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ADAPTIVE NEURO FUZZY INFERENCE SYSTEM BASED SENSORLESS ROTOR POSITION ESTIMATION OF SRM

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ABSTRACT

This paper presents sensorless rotor position estimation of Switched Reluctance Motor (SRM) where the position is to be determined by Adaptive Neuro Fuzzy Inference System (ANFIS). The rotor position sensing is very essential for the SRM for its efficient operation. Previously rotor position sensors are used to estimate the position of rotor for SRM. Due to its drawback the sensors have to be replaced by sensorless techniques. So in this paper ANFIS is used to map the nonlinear behavior of the SRM and rotor position is estimated. Mapping is done by the inputs of flux linkage and current to the rotor position as its output. The error between the target and the actual rotor position output is to be calculated. Also the time period of the process, Mean Absolute Error (MAE), Mean Square Error (MSE) and MSEREG are calculated and the comparison is to be made among them. Then comparison of different membership functions, number of epochs and number of membership functions are being carried out for ANFIS. The performance of the ANFIS is analyzed using the error and efficiency. The proposed application will proves the superiority of ANFIS for the rotor position estimation.

Keywords: ANFIS, nonlinear, rotor position, sensorless, SRM.

1. INTRODUCTION

SRM is a special electrical machine which is worked based on variable reluctance principle. Rotor of the machine moves from high reluctance position to low reluctance position. The rotor has no winding and no permanent magnet. It is made up of laminated steel. The stator has only winding. The motor is more rugged, low cost and low losses. But it has certain limitations such as torque ripple, nonlinear characteristics, rotor position requirement and acoustic noise. This paper addresses the issue of rotor position estimation.

T.J.E. Miller and M. Mc Gilp [1] proposed a nonlinear theory to estimate the rotor position of SRM. In this paper the authors modeled the SRM using cubic spline method. They also pointed out the demerits of piecewise linear methods. But the proposed method has complex mathematical equations. D.A. Torrey and J.H. Lang [2] described an analytical method to analyze the nonlinear magnetic characteristics of SRM. But this method also requires complex mathematical equations. H.J. Guo et al. [3] proposed a novel sensorless method for SRM based on nonlinear characteristics. This method has complexity in nature. Duck-Shick et al. [4] described a sensorless scheme based on search coil method. In this method it requires strong search coils. Usage of this method has more vibrations. Wendyam. F. Traore and Roy A. Mc Cann [5] proposed a flux estimation scheme based on two dimensional least square methods. But this method is only an approximate solution and complex one. Liviu E. Somesan et al. [6] proposed two methods to determine magnetic flux linkage and torque values. In the first method aligned and unaligned positions are considered for analysis. This method is simple but not accurate. In the second method aligned, unaligned and average positions are considered for analysis. This method is more accurate but complicated than the first model. A.Peniak et al [7] proposed optimization of SRM parameters. Nonlinear mapping of torque-current-flux linkage and inductance-current-flux linkage are also addressed. Moreover Power, Losses and Torque values are optimized. Nonlinear mapping is not clearly addressed. P. Srinivas and P. V. N. Prasad [8] proposed direct torque control based SRM. In this paper they compared the simplified torque equation method with FEA method. But FEA has more complications for implementation. The reference papers [9-12] proposed artificial neural network based rotor position estimation scheme for SRM. These methods have less prediction accuracy. R.A. Gupta et al. [13] proposed fuzzy logic based estimator for rotor position estimator. They have compared the results with experimental setup. But they are using more amounts of rules and it occupies more memory and processing time also more. S. Kanagavalli and A. Rajendran [14] proposed computational intelligence techniques for rotor position estimation. But they are using simulink based implementation and not described clearly. S. Paramasivam et al. [15] proposed a real time estimation of rotor position for SRM. This paper compares ANN and ANFIS based rotor position estimation. T. Lachman et al. [16] compared the fuzzy logic, ANN and ANFIS based SRM. But this paper [16] uses more rule and low number of data for analysis. In the present work less number of rules and more amounts of data are used for the performance analysis. The data used in this present work is referred in [15]. The ANFIS is created and rotor position estimation using MATLAB coding [17]. However due to the above said problems this paper addresses the rotor position estimation by ANFIS. This method is more accurate and fast than other methods. This paper is organized as follows, section II introduces SRM. Section III explained

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about the proposed method. In Section IV ANFIS is described. In Section V results and discussion is given. Finally conclusion is made in section VI.

