



Estimation of electromagnetic profile of switched reluctance generator for wind energy conversion system

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Abstract

Generation of electrical energy from the abundantly available wind power is gaining increasing importance throughout the world in the field of renewable energy. The major machineries used in the wind energy conversion system (WECS) are generator and turbine units. The efficiency of WECS greatly depends on the performance of the generator used. In recent years, Switched Reluctance Generator (SRG) is replacing conventional induction generators and permanent magnet synchronous generators in the field of wind energy generation system. The performance accuracy of switched reluctance generator significantly relies on the precision of its machine modelling. The three modelling parameters of SRG are its phase flux linkage, phase current and rotor position. This paper presents the fuzzy logic based flux linkage estimation technique for SRG. The main objective of this work is to determine the suitable membership function for SRG. The various types of membership functions available in fuzzy logic such as Trapezoidal, Gbell, Gaussian, Psigmoid and Triangular functions are used to

develop the flux linkage profile. The flux linkage profiles estimated from all these membership functions are compared. The results of these comparisons are analyzed and presented in detail. From the analysis of results, it has been proved that the kind of non-linearity exhibited by SRG is well handled by triangular membership function. The developed electromagnetic profile is persuaded to act as a potential candidate in real time wind energy conversion system.

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

1 Introduction

The operating region of SRG is highly saturated and hence the machines magnetic characteristics are extremely non-linear [1]. Due to this, the flux linkage and torque parameters of SRG are nonlinear functions of current (I) and rotor position(θ). For real time control of SRG, accurate estimation of its flux linkage characteristics $\Psi(I, \theta)$, is the prime requisite [2]. Most of the published literatures have developed linear mathematical model for SRG that is not suitable for practical applications. Some literatures have proposed nonlinear models for the machine. Analytical methods are discussed in [3] and [4] in which the analytical expressions are derived for $L(I, \theta)$. In [5], magnetic theory based estimation is carried out. Both these methods are time consuming. Finite element method which provides precise results is employed in [6], but it requires complicated mathematical calculations and computational effort. Artificial neural network algorithms are used in [7] and [8] that need numerous data for training. Adaptive neuro fuzzy inference system and statistical regression are implemented in [9-11]. In this paper, flux linkage for SRG is estimated using fuzzy logic from the fuzzy logic toolbox in MATLAB. Fuzzy Inference System (FIS) for estimating SRG flux linkage has been developed using various membership functions. The accuracy of all these methods is compared. This paper has been organized as follows. The magnetization characteristics of SRG is presented in section 2. Section 3 presents the flux linkage estimation using various membership functions. The com-

parison between the results of individual membership functions and actual magnetization data is discussed in each sub section. Comparison of observations is presented in section 4 and the conclusive remarks are discussed in section 5.

2 Magnetization Characteristics of SRM

Fig. 1 shows the highly non-linear flux linkage curves of a 6/4 pole SRG from [12]. It shows the relation between the flux linkage with the current and rotor position. The curve is linear up to saturation after which the correlation between Ψ and i is highly non-linear as θ moves from unaligned (0 deg) to aligned position (45 deg). The parameters current, rotor position and flux linkage are extracted from these curves and utilized in estimating flux linkage based on various membership functions.

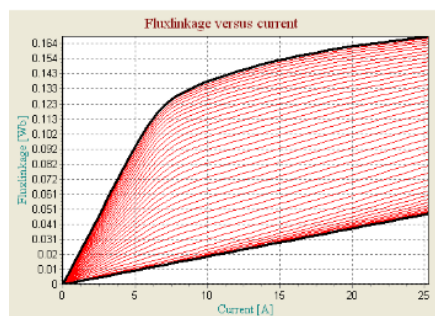


Fig. 1. Flux linkage curves of SRG

3 Fuzzy logic based Flux linkage estimation of SRG using various membership functions

The fuzzy inference system (Mamadani) based flux linkage estimation of SRG is carried out using fuzzy logic toolbox in MATLAB. The two inputs to FIS are current and rotor position. The output of FIS is $\Psi(I, \theta)$. The magnetization data for SRG are taken from [12] for one electrical cycle with the ranges of $0 \leq I \leq 25A$, $0 \leq \theta \leq 45deg$ and $0.0014 \leq L \leq 0.02H$.

