



EVALUATION OF INDUCTANCE PROFILE FOR SWITCHED RELUCTANCE GENERATOR

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Abstract

Generator and turbine units are the major machineries used in the wind energy conversion system. The efficiency of such system depends greatly on the generators performance. Switched Reluctance Generator (SRG) is slowly replacing conventional induction and permanent magnet synchronous generators in the area of wind energy generation system. This paper presents the fuzzy logic based inductance profile evaluation technique for SRG. The main objective of this work is to determine the suitable fuzzy membership function for inductance profile estimation. The various membership functions such as Trapezoidal, Gbell, Gaussian, Psigmoid and Triangular functions are used to develop the non linear inductance pattern for SRG. The results of inductance profiles estimated from all these membership functions are compared, analyzed and presented in detail. From the analysis of results, it has been proved that the triangular membership function has developed a good inductance profile compared with the other functions. The high non-linearity nature of SRG is well handled by triangular membership function. The developed FIS for SRG is certain to be a

prospective candidate in real time wind energy conversion system.

Keywords: Switched Reluctance Generator (SRG), Non-linear inductance profile, Fuzzy logic, Fuzzy inference system, membership functions.

1 INTRODUCTION

The SR machine operates in a highly saturated region and hence the machine demonstrates extremely non-linear electromagnetic characterization 1. Due to this, the inductance (L), flux linkage (Ψ) and torque (T) parameters of SRG are nonlinear functions of current (I) and rotor position(θ). The accurate function of SRG significantly relies on the precise estimation of its significant parameters such as torque and rotor position. For accurate real time control of the machine, the torque must be determined accurately which depends on the accurate estimation of its rotor position. In turn, the rotor position relies greatly on the magnetization characteristics of the machine, which necessitates the accurate Inductance profile $L(I, \theta)$ estimation for SRG.

Most of the published literatures on SR machine presented linear mathematical inductance profile that is not appropriate for practical applications. Some literatures have proposed nonlinear machine models. Analytical methods are discussed in [2],[3] in which the analytical expressions are derived for $L(I, \theta)$. Magnetic theory based system is developed in [4]. Both these methods are time consuming. Finite element method is employed in [5], but it involves complex numerical calculation and computational effort. Artificial neural network (ANN) algorithms are used in [6],[7] that require numerous training data. Adaptive neuro fuzzy inference system and statistical regression are implemented in [8-10]. In this paper, inductance profile for SRG is estimated based on fuzzy logic process using fuzzy logic toolbox in MATLAB. Fuzzy Inference System (FIS) for SRM inductance profile is developed using various membership functions.

This paper has been organized as follows. The magnetization characteristics of SR machine are discussed in section 2. Section 3 presents the SRM inductance profile using various membership functions. The $L(I, \theta)$ based on Trapezoidal, Gauss, Psigmoid, Gbell and triangular membership function is presented in sections 3.1 to

3.5 respectively. The comparison of the estimated $L(I, \theta)$ profiles and actual magnetization profile is discussed in each section. Comparison of all these models are presented in section 4 and the conclusive remarks are discussed in section 5.

2 MAGNETIZATION CHARACTERISTICS OF SRM

The extreme non-linear magnetization curves of a 6/4 pole SRG obtained from 11 is shown in Figure 1. It shows the relation of $\Psi(I, \theta)$ and hence $L(I, \theta)$. For the machine under consideration, one electrical cycle is from 0 deg to 45 deg. The curve is linear up to saturation after which the correlation between L and i is highly non-linear as θ moves from unaligned (0 deg) to aligned position (45 deg). The Ψ values for various rotor position are extracted from this curve and the corresponding L values are computed using the relation $L = \Psi / I$. The parameters current, rotor position and inductance are extracted from these curves and utilized in building fuzzy inductance model based on various membership functions.

