FUZZY LOGIC BASED INDUCTANCE MODELING OF A SWITCHED RELUCTANCE MACHINE

Susitra D.[1] and Paramasivam S.[2]

[1]Research Scholar, Satyabama University, Chennai
[2]R & D, ESAB Group, Sriperampudur, Kancheepuram
E-mail: [1]suchithradhanraj@yahoo.co.in, [2]paramasathya@yahoo.com

Abstract

The Switched reluctance machine (SRM) can be operated as a motor/generator which is the subject of interest by many researchers in the field of electrical machines for the last few decades. Many research papers have concluded that Switched Reluctance Generator (SRG) has proved to be a valid alternative to the classical generators in many industrial applications especially in the field of wind energy generation system. The magnetization characteristics of the SRM is highly non-linear making the flux linkage and torque as the non-linear functions of both the current (Iph) and rotor position (θ). Establishing this high precision nonlinear mapping between $L(I, \theta)$, current (Iph) and rotor position (θ) are the base to model the machine accurately for the analysis and control of any SRG system. The generating or motoring mode of operation of the machine depends greatly on the value of rising or falling inductance. Hence it needs to be modeled more accurately for the practical applications.

This paper presents a fuzzy logic based modeling technique for building the Non-linear inductance model of a Switched reluctance Machine (SRM). Fuzzy inference system (FIS) is built and used for the nonlinear inductance calculation by using the data set from the magnetization characteristics of a 6/4 pole SRM. Fuzzy logic technique is greatly suited to model general non linear mapping between input and output spaces. In this paper, a computationally efficient inductance model for SRM is developed. SRM Model for the phase Inductance $L(I, \theta)$ using FIS has been successfully arrived, tested and presented for various values of phase currents(Iph) and rotor positions (θ) of a non linear SRM. It is observed that fuzzy logic technique is suitable for Inductance $L(I, \theta)$ modeling of SRM which is tested to be in good agreement with the training data used for modeling.

Keywords: Non-linear inductance model, Fuzzy logic technique, Switched reluctance machine (SRM).

I. INTRODUCTION

The magnetization characteristics of the SRM is highly non-linear [1] owing to the fact that the working zone of SRG is a highly saturated magnetic circuit which together with the effects of eddy currents, magnetic hysteresis and its special double salient structure and non uniform air gap makes the flux linkage and torque as the non-linear functions of both the current (Iph) and rotor position (θ). Establishing this high precision nonlinear mapping between $L(I, \theta)$, current (Iph) and rotor position (θ) are the base to model the machine accurately for the analysis and control of any SRG system. The electromagnetic characterization of SRG has a direct impact on the electrical analysis, design and application. Many researchers have developed numerical models for SRG, most of which are only linear models which cannot be applied for the practical control applications. Some of the research publications have proposed nonlinear SRM models using various techniques which are generally categorized as (a) Analytical methods [2] – [11] in which the analytical expressions are derived, most of which are based on Fourier series to characterize the flux linkage and torque with respect to current and rotor position. However, the calculation is time consuming and in any way the model would not be worth for online control applications (b) based on magnetic theory [12] which are usually used to compute the magnetic characteristics of the machine, (c) finite element methods (FEM) [13], [14] which provides accurate results but requires tremendous numerical procedure and computational effort and (d) Various Neural network (NN) methods [15]–[23]. The above methods have either faster computational speed or good accuracy but not both. In this present work, non-linear inductance model of SRG is developed based on fuzzy logic technique using fuzzy logic toolbox from MATLAB. Also the Comparison between the results of FIS inductance model with actual inductance values are presented. This paper has been organized as follows. Section 2 presents the mathematical model of SRG and the necessity of inductance modeling. The nonlinear inductance model based on fuzzy logic technique is presented in section 3. The comparison between FIS model and actual magnetization data models is discussed in section 4 and the conclusive remarks are presented in section 5.