3.1 Flux linkage estimation of SRG using GBELL membership function

The input (current & rotor position) and output membership (flux linkage) functions shown in Fig .2(a) and 2(b) and 2(c) respectively.

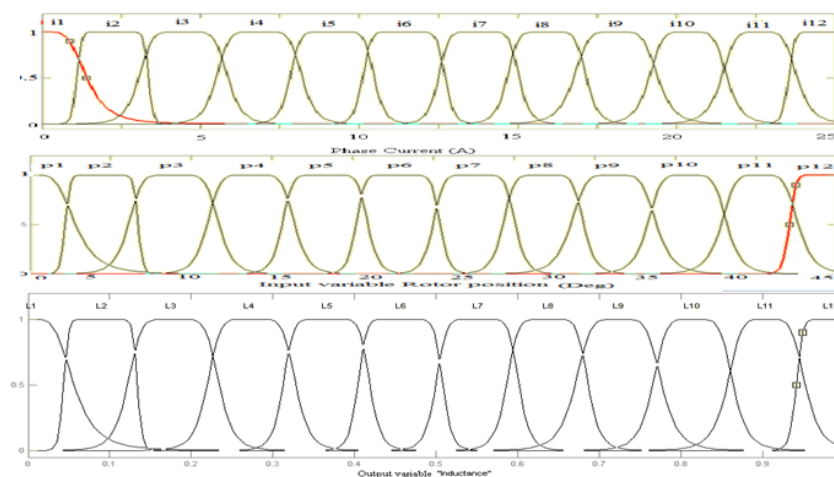


Fig 2. GBELL MF for input and output variables (a) Phase Current (b) Rotor Position (c) Flux linkage

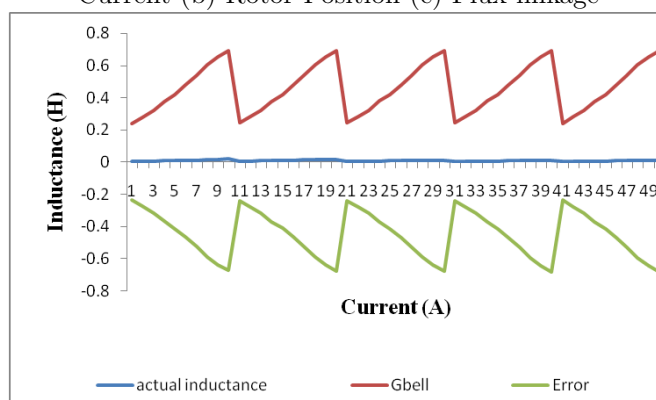


Fig.3 Comparison of actual and estimated $\Psi(I, \theta)$

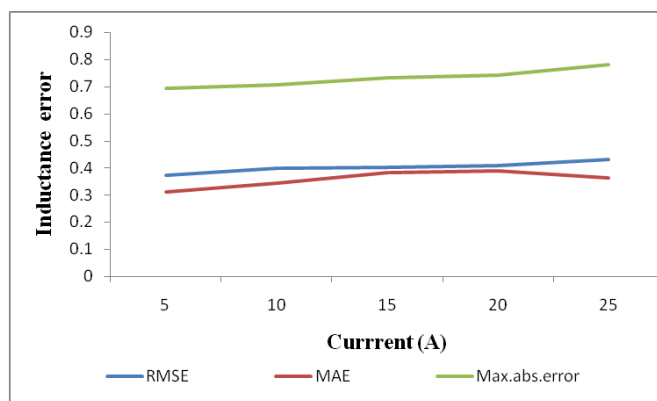


Fig.4 Errors at various operating currents
Table 1. Various errors in (I,) using GBELL MF

Flux linkage Errors (Error in V/s)	5 A	10 A	15 A	20 A	25A
RMSE	0.491	0.373	0.483	0.399	0.411
SSE	9.4	10	10	10	10
MAE	0.297	0.313	0.401	0.4	0.3436
MAVE	0.7	0.7	0.721	0.738	0.78

The comparison between the actual flux linkage values and the values predicted from GBell MF based FIS is shown in Fig. 3. The results are analysed based the statistical error measures such as maximum absolute error, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). These errors are shown in Fig.4 and presented in Table.1. With the careful examination of errors, it is observed that the Gbell MF based FIS is not in concurrence with the actual data and hence is not suitable for estimating the flux linkage parameters for SRG.