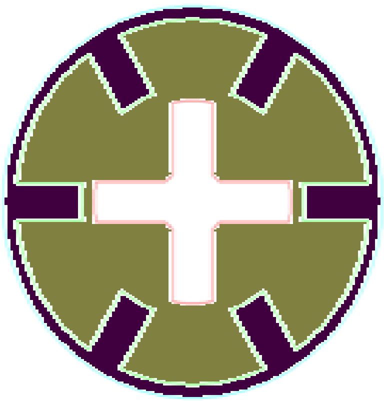

Figure-1. SRM model for 6/4.

2. SWITCHED RELUCTANCE MOTOR

SRM working is based on switched reluctance principle. The reluctance value in SRM is varied from unaligned position to aligned position. In aligned position the air gap as well as reluctance values are low. Since the reluctance is directly proportional to length of air gap. In unaligned position the air gap as well as reluctance is more. Reluctance is nothing but opposition to creation of flux. Hence the rotor poles are attracted by stator poles thereby movement of the poles taking place from unaligned position to aligned position. This is done when excitation of rotor poles occurred. For proper working of SRM rotor position details are essential. Rotor position information is sensed by sensors. But the usage of sensors has certain limitations such as occupies more space, electrical and mechanical loose contacts, deposit of dust particles and costly. So the sensors are replaced by sensorless methods such as fuzzy logic, artificial neural networks and ANFIS. Moreover SRM has salient poles in the stator and rotor. This introduces the nonlinear nature of SRM. The nonlinear characteristics can be easily analyzed by soft computing techniques. The inputs of the soft computing techniques are current and flux linkage, which are derived from the terminals of SRM stator. Using these values rotor position has been estimated by soft computing techniques. The rotor position information is fed to a processor. Based on the rotor position information firing pulses are produced for triggering of power electronic devices of a converter. The converter output excites the phase winding of the SRM. The same process repeated for other phases. The voltage equation for SRM is given in eq. (1).

$$V = R \times I + \frac{d\varphi}{dt} \qquad (1)$$

Where, I - Motor stator current,

R - Stator resistance

V - Voltage input to the motor

Φ - Flux

The SRM taken for analysis consists of 6 stator poles and 4 rotor poles. The 6/4 combination of machine structure is shown in Figure-1. SRM specifications are given in Table-1.

Table-1. SRM Specifications.

S. No.	SRM	
	Parameters	**Values**
1	Number of stator poles	6
2	Number of rotor poles	4
3	Speed(RPM)	1250
4	Rotor pole arc	32°
5	Stator pole arc	29°

Flux linkage of any phase in SRM is computed by using Faraday's law from equation (2)

$$\Psi = \int (V - I \times R) \qquad (2)$$

Where, Ψ- flux linkage

3. PROPOSED METHOD

In this paper ANFIS based hybrid algorithm is used to estimate the rotor position. ANFIS is a combination of ANN and Fuzzy logic system. ANFIS uses least mean square and back propagation algorithm. ANFIS based SRM is created and various performance parameters have been calculated. The performance parameters are error, MSE, MAE, MSEREG and Elapsed time. These parameters are calculated for various membership functions like Gbell mf, Triangular mf, Trapezoidal mf and Gauss mf. For the entire process data are stored in Micro soft Excel sheet. There are totally 480 different data have been taken for the analysis. This data consists of current, flux linkage and rotor position details. For the analysis 240 data have been taken for training and 240 data for testing. The testing data are different from training data. Figure-2 indicates the proposed block diagram. In the block diagram the flux linkage and current values are the input to the soft computing and rotor position as the output. The input values are retrieved from the stator terminals.