II. MATHEMATICAL MODEL OF SRG AND THE NECESSITY OF INDUCTANCE MODELLING

A Switched Reluctance Motor (SRM) is a rotating electric machine where both stator and rotor have salient poles as shown in Fig. 1. The stator winding comprises a set of coils, each of which is wound on a pole. SRM's differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles. The individual phases are sequentially excited such that the motor rotates in the desired direction. The current pulses are to be applied to the phase windings at the appropriate rotor position relative to the excited phase for effective control.

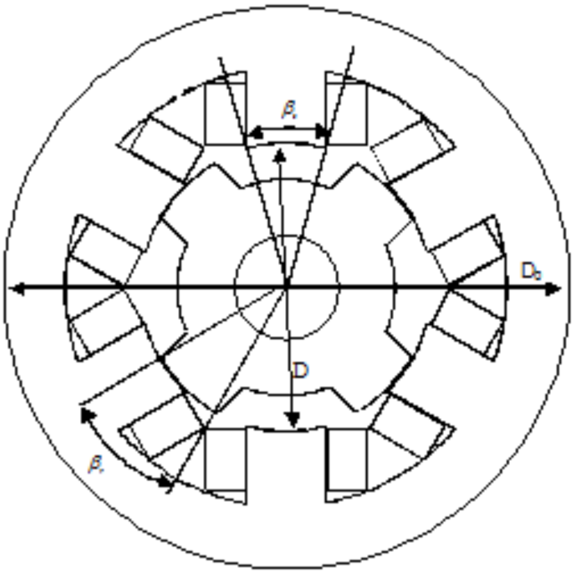


Fig. 1. 6/4 Pole SRM

The inductance profile of SRM varies epending on the magnitude of the excited phase current and the relative position of the rotor with respect to the stator pole axis. In an ideal machine with equal stator and rotor pole axis the variation is triangular shaped when the saturation of the core and leakage fluxes are neglected. In a practical SRM the variation of inductance is nonlinear. It is maximum when the stator and rotor poles are coincident, which is referred as the aligned position. Minimum inductance occurs when the rotor inter polar axis coincides with the excited stator pole axis. This position is referred as the unaligned position. All other positions are referred as intermediate positions. When a particular stator phase is excited, the rotor pole nearer to it tends to align with the excited pole, thus producing a torque. Thereafter the amount of torque developed depends on the rate of change of inductance with rotor position and also magnitude of the excited current. Successful and reliable operation of SRM requires a controller, power converter and position sensors. The positive torque is produced when the phase is switched on during the rising inductance, negative torque is produced when the phase is switched on during the falling inductance and zero torque is produced when the phase is switched on during the constant inductance. Hence the SR machine can transform reversible modes of generating and motoring by controlling the power switches in converter circuit. The mode of operation of the machine depends greatly on the value of inductance. it needs to be modelled more accurately for the practical applications.

2.1. Voltage equation

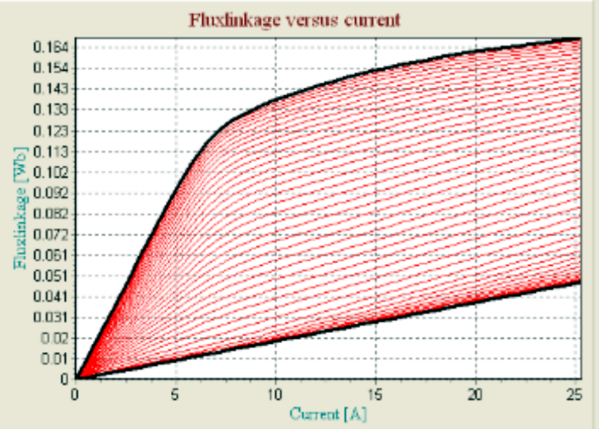


Fig. 2. Magnetization Characteristics of the SRM

Fig. 2 illustrates a magnetization characteristics of a 6/4 pole SRM from [24]. It is a function between the magnetic flux linkage (Ψ), the phase current (i) and the rotor position (θ). The magnetization characteristic of SRM shows the non-linearity of the motor. When the excitation current is less, the magnetization curve is linear. As the excitation current increases, the relationship between ø and *i* become nonlinear as the rotor position changes from unaligned position to the aligned position.