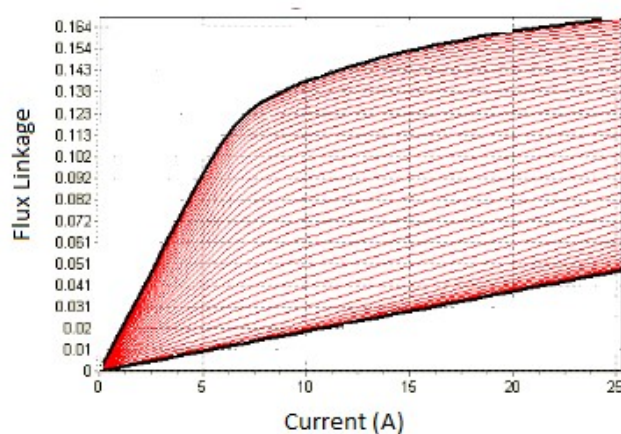


Figure 1: Inductance curves of SRG

3 FUZZY LOGIC BASED INDUCTANCE MODELLING OF SRM USING VARIOUS MEMBERSHIP FUNCTIONS

The Mamadani type fuzzy inference system is used to determine the inductance parameter for SRG using fuzzy logic toolbox in MATLAB. The two inputs to the FIS are current and rotor position. The output of FIS is $L(I, \theta)$. The magnetization data for SRG are taken from 11 for one electrical cycle with the ranges of $0 \leq I \leq 25$ A , $0 \leq \theta \leq 45$ deg and $0.00142 \leq L \leq 0.022$ Henry. This data set is fed as expert knowledge for building FIS.

A. Evaluation of Inductance parameter using GBELL membership function

The twelve GBELL membership functions for the input and output variables such as current, rotor position and phase inductance are shown in Figure 2(a), 2(b) and 2(c) respectively.

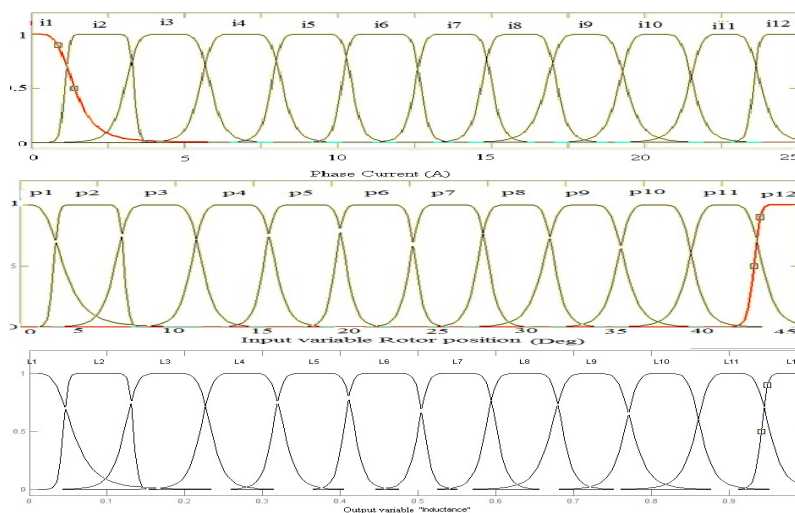


Figure 2: GBELL MF for input and output variables (a) Phase Current (b) Rotor Position (c) Phase Inductance

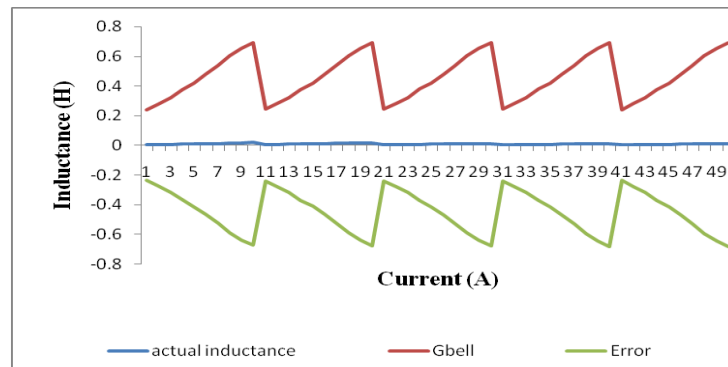
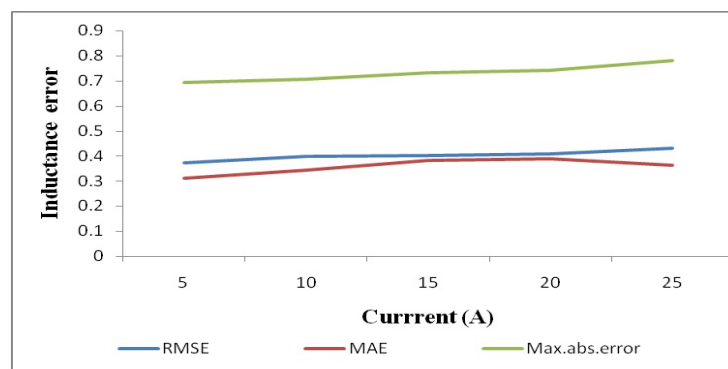
Figure 3: Comparison of $L(I, \theta)$ for original and GBELL FIS

