of current and rotor position. This highly coupled nonlinear and complex structure of the SRM make the design of the controller difficult.

The fuzzy control also works as well for complex nonlinear multi-dimensional system, system with parameter variation problem or where the sensor signals are not precise. The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect.

The concept of FLC is to utilize the qualitative knowledge of a system to design a practical controller. For a process control system, a fuzzy control algorithm embeds the intuition and experience of an operator designer and researcher. The control doesn’t need accurate mathematical model of a plant, and therefore, it suits well to a process where the model is unknown or ill-defined and particularly to systems with uncertain or complex dynamics [1].

As an intelligent control technology, fuzzy logic control (FLC) provides a systematic method to incorporate human experience and implement nonlinear algorithms, characterized by a series of linguistic statements, into the controller. In general, a fuzzy control algorithm consists of a set of heuristic decision rules and can be regarded as an adaptive and nonmathematical
control algorithm based on a linguistic process, in contrast to a conventional feedback control algorithm [2, 3].

This paper focuses on speed control of an 8/6 SRM based on a simplified model. This simplified model limits the operation of the motor completely into its linear flux region. This paper proposes to control SRM drives using fuzzy logic control (FLC), which is mainly applied to complex plants, where it is difficult to obtain an accurate mathematical model or when the model is severely nonlinear. FLC has the ability to handle numeric and linguistic knowledge simultaneously [4].

In this paper the application of fuzzy logic in switched reluctance motor speed control is described. The organization of this paper is as follows: in section 2, the control principle for switched reluctance motor drive is presented; in section 3, the proposed controller is described, and used to control the speed of the switched reluctance motor. Simulation results are given to show the effectiveness of this controller. Conclusions are summarized in the last section.

2. SRM model

2.2. Description of the system

In a switched reluctance machine, only the stator presents windings, while the rotor is made of steel laminations without conductors or permanent magnets. This very simple structure reduces greatly its cost. Motivated by this mechanical simplicity together with the recent advances in the power electronics components, much research has being developed in the last decade. The SRM, when compared with the AC and DC machines, shows two main advantages:

- It can achieve very high speeds (20000 - 50000 r.p.m.) because of the lack of conductors or magnets on the rotor.

The switched reluctance machine motion is produced because of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position [5].

A cross-sectional view is presented in figure 1.

![Fig. 1. – Switched reluctance motor.](image1)

The schematic diagram of the speed control system under study is shown in figure 2. The power circuit consists with the H-bridge asymmetric type converter whose output is connected to the stator of the switched reluctance machine. Each phase has two IGBTs and two diodes. The parameters of the switched reluctance motor are given in the Appendix [6, 7].

![Fig. 2. – Control of the SRM.](image2)
The FLC inputs are obtained by manipulating the speed reference and feedback, while the FLC output is integrated to produce the current reference.

### 2.2. Machine equation

The switched reluctance motor has a simple construction, but the solution of its mathematical models is relatively difficult due to its dominant non-linear behaviour. The flux linkage is a function of two variables, the current I and the rotor position (angle $\theta$).

The mathematical model from the equivalent circuit is:

$$V_j = RI_j + L(i,\theta) \frac{di}{dt}$$

$$\frac{d\psi_j}{dt} + \frac{d\psi_j}{d\theta} \omega$$

In which: $j = 1,2,...,4$ and $\omega = \frac{d\theta}{dt}$

The motion equation is:

$$J \frac{d\omega}{dt} = T_e - T_i - f\omega$$

It is a set four non-linear partial differential equations, its solution neglecting the nonlinearity of magnetic saturation.

$$\psi(i,\theta) = iL(\theta)$$

It can be written as

$$V_j = RI_j + L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} \omega$$

$$T_e = \frac{1}{2} \frac{dL(\theta)}{d\theta} i^2$$

The average torque can be written as the superposition of the torque of the individual motor phases:

$$T_e = \sum_{phase=1}^{n} T_{phase}$$

Where $V$ - the terminal voltage, $I$ - the phase current, $R$ - the phase winding resistance, $\psi$ - the flux linked by the winding, $J$ - the moment of inertia, $f$ - the friction, $L(\theta)$ - the instantaneous inductance and $T_e$ is the total torque.