The equivalent circuit model of the excited phase othe SRM is shown in Fig. 3.

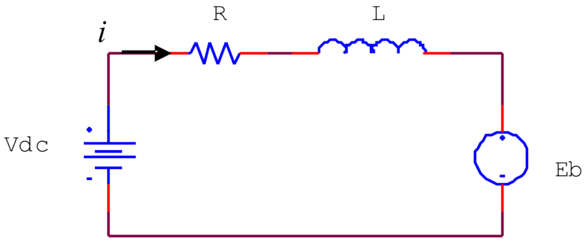


Fig. 3. Per phase equivalent circuit of the SRM

According to Fig. 3, the instantaneous voltage across the terminals of a phase of SRM winding related to the flux linked in the winding is given by,

$$V_{ph}(t) = i_{ph}(t)\, r_{ph} + \frac{d\Psi_{ph}(i_{ph}, \theta_{ph})}{dt} \tag{1}$$

$$\Psi_{ph} = \int (V_{ph} - i_{ph} r_{ph})\, dt \tag{2}$$

In general, the phase flux linkage and hence the phase inductance in SRM varies as a function of rotor position (i_{ph}) and phase current (θ_{ph}). It is due to doubly salient construction and magnetic saturation effects of the SRM. Hence (1) can be written as

$$V_{ph} = i_{ph} r_{ph} + \frac{d[L_{ph}(i_{ph}, \theta), i_{ph}]}{dt} \tag{3}$$

$$V_{ph} = i_{ph} r_{ph} + L_{ph} \frac{di_{ph}}{dt} + i_{ph} \frac{\partial L_{ph}}{d\theta} \frac{d\theta}{dt} \tag{4}$$

$$V_{ph} = i_{ph} r_{ph} + \left[L_{\pi} \frac{di_{ph}}{dt} + \frac{1}{2} i_{ph} \frac{dL_{ph}}{d\theta} \omega \right] + \frac{1}{2} i_{ph} \omega \frac{dL_{ph}}{d\theta} \tag{5}$$

2.2. Torque equation

When a phase of the SRM is excited by a voltage source, the instantaneous power is obtained by multiplying (5) by i_{ph}.

$$P = V_h i_{ph} = i_{ph}^2 r_{ph} + i_{ph} L_{ph} \frac{di_{ph}}{dt} + \omega^2 ph \frac{dL_{ph}}{d\theta} \tag{6}$$

$$V_{ph} i_{ph} = i_{ph}^2 r_{ph} + \frac{d}{dt}\left(\frac{1}{2} L_{ph} i_{ph}^2 \right) + \frac{1}{2} \omega_{ph}^2 \frac{dL_{ph}}{d\theta} \tag{7}$$

$$V_{ph} i_{ph} = i_{ph}^2 r_{ph} + \frac{dw_f}{dt} + T_m \omega \tag{8}$$

where $W_f = \frac{1}{2} L_{ph} i_{ph}^2$ (9)

is the stored energy in the field

and $T_m = \frac{1}{2} i_{ph}^2 \frac{dL_{ph}}{d\theta}$ (10)

is the instantaneous torque developed by the energised phase, when the inductance variation is linear. The LHS of the equation (8) represents the instantaneous electrical power supplied to the motor. The first term of the RHS represents the power loss in the phase resistance, the second term represents the derivative of stored energy in the magnetic field and the third term represents the mechanical power developed by the motor.

III. INDUCTANCE MODELLING OF SRG USING FUZZY LOGIC TECHNIQUE

In this section the fuzzy inference system under consideration has two inputs, current (i) and rotor position (i) and one-output , phase inductance, $L(I, \theta)$. Each input has twelve membership functions. Then the rule base contains one hundred and forty four fuzzy if-then rules of Mamadani type. For the present model, the inductance profile values are taken for an interval of unaligned to aligned rotor position from [25]. The ranges of the input magnetization data are $0 \leq I\theta \leq 25A$ and $0 \leq \theta \leq 45$ deg. The fuzzy inference system is shown in fig. 4.