Figure 4: Errors at different operating currents

Table 1: Various errors in $L(I, \theta)$ using GBELL MF model

Inductance Errors (Error in Henry)	5 A	10 A	15 A	20 A	25 A
RMSE	0.373	0.398	0.401	0.409	0.431
SSE	9.547	9.872	10.002	10.014	10.131
MAE	0.311	0.342	0.382	0.388	0.3634
MAVE	0.693	0.706	0.732	0.740	0.779

The comparison between the actual inductance values and the values predicted from GBell MF based FIS model is shown in Fig-

ure 3. The results are analysed based the statistical error measures such as maximum absolute value (MAVE) error, Mean Absolute Error (MAE), Sum of squared error (SSE) and Root Mean Square Error (RMSE). These errors are shown in Figure 4 and presented in Table 1. With the careful examination of errors , it is obvious that the FIS model using Gbell membership function is not in concurrence with the actual data and hence is non suitable for estimating the inductance parameters for SRG.

B. Evaluation of Inductance parameter using Gauss membership function.

The membership functions for input and output variables are as shown in Figure .5(a) and 5(b) and 5(c) respectively.

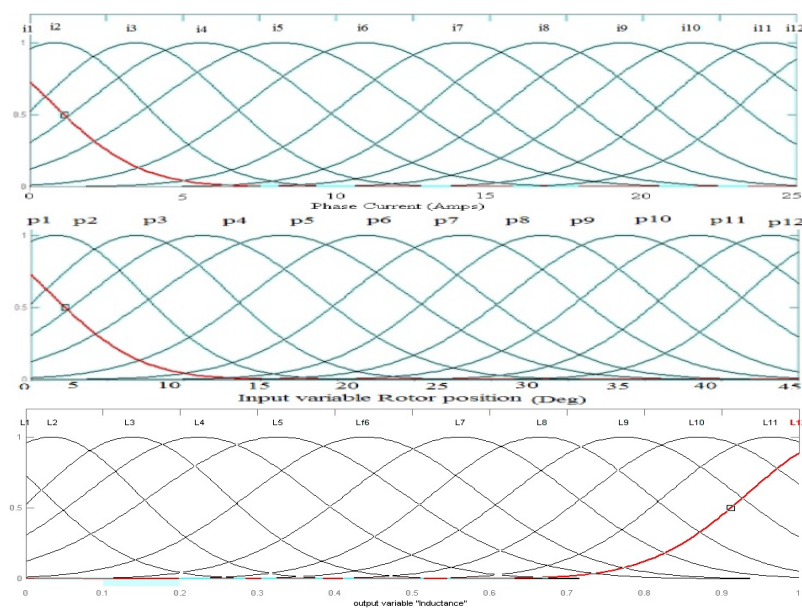


Figure 5: Gauss MF for input and output variables (a) Phase Current (b) Rotor Position (c)Phase Inductance

The comparison between the actual inductance values and the values predicted from Gauss MF based FIS model is shown in Figure 6. The various errors are shown in Figure 7 and presented in Table

2. With the careful examination of errors, it is obvious that the FIS model using Gauss membership function is also not in concurrence with the actual data and hence is non suitable for estimating the SRG inductance parameters.