3.2 Flux linkage estimation of SRG using Gauss membership function.

The membership functions for the SRM input and output variables such as current , rotor position and phase flux linkage are as shown in Fig .5(a) and 5(b) and 5(c) respectively.

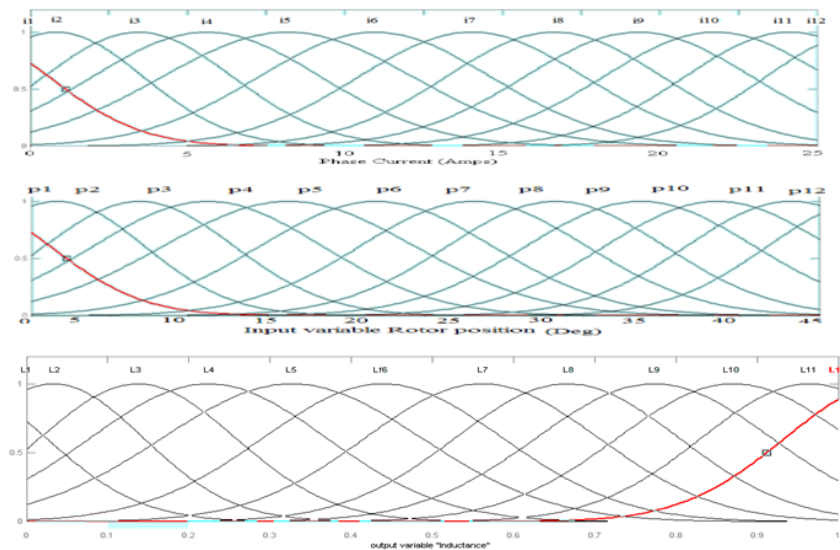


Fig.5. Gauss MF for input and output variables (a) Phase Current (b) Rotor Position (c) Flux linkage

The comparison between the actual flux linkage values and the values predicted from Gauss MF based FIS is shown in Fig. 6. The various errors are shown in Fig.7 and presented in Table.2. With the careful examination of errors, it is obvious that the FIS using Gauss membership function is not in concurrence with the actual data and hence is not suitable for estimating the flux linkage parameters for SRG.

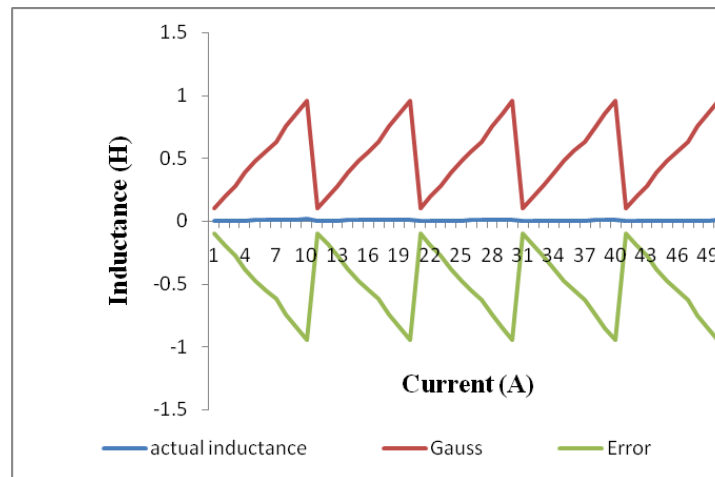


Fig.6 Comparison of actual and estimated (I,)