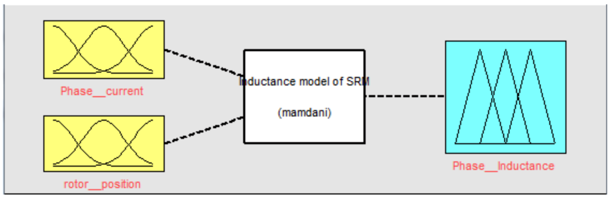


Fig. 4. Fuzzy Inference System for Non linear Inductance model of SRM

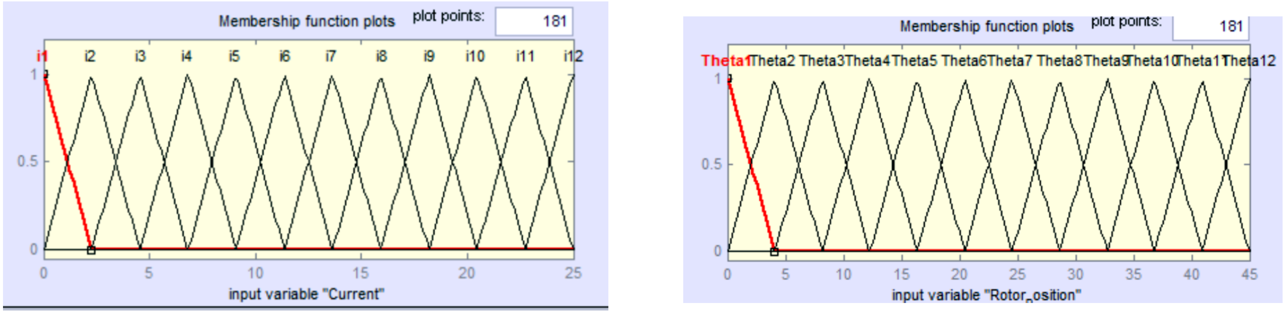
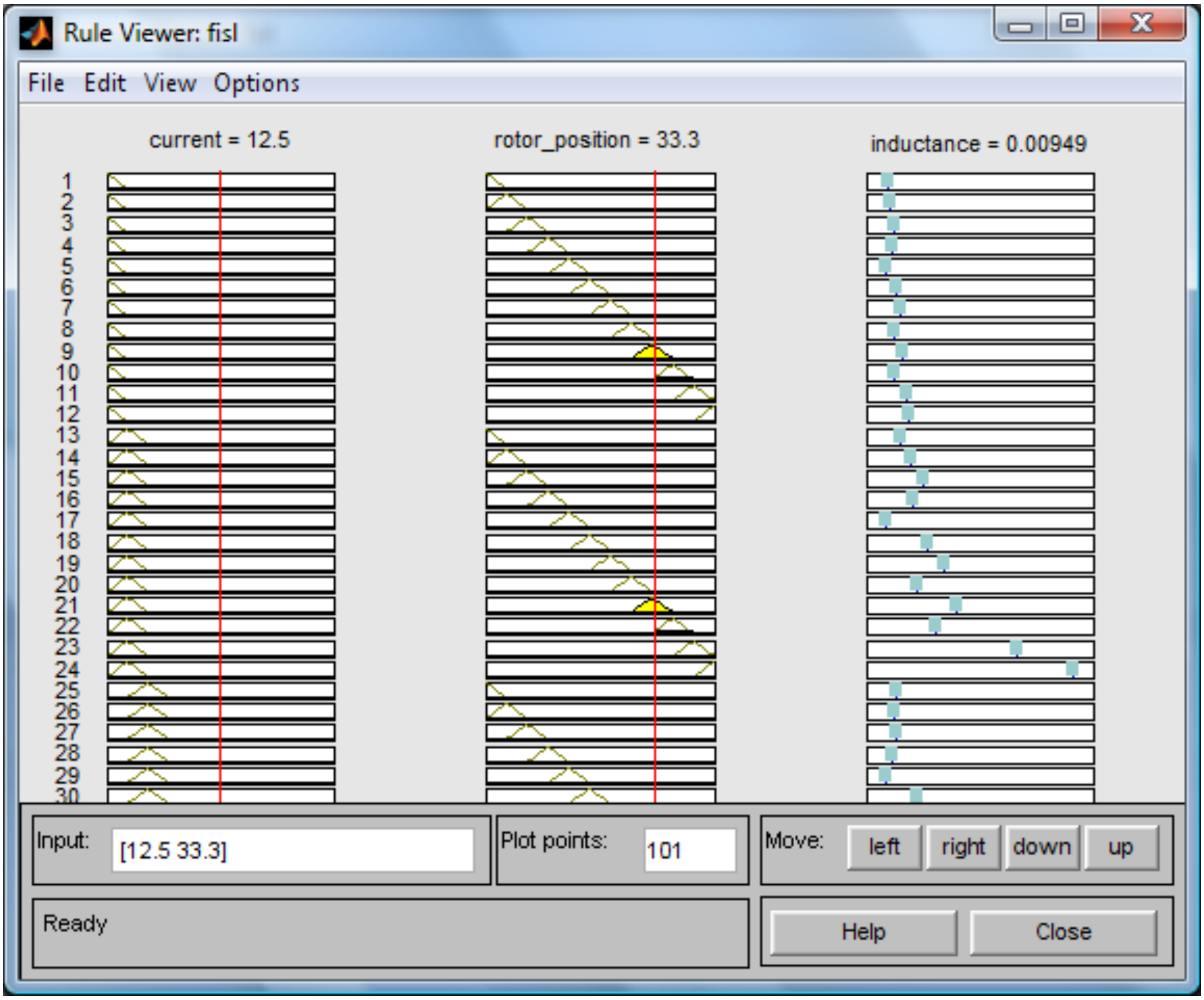