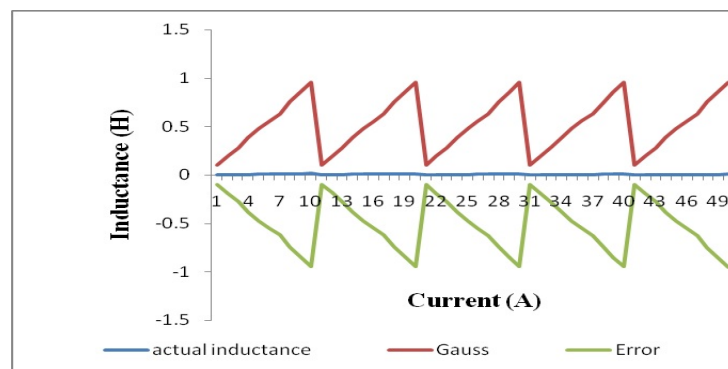


Figure 6: Comparison of $L(I, \theta)$ for original and Gauss FIS

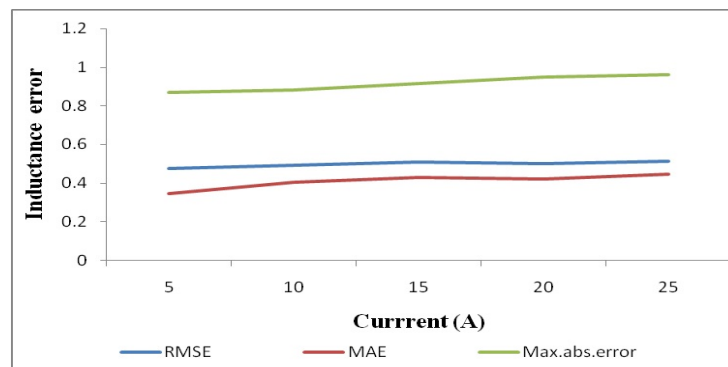


Figure 7: Errors at various operating currents

With the careful observation from the comparison charts and error values, it is evident that the FIS model using Gaussian membership function is not showing any agreement with the actual results and proves to be not appropriate for estimating the non-linear inductance of SRG.

Table 2: Various errors in $L(I, \theta)$ using Gauss MF model

Inductance Errors (Error in Henry)	5 A	10 A	15 A	20 A	25 A
RMSE	0.475	0.491	0.506	0.501	0.512
SSE	14.612	14.873	15.206	15.413	15.706
MAE	0.344	0.405	0.431	0.424	0.448
MAVE	0.871	0.883	0.917	0.946	0.960

C. Evaluation of Inductance parameter using Psigmoid membership function

The membership functions for current, rotor position and phase inductance are as shown in Figure .8(a) and 8(b) and 8(c) respectively.

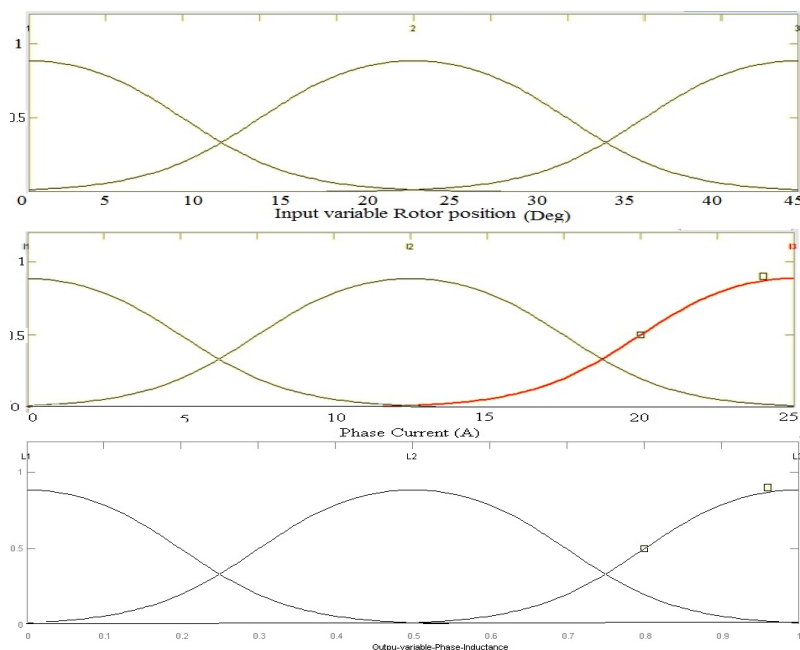


Figure 8: PSigmoid MF for input and output variables (a) Phase Current (b) Rotor Position (c) Inductance