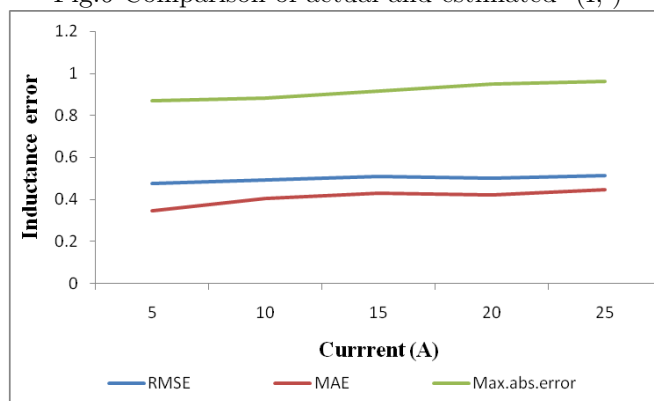


Fig.7 Errors at various operating currents

Table 2. Various errors in $\Psi(I, \theta)$ using Gauss MF

Flux linkage Errors (Error in V/s)	5 A	10 A	15 A	20 A	25A
RMSE	0.5	0.5	0.5	0.5	0.5
SSE	14.6	15	15	15.5	16
MAE	0.3	0.4	0.4	0.4	0.45
MAVE	0.9	0.9	0.9	0.9	1

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

3.3 Flux linkage estimation of SRG using Psigmoid membership function

The input and output membership functions for SRG variables such as current, rotor position and flux linkage are as shown in Fig. 8(a) and 8(b) and 8(c) respectively.

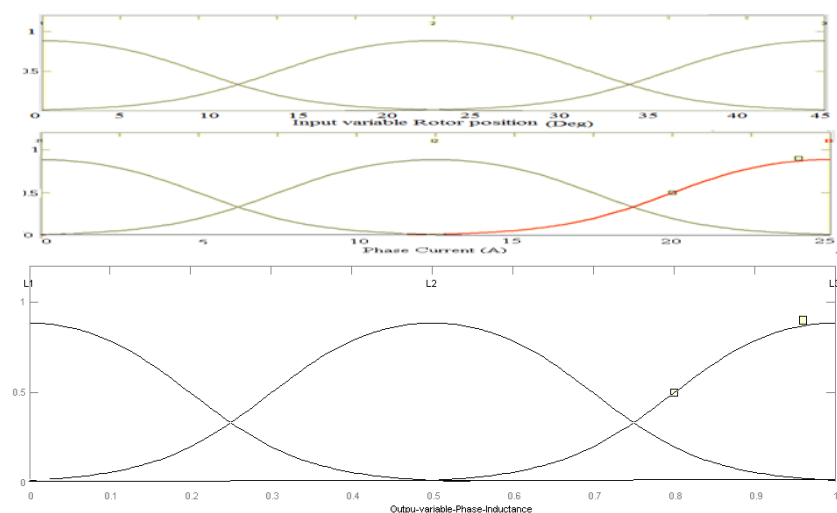


Fig.8. PSigmoid MF for input and output variables (a) Phase Current (b) Rotor Position (c) Flux linkage

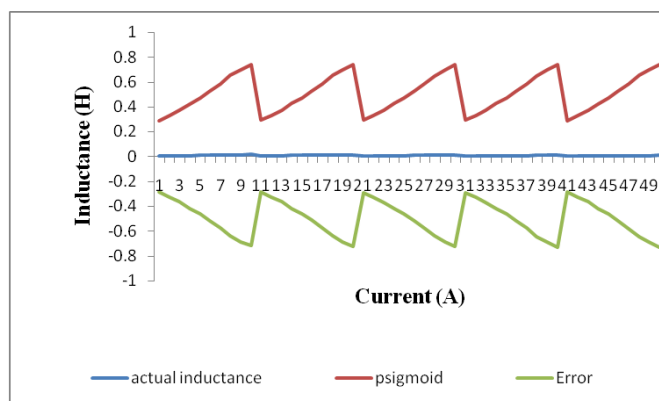
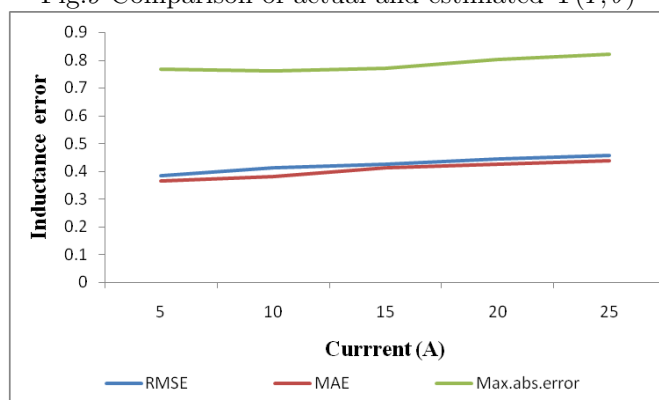
Fig.9 Comparison of actual and estimated $\Psi(I, \theta)$ 