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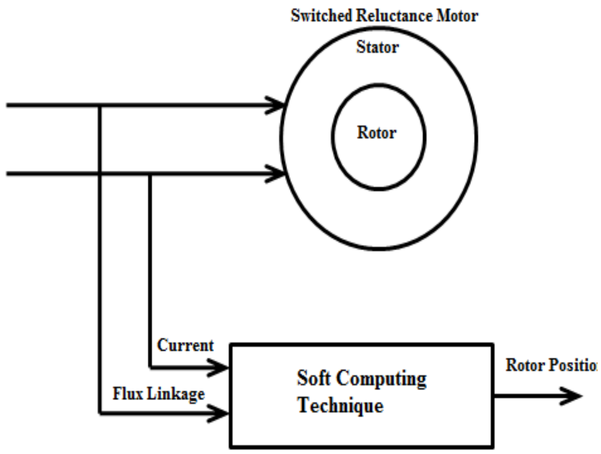

Figure-2. Block Diagram of proposed method.

4. ANFIS

ANFIS was proposed by Roger Jang [18] from Tsing Hua University, Taiwan in the year 1993. ANFIS is a combination of ANN and Fuzzy logic system. ANFIS consists of five layers. The first layer consists of membership functions as computation layers. The membership can be any type of membership function. The second layer is used to find minimum or product of inputs from rule base. The third layer is used to normalize the weights for the network. The fourth layers output is the linear function of third layers output and generates the rule output. In fifth layer each rule output is summed up. ANFIS has smoothness due to fuzzy interpolation and adaptability due to neural network back propagation. ANFIS approach is based on many inputs and a single output. In this paper two inputs, current and flux linkage and a single output rotor position is taken for analysis. The single output is manipulated by the degree of membership function. ANFIS uses two algorithms. They are least mean square algorithm and back propagation algorithm. Back propagation is used as reverse pass and least mean square uses forward pass.

A. Mean least square algorithm

This algorithm is one type of supervised training algorithm. It is an adaptive algorithm which uses gradient based method of steepest descent. It is a simple method. It doesn't require any complex functions. It is very efficient and effective method. The network actual output is compared with the target output. This gives the error of the system. This algorithm adjusts the weights and biases of the network until the specified epochs is reached or minimum error is reached. For this process ANFIS uses training and testing procedures. In this paper for training and testing different data are used. If more data are used then accurate results can be obtained. The Eq. 3 and 4 indicates the weight and bias updation [10].

$$W(k+1) = W(k) + 2 * \alpha * e(k) * pT(k) \quad (3)$$

$$b(k+1) = b(k) + 2 * \alpha * e(k) \quad (4)$$

Where W – represents the weight

e – represents the error

b – represents the bias

α – represents the learning rate

pT – represents the input

B. Back propagation algorithm

This algorithm is efficient method for altering the weights. This method is used to learn a set of training data with differentiable activation functions. This network provides good response to the input and output pairs. Then testing of the data can be done and errors are calculated. The error calculated by this method is minimized by generalized delta rule. This method uses chain rule for its efficient operation. The input layer is connected to hidden layer and hidden layer is connected to output layer. Any number of hidden layers can be used. The layers are connected by synaptic weights and bias terms. If the number of hidden layers is large then computation is more complex and convergence speed will be decreased.

5. RESULTS AND DISCUSSIONS

Results are obtained by MATLAB and are discussed in this section. The current and flux linkage values are given as the input and rotor position is estimated as the output of ANFIS. ANFIS has been trained by 240 data and trained by another 240 data. The testing data are different from training data. These magnetic data are stored in Microsoft Excel sheet. The data are read from the Excel sheet for training and another 240 data are read for testing purpose. The rotor position estimated by ANFIS is compared with the target value and different parameters are determined and tabulated. Error curve for triangular mf training data is shown in Figure-4 and membership function curve is shown in Figure-5. The testing curve for triangular mf is shown in Figure-6. In training data error curve the error value never exceed 1.5° error. But in testing data error curve the error value is exceeding 3° for some data. Those values are said to be wrongly predicted values.