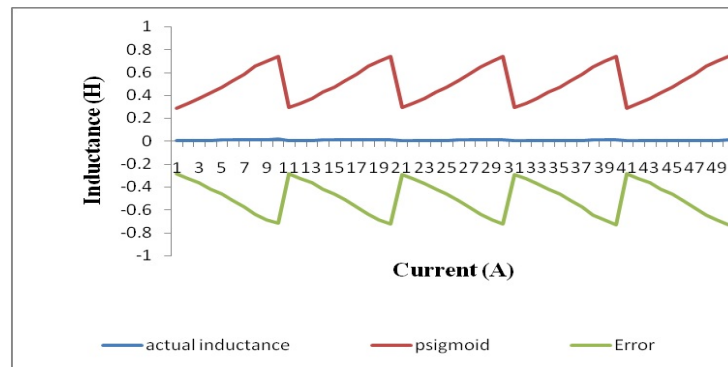
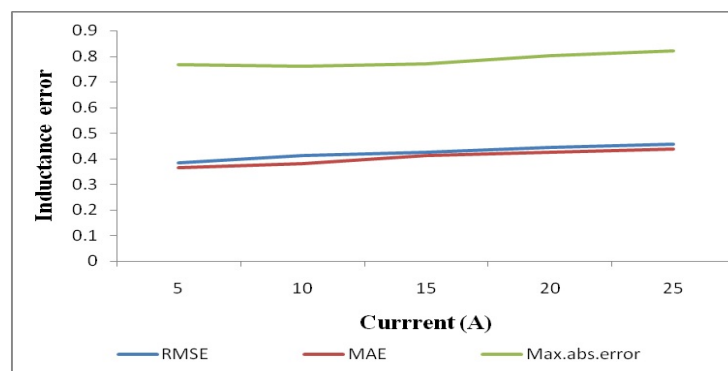
Figure 9: Comparison of $L(I, \theta)$ for original and Psgmoid FIS

Figure 10: Errors at different operating currents

Table 3: Various errors in $L(I, \theta)$ using PSigmoid MF model

Inductance Errors (Error in Henry)	5 A	10 A	15 A	20 A	25 A
RMSE	0.384	0.411	0.426	0.442	0.456
SSE	11.246	12.024	12.163	12.277	12.492
MAE	0.364	0.380	0.412	0.425	0.438
MAVE	0.766	0.761	0.77	0.8	0.82

The comparison between the actual inductance values and the values predicted from the Psgmoid MF based FIS is shown in Figure 9. The various errors are shown in Figure 10 and presented in

Table 3. With the careful examination of errors , it is obvious that the FIS model using Psigmoid membership function is not in good accuracy with the actual data and hence is considered non suitable for estimating the inductance parameters for SRG.

D. Evaluation of Inductance parameter using Trapezoidal membership function

The membership functions for the variables are shown in Figure 11(a) and 11(b) and 11(c) respectively.

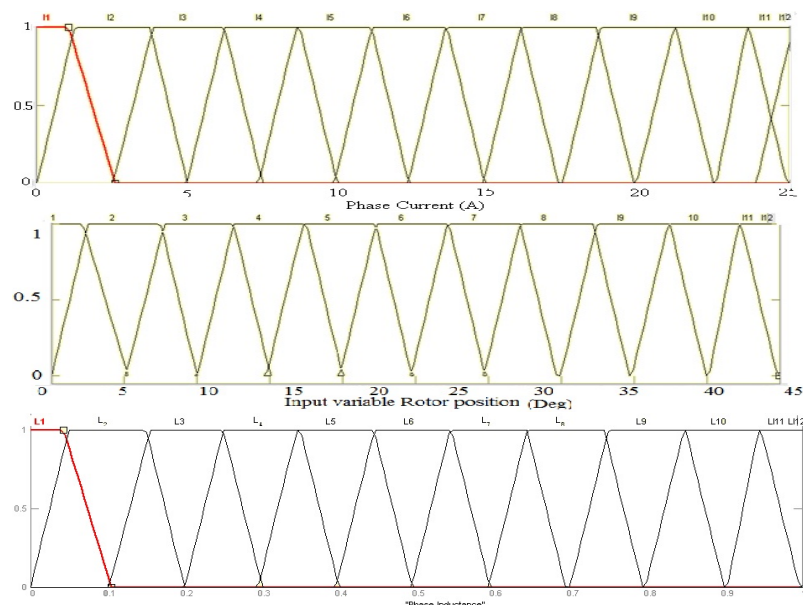


Figure 11: Trapezoidal MF for input and output variables (a) Phase Current (b) Rotor Position (c) Inductance

The comparison between the actual inductance values and the values predicted from triangular MF based FIS is shown in Figure 12. The various errors are shown in Figure 13 and presented in Table 4. With the careful examination of errors , it is obvious that the FIS model using trapezoidal membership function is not in agreement with the actual data and hence this MF also does not fit to estimate the $L(I, \theta)$ for SRG.