Fig.10 Errors at various operating currents

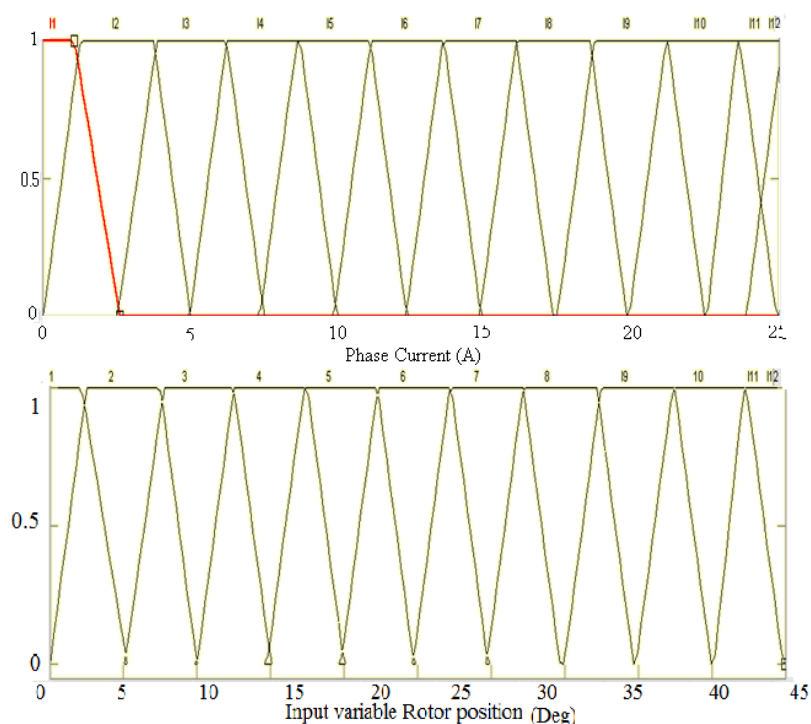
The comparison between the actual flux linkage values and the values predicted from Psgmoid MF based FIS is shown in Fig. 9. The various errors are shown in Fig.10 and presented in Table.3. With the careful examination of errors, it is obvious that the FIS using Psgmoid membership function is not in concurrence with the actual data and hence is not suitable for estimating flux linkage parameters for SRG.

Table 3. Various errors in $\Psi(I, \theta)$ using PSigmoid MF

Flux linkage Errors (Error in V/s)	5 A	10 A	15 A	20 A	25A
RMSE	0.401	0.399	0.412	0.46	0.43
SSE	11	12	12	12	12.5
MAE	0.371	0.40	0.398	0.403	0.411
MAVE	0.8	0.8	0.8	0.8	0.8

3.4 Flux linkage estimation of SRG using Trapezoidal membership function

The input and output membership functions for current, rotor position and flux linkage are as shown in Fig .11(a) and 11(b) and 11(c) respectively.