### 3. SRM fuzzy logic speed controller

#### 3.1. Fuzzy logic principle

The structure of a complete fuzzy control system is composed from the following blocs:
- Fuzzification,
- Knowledge base,
- Inference engine,
- Defuzzification.

Figure (3) shows the structure of a fuzzy logic controller.

The fuzzification module converts the...
crisp values of the control inputs into fuzzy values. A fuzzy variable has values which are defined by linguistic variables (fuzzy sets or subsets) such as low, Medium, high, big, slow… where each is defined by a gradually varying membership function. In fuzzy set terminology, all the possible values that a variable can assume are named universe of discourse, and the fuzzy sets (characterized by membership function) cover the whole universe of discourse. The shape fuzzy sets can be triangular, trapezoidal, etc [5, 7].

A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of a designer and researcher. The data base and the rules form the knowledge base which is used to obtain the inference relation (R). The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristics, it contains a collection of fuzzy conditional statements expressed as a set of IF-THEN rules, such as:

\[ R^{(i)} : \text{If } x_1 \text{ is } F_1 \text{ and } x_2 \text{ is } F_2 \ldots \text{and } x_n \text{ is } F_n \text{ THEN } Y \text{ is } C^{(i)}, \text{ i=1, ..., m} \]

where \( (x_1, x_2, \ldots, x_n) \) is the input variables vector, \( Y \) is the control variable, \( m \) is the number of rules, \( n \) is the number fuzzy variables, \( (F_1, F_2, \ldots, F_n) \) are the fuzzy sets.

For the given rule base of a control system, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (the output fuzzy variable) [8, 9].

The composition operation is the method by which such a control output can be generated using the rule base. Several composition methods, such as max-min or sup-min and max-dot have been proposed in the literature.

The mathematical procedure of converting fuzzy values into crisp values is known as ‘defuzzification’. A number of defuzzification methods have been suggested. The choice of defuzzification methods usually depends on the application and the available processing power. This operation can be performed by several methods of which the centre of gravity (or centroid) and the height methods are common [9, 10].

3.2. Fuzzy logic controller

The general structure of a complete fuzzy control system is given in figure (4). The plant control \( u \) is inferred from the two state variables, error \( (e) \) and change in error \( de \) [10].

The actual crisp inputs are approximated to the closer values of the respective universes of discourse. Hence, the fuzzyfied inputs are described by singleton fuzzy sets.

The elaboration of this controller is based on the phase plan. The control rules are designed to assign a fuzzy set of the control input \( u \) for each combination of fuzzy sets of \( e \) and \( de \) [11, 12].

Table 1 shows one of possible control rules.

![Fig.4. Basic structure of fuzzy control system.](image-url)
Table 1. Rules Base for speed control.

<table>
<thead>
<tr>
<th>dU</th>
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<td>PB</td>
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Table (1) shows the rules base. The rows represent the rate of the error change \( \dot{e} \) and the columns represent the error \( e \). Each pair \((e, \dot{e})\) determines the output level NB to PB corresponding to \( u \).

Here NB is negative big, NM is negative medium, NS is negative small, ZR is zero, PB is positive big, PM is positive medium and PS is positive small. NB, NM, NS ..., are labels of fuzzy sets and their corresponding membership functions are depicted in figures 5 and 6, respectively.

The inferred value of the control action in correspondence to the values \( X_{10}, X_{20}, ..., X_{n0} \) of the states can be obtained by the Centre of Gravity method [13] [14]:

\[
    u = \frac{\sum_{j=1}^{n} \alpha_j u_j}{\sum_{j=1}^{n} \alpha_j}
\]  

(8)

where \( \alpha_j \) is the degree of fulfilment of the j-th control rule. It can be computed by

\[
    \alpha_j = \mu_{q_j}(X_{10}) \ast \mu_{q_2}(X_{20}) \ast ... \ast \mu_{q_n}(X_{n0})
\]  

(9)

where \( \mu_{q_j}(X_{10}) \) is the grade of membership of \( X_{10} \), to \( A_{ji} \), and the \( \ast \) operator is the triangular norm.