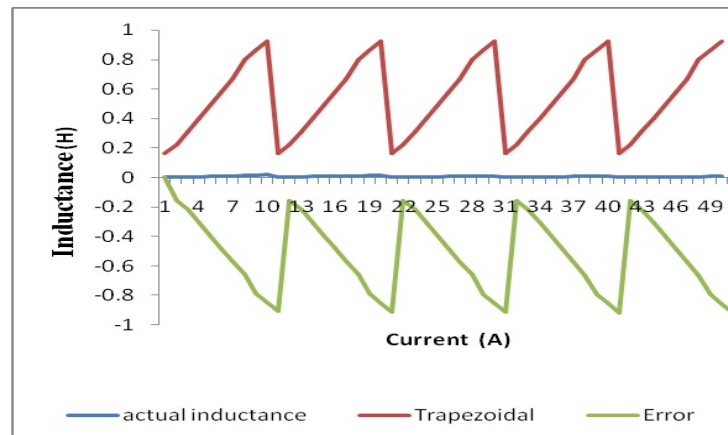
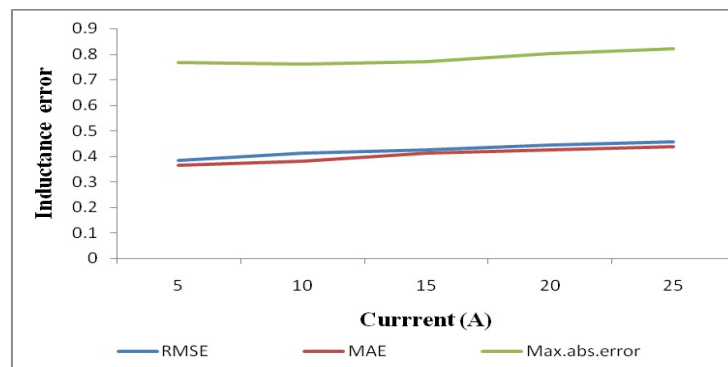
Figure 12: Comparison of $L(I, \theta)$ for original and Trapezoidal FIS

Figure 13: Errors at various operating currents

Table 4: Various errors in $L(I, \theta)$ using PSigmoid MF model

Inductance Errors (Error in Henry)	5 A	10 A	15 A	20 A	25 A
RMSE	0.495	0.501	0.514	0.521	0.524
SSE	16.183	16.327	16.341	16.433	16.465
MAE	0.459	0.463	0.465	0.473	0.470
MAVE	0.895	0.901	0.907	0.912	0.925

E. Evaluation of Inductance parameter using Triangular membership function

The triangular membership functions for are shown in Figure 14(a) , (b) and (c) for the input and output variables respectively. The generated rules in the fuzzy rule base for SR machine after training the system with the static motor data is shown in Table 5. the rule base contains 144 fuzzy IF-THEN rules.

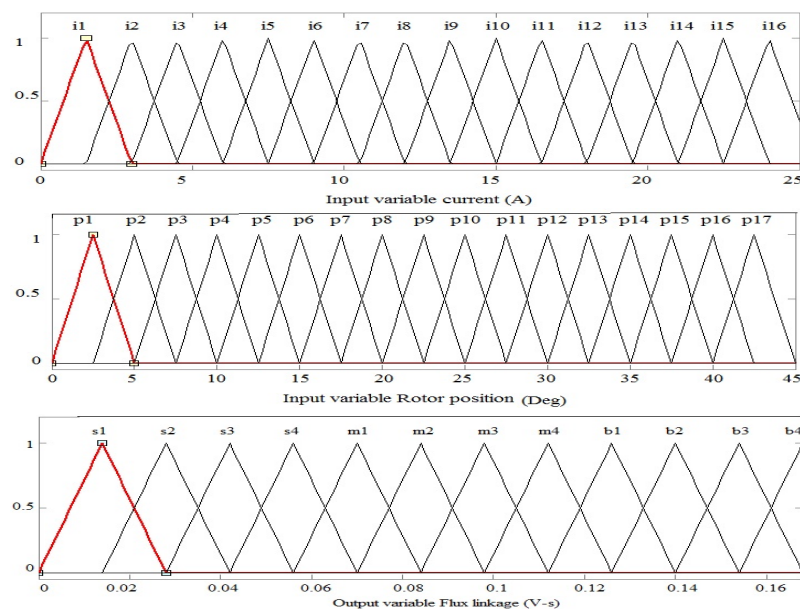


Figure 14: Trapezoidal MF for input and output variables (a) Phase Current (b) Rotor Position (c) Inductance