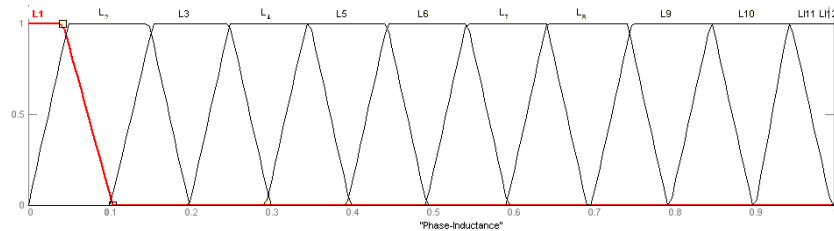


Fig.11. Trapezoidal MF for input and output variables (a) Phase Current (b) Rotor Position (c) Flux linkage

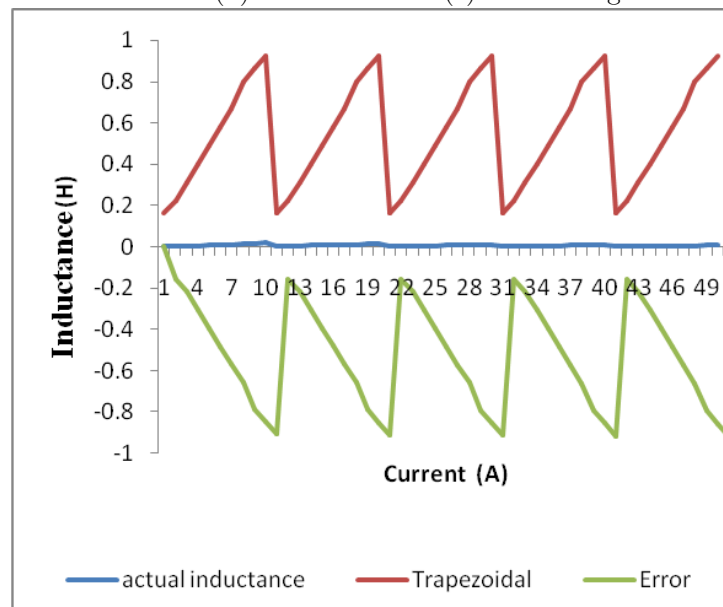


Fig.12 Comparison of actual and estimated $\Psi(I, \theta)$

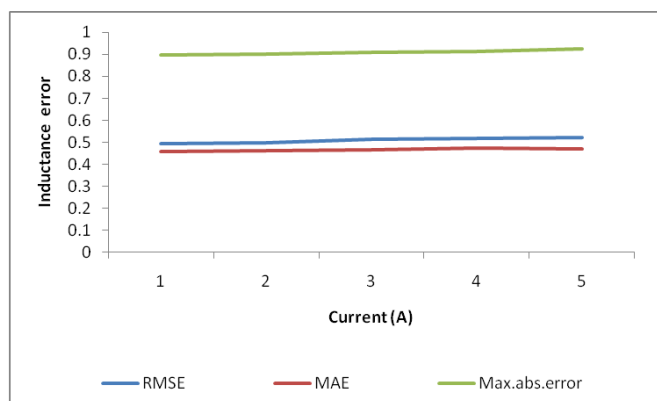


Fig.13 Errors at various operating currents

The comparison between the actual flux linkage values and the values predicted from trapezoidal MF based FIS is shown in Fig. 12. The various errors are shown in Fig.13 and presented in Table.4. With the careful examination of errors, it is obvious that the FIS using trapezoidal membership function is not in concurrence with the actual data and hence is not suitable for estimating the flux linkage parameters for SRG.

Table 4. Various errors in $\Psi(I, \theta)$ using Trapezoidal MF

Flux linkage Errors (Error in V/s)	5 A	10 A	15 A	20 A	25A
RMSE	0.51	0.5	0.5	0.5	0.5
SSE	16.0	16.0	16.0	16.5	16.49
MAE	0.44	0.46	0.46	0.47	0.49
MAVE	0.9	0.9	0.9	0.9	0.9

3.5 Flux linkage estimation of SRG using Triangular membership function

The input and output membership functions for i , and θ are shown in Fig .14(a) , (b) and (c) respectively. The generated rules in the fuzzy rule base for SRG after training the system with the static motor data is shown in Table.5.