Fig. 5. (a) phase current

Fig. 5. (b) rotor position

Fig. 5. membership functions for the input variables

The input membership functions for *i* and θ are as shown in Fig. 5.(a) and 5.(b) respectively. Fig. 6 shows the FIS rule viewer. The first two columns show the membership functions referenced by the two input parameters current and rotor position and the third column of plots shows the membership functions referenced by the output variable phase inductance. The Rule Viewer interprets the entire fuzzy inference



Input: [12.5 33.3]

Plot points: 101

Ready

Fig. 6. Fuzzy Rule viewer

process at once. The mapping surface of the phase inductance with respect to rotor position and phase current is shown in Fig. 7. It is seen from the mapping surface that initially with the increment of the current the flux linkage and hence the inductance increases rapidly, while in the saturation region, the increment of inductance for the increment of current is slower.

The developed model using FIS has a very simple structure, fast computational speed and characteristic of robustness and presents a superior performance when applied to modeling, prediction and control.

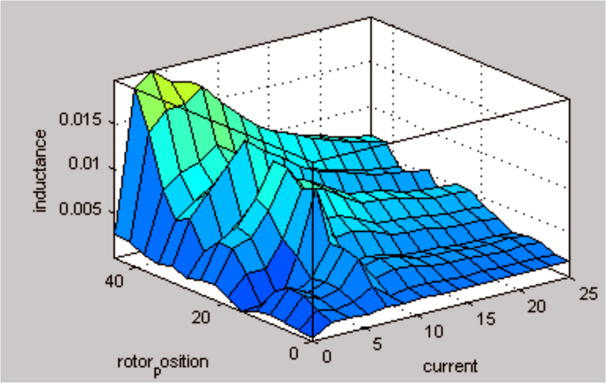


Fig. 7. Nonlinear mapping surface of the Inductance

IV. COMPARISON OF ACTUAL AND FUZZY LOGIC BASED INDUCTANCE MODELS OF SRM

The accuracy of the inductance model of SRG using fuzzy logic is validated from Fig. 8 which gives the comparison between the actual inductance values and the values predicted from FIS model. It is clearly visible from Fig. 8 that the inductance values from the FIS estimator are in good agreement with the actual inductance values for the complete range of test data set. The proposed inductance model based on fuzzy logic uses the data from the magnetization characteristics of the machine. The error in the FIS predicted inductance values from the true values for different operating conditions is shown in Fig. 9. Apart from the