The relationship between the actual inductance values and the values predicted from triangular MF based FIS is shown in Figure 15. From this figure, it is observed that there exists fair concurrence between the estimated and actual inductance values. The errors are shown in Figure 16 and presented in Table 6. With the careful examination of errors, it is obvious that the FIS using triangular membership function is in fair agreement with the actual results and proves to be best suitable for developing SRG model with lesser errors for the entire set of data range.

Table 5: Fuzzy rule base for inductance model

	U1	U2	U3	U4	U5	IM1	IM2	A5	A4	A3	A2	A1
S1	S1	S2	S2	S3	S4	B1	B1	B2	B2	B3	B4	B4
S2	S1	S2	S2	S3	S4	B1	B1	B2	B2	B3	B3	B3
S3	S1	S2	S2	S3	S4	B1	B1	B1	B2	B2	B3	B3
S4	S1	S2	S2	S3	S4	B1	B1	B1	B2	B2	B3	B3
S5	S1	S2	S2	S3	S4	B1	B1	B1	B2	B2	B2	B3
M1	S1	S2	S2	S3	S3	B1	B1	B1	B1	B2	B2	B2
M2	S1	S2	S2	S3	S3	B1	B1	B1	B1	B2	B2	B2
B1	S1	S2	S2	S3	S3	S4	S4	B1	B1	B1	B2	B2
B2	S1	S2	S2	S3	S3	S4	S4	B1	B1	B1	B2	B2
B3	S1	S1	S2	S3	S3	S3	S3	S4	B1	B1	B1	B1
B4	S1	S1	S1	S3	S3	S3	S3	S4	B1	B1	B1	B1
B5	S1	S1	S1	S2	S2	S3	S3	S3	S4	S4	S4	S4

Table 6: Various errors in $L(I, \theta)$

Current (A)	Inductance error (H) For θ varying from 0 to 45 deg at each phase current		
	L_RMSE	L_MAE	L_MAVE
5	0.0044813	0.0038234	0.01055
10	0.0031187	0.003549	0.00743
15	0.001241	0.003596	0.006867
20	0.001229	0.003511	0.0061
25	0.00188	0.002132	0.00417

(S:Small, M:Medium, B:Big, i:Current, θ :Rotor position)

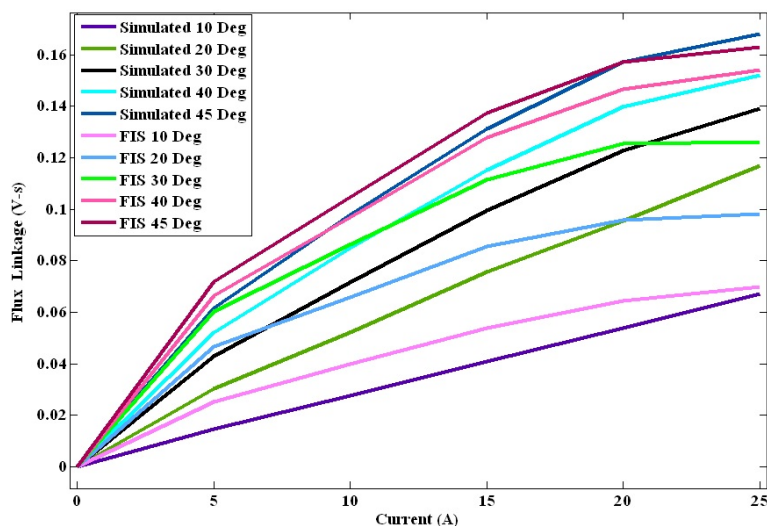


Figure 15: Simulated Vs FIS inductance profiles

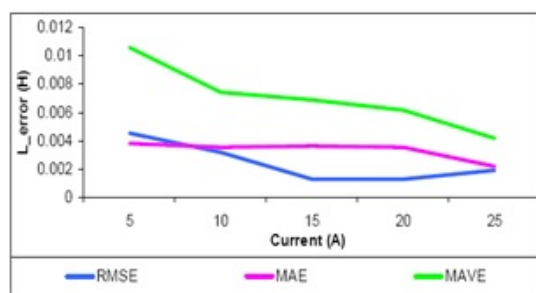


Figure 16: FIS errors at various operating currents

4 COMPARISON OF SRG INDUCTANCE MODELS USING VARIOUS MEMBERSHIP FUNCTIONS

In this section, an overall comparison of the $L(I, \theta)$ system developed from various FIS membership functions is presented. Figure17 shows the graphical representation of different types of errors occurred from various membership functions. The nonlinear mapping

surface of $L(I, \theta)$ for Triangular MF based FIS is shown in Figure18.