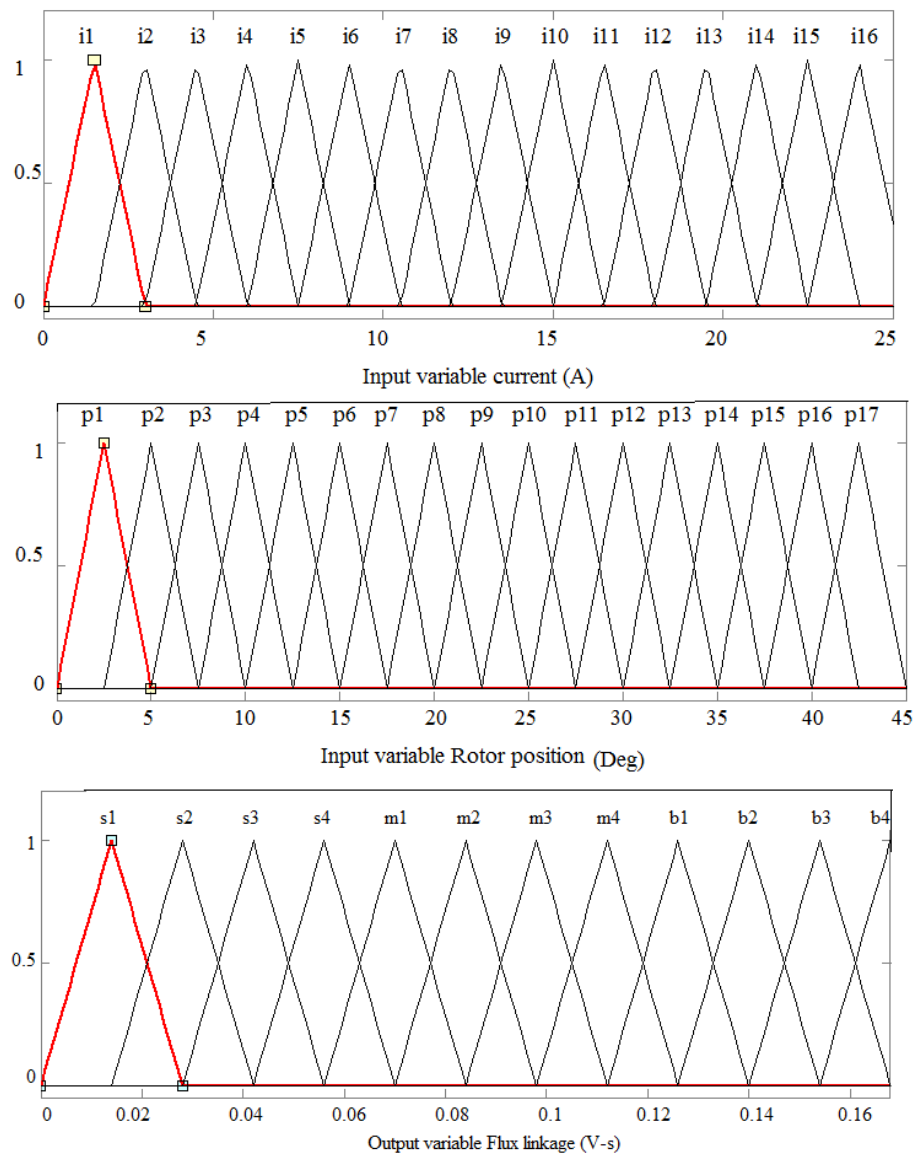


Fig.14. Triangular MF for input variables

The comparison between the actual flux linkage values and the values predicted from triangular MF based FIS is shown in Fig. 15.

From this figure, it is observed that there exists fair concurrence between the estimated and actual flux linkage values. The errors are shown in Fig.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 the suitable for estimating flux linkage profile for SRG with lesser errors for the entire set of data range.