In the diagram of figure 5, \( e \) represents the speed error and \( \dot{e} \) the derivative of the speed error. The output of the regulator is given by [5]

\[
    U(k) = U(k-1) + dU(k)
\]  

(10)

In the input of the fuzzy controller there are two scale factors, gain \( e \) and gain \( de \), that allow changing the fuzzy controller sensitivity without changing its structure. We need first to establish the maximum limits of each universe of discourse. The universe of discourse of the error signal is computed by

\[
    |e| = \omega_{\text{max}} - (-\omega_{\text{max}}) = 2 \omega_{\text{max}}
\]  

(11)

To get the error derivative limits, it is necessary to know the maximum torque that the machine can provide. Knowing the mechanical equation (without load)

\[
    J \frac{d\omega}{dt} = \Gamma
\]  

(12)

We get the limits of \( \dot{e} \) as

\[
    |\dot{e}| = \frac{\Delta t}{J} \Gamma_{\text{max}}
\]  

(13)

with \( \Delta t \) is the numeric integration step.
4. Simulation and results

To show the fuzzy controller performances we have simulated the system described in figure 1. The simulation of the starting mode without load is done. The test consisted in to control the motor speed at $\omega_{\text{ref}} = 100 \text{ rad/s}$ and to apply an external load at $t = 1\text{s}$ with a value of $\Gamma_l = 1,2 \text{ N.m}$. The simulation is realized using the SIMULINK software in MATLAB environment. Figure 7 shows the performances of the fuzzy controller.

Figure 8 shows the very good performances reached by the fuzzy controller. Indeed, one notes that the overshoot is less important in the case of the fuzzy regulator, with a best response time without increasing the overshoot.

For this test, the fuzzy controller proves to be well more robust because the speed curve is hardly of its reference, as shown in figure 8-d. On the other hand, the speed signal evolution obtained with the PI controller deviates about 10% from its reference value (figure 8-a). An explanation can be given while observing the phase currents. If one observes figure 8-e, one notices that the motor current with the fuzzy controller has a lower response time. This is due to the non-linearity of the fuzzy controller because, when the load is applied, the fuzzy controller stays immediately in the zone where $dI$ has the maximum value. The
decreasing speed oscillations with the PI controller are owed to a slower reaction of the current, as shown in figure 8-b.

4.1. Robustness tests

In order to test the robustness of the proposed control, we have studied the speed performances. Two cases are considered:

1. Inertia variation,
2. Stator resistance variation.

The figure 9 shows the tests of the robustness: a) the robustness tests concerning the variation of the resistances, b) the robustness tests in relation to inertia variations.

Figure 9-b shows the parameter variation does not allocate performances of proposed control. The speed response is insensitive to parameter variations of the machine, without overshoot and without static error. The other performances are maintained.

7. Conclusion

The paper presents a new approach to robust speed control for switched reluctance motor. It develops a simple robust controller to deal with parameters uncertain and external disturbances and takes full account of system noise, digital implementation and integral control. The control strategy is based on FLC approaches.

The simulation results show that the proposed controller is superior to conventional controller in robustness and in tracking precision. The simulation study clearly indicates the superior performance of fuzzy control, because it is inherently adaptive in nature. It appears from the response properties that it has a high performance in presence of the plant parameters uncertain and load disturbances. It is used to control system with unknown model. The control of speed by FLC gives fast dynamic response without overshoot and zero steady-state error.

Appendix

Phase number 4; Number of stator poles 8; 22.6° pole arc; Number of rotor poles 6; 23.0° pole arc; Maximum inductance 9.15 mH (unsaturated); Minimum inductance 1.45 mH; Phase resistance $R=0.3\Omega$; Moment of inertia $J=0.0027\text{Kg/m}^2$; Friction $f=0.0067\text{Nm/s}$; Inverter voltage $V=100\text{V}$.

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Biography

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