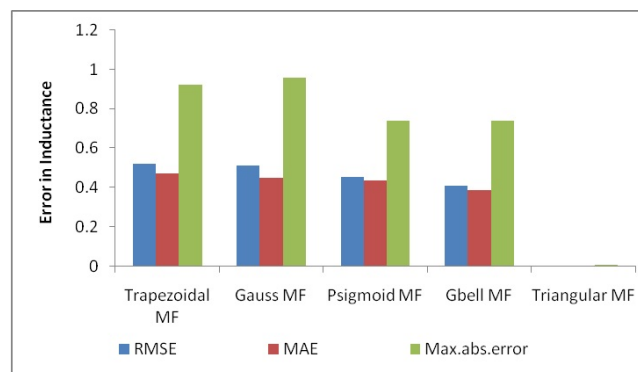


Figure 17: Errors at various operating currents

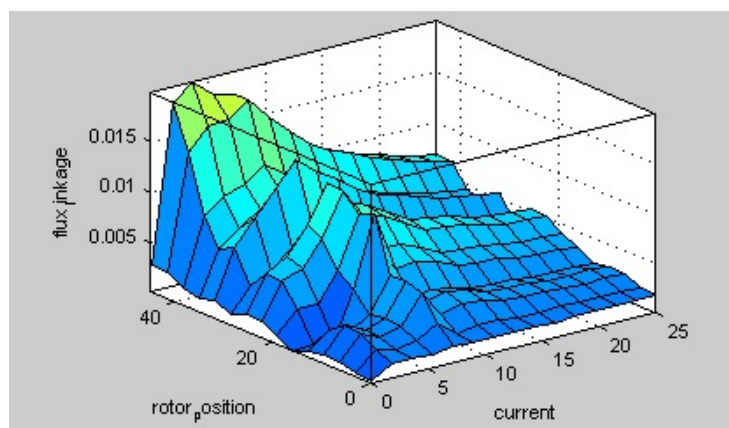


Figure 18: Nonlinear mapping surface of $L(I, \theta)$

Apart from graphical representation, The quantity of errors from various membership functions are tabulated in Table 7. From the comparison charts and error table, it is observed that the errors in Trapezoidal and gaussian MF are very high. Compared to this, the errors in Psigmoid and Gbell MF are lesser. But still these errors are not within tolerant accuracy limits. From the overall observation, it is inferred that the triangular MF based SRG has the

least errors. Compared with all the other models, this $L(I, \theta)$ system of SRG is tested to be in fair agreement with the training data used for modeling. The error values are well within the tolerance limits.

Table 7: Various errors in $L(I, \theta)$

Types of Errors	For θ varying from 0 to 45 deg at each phase current 1 to 25A				
	Trapezoidal MF	Gauss MF	<u>Psigmoid</u> MF	<u>Gbell</u> MF	Triangular MF
RMSE	0.524	0.512	0.456	0.409	0.00478
MAE	0.470	0.448	0.438	0.388	0.003322
MAVE	0.925	0.960	0.740	0.740	0.01055

5 CONCLUSION

In this paper, an inductance profile for a 3 phase ,6/4 pole switched reluctance machine is estimated. The main objective of this work to determine the suitable membership function for SRG has been met. The FIS based SRM inductance profiles using various membership functions such as Triangular, Trapezoidal, Gbell, Gaussian and Psigmoid are estimated. All the developed inductance profiles are tested with the actual inductance values obtained from SR-DaS and the comparative analysis is performed. It is noted that the profile estimated from triangular membership function is in fair concurrence in accordance to the actual set of magnetization data. The developed FIS based SRG inductance profile using triangular membership function has a very simple structure, fast computational speed and characteristic of robustness and presents a good performance when applied to modeling, prediction and real time control.

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