Table. 5 Fuzzy rule base for flux linkage

I/ θ	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	S3	S3	S3	S3	S4	S4	S4	S4

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

Table. 6 Various errors in $\Psi(I, \theta)$

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

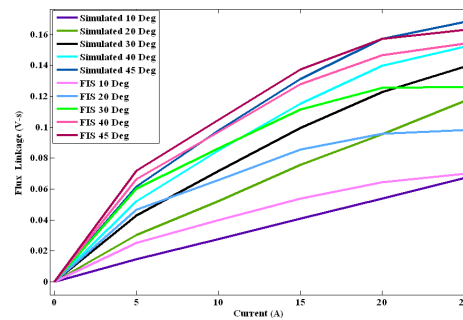


Fig. 15 Simulated Vs FIS flux linkage profiles

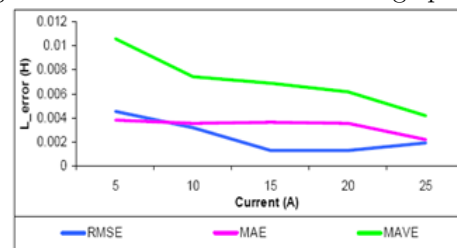


Fig. 16 Errors at various operating currents

4 Comparison Of SRG flux linkage estimated from various membership functions

In this section, an overall comparison of the $\Psi(I, \theta)$ estimated from various FIS membership functions is presented. Fig.17 shows the graphical representation of different types of errors occurred from various membership functions. The nonlinear mapping surface of $\Psi(I, \theta)$ is shown in Fig.18.

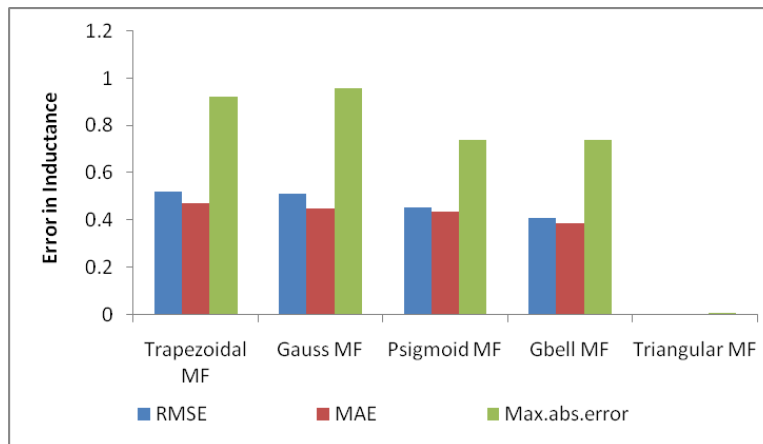
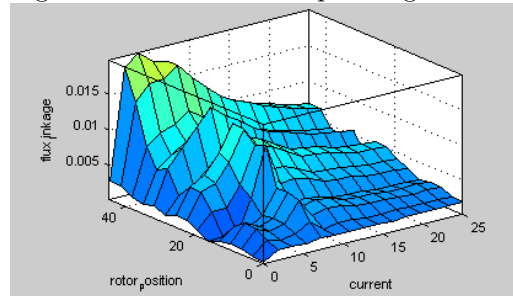


Fig.17 Errors at various operating currents

Fig.18. Nonlinear mapping surface of $\Psi(I, \theta)$

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 FIS for SRG has the least errors. The estimated $\Psi(I, \theta)$ is tested to be in fair agreement with the training data used. The error values are well within the tolerance limits.

Table 7. Comparison of $\Psi(I, \theta)$ errors from various membership Function

Types of Errors	For θ varying from 0 to 45 deg at each phase current 1 to 25A				
	Trapezoidal MF	Gauss MF	Psigmoid MF	Gbell MF	Triangular MF
RMSE	0.5	0.5	0.5	0.4	0.005
MAE	0.5	0.45	0.4	0.4	0.003
MAVE	1.0	1.0	0.7	0.7	0.01

5 Conclusion

In this paper, an electromagnetic profile for a three phase, 6/4 pole switched reluctance machine is developed. The suitable fuzzy membership function for estimating flux linkage of SRG is determined. From the performed analysis, it is observed that the profile estimated from triangular membership function is in good concurrence in accordance to the actual magnetization data set. The developed FIS for SRG using triangular membership function has a very simple structure, fast computational speed and characteristic of robustness and presents a good performance when applied to modelling, prediction and control.

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