graphical representation, root-mean-squared error, mean absolute error and maximum absolute error for FIS model at different operating conditions are presented in Table. I. Fig. 9 shows the root mean square errors (L_RMSE), mean absolute errors and maximum absolute errors at various operating conditions. With the careful observation from the comparison charts and error values, it is evident that the FIS model is in good agreement with the actual results and proves to be the accurate model with least errors for the entire set of data range.

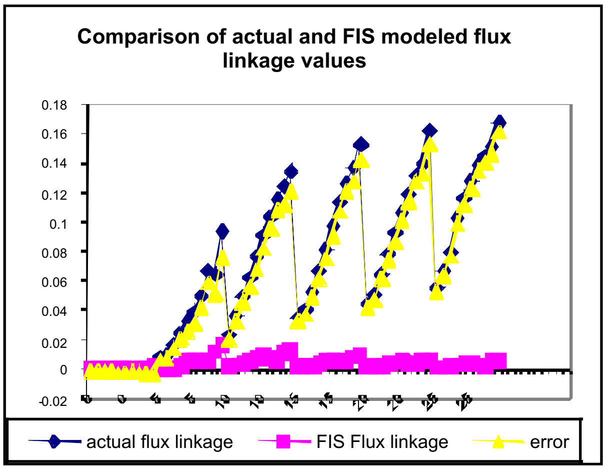


Fig. 8 comparison of phase inductance between actual Inductance and FIS model Inductance

Table I Root-mean-squared error, Mean absolute error and Maximum absolute error at different operating conditions

Operating Currents	L_RMSE	L_MAE	L_max.abs.error
0	0.0016	.00139	.0028
5	0.04	.0339	.0764
10	0.0816	.0745	.121
15	0.0928	.085	.143
20	0.1	.0945	.154
25	0.116	.111	.161

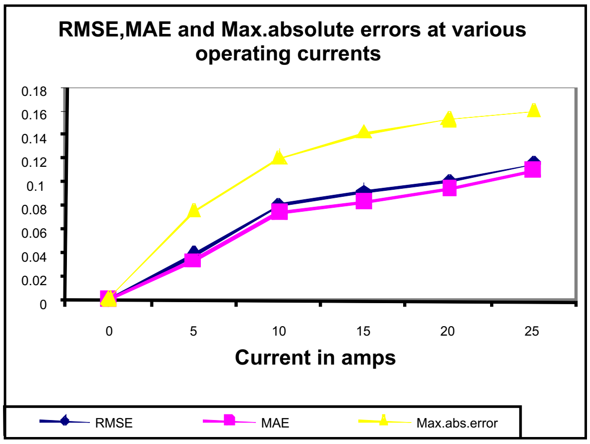


Fig. 9. RMSE, MAE and Max. abs. errors for FIS based Inductance model

V. CONCLUSION

This paper has presented a modeling technique for a 3 phase, 6/4 pole switched reluctance machine for obtaining the nonlinear inductance model by means of fuzzy logic technique. The FIS based inductance model is built and tested with the actual inductance values obtained from the magnetization data of the machine. The results of FIS model are in good agreement with the actual data yielding negligible error for the complete range of the test data. The investigations carried out in this paper prove that the proposed method is capable of estimating the inductance model for SRG within acceptable accuracy limits and are sure to present a superior performance when applied to modelling, prediction and control. The method is very simple and easy to implement and are sure to replace any computationally intensive numerical model of SRG.

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