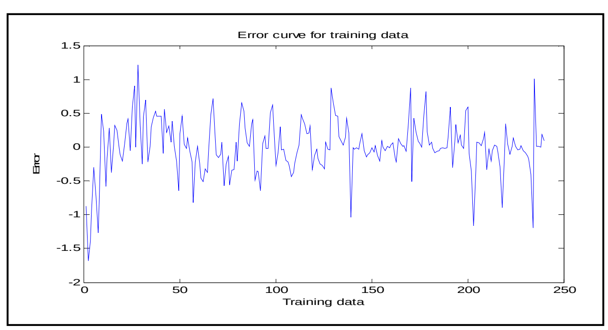

Figure-3. Error curve for training data for triangular mf.

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Figure-4. Error curve for testing data for triangular mf.

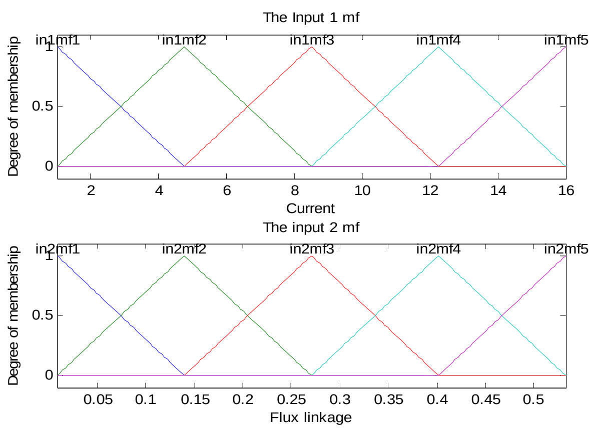

Figure-5. Triangular Membership function curve.

Error curve for testing data is given in Figure-6 and mf curve for Gbell mf is shown in Figure-7. Figure-8 shows the error curve for training data. In the testing and training curves 0 to 240 indicates the data. The error in the curve indicates the difference between estimated and target values. In this work the efficiency indicates the number of correctly estimated values of position. The error indicates wrongly estimated rotor position.

A. Based on number of epochs

Table-II shows the comparison based on number of epochs variation. In this comparison the number of membership functions taken is fixed and its value is 7. Here Gbell mf is taken for comparison. The factors such as MSE, MAE, MSEREG and elapsed time are compared for different values of epochs. It is observed that for large number of epochs the time period and error values are large. The number of epochs taken for comparison is 100, 200, 300 and 500.

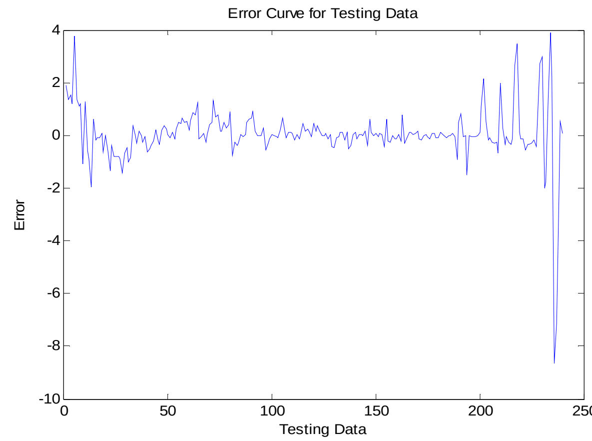

Figure-6. Testing data error curve for Gbell Membership function.

Table-2. Ccomparison for mf 7 and gbell mf based on epochs.

Epochs	Parameters			
	Elapsed Time	***MAE***	***MSE***	***MSEREG***
100	46.7464	0.5396	0.785	0.7065
200	72.1179	0.5396	0.785	0.7065
300	98.5685	0.5522	0.7982	0.7184
500	143.6829	0.73	2.2143	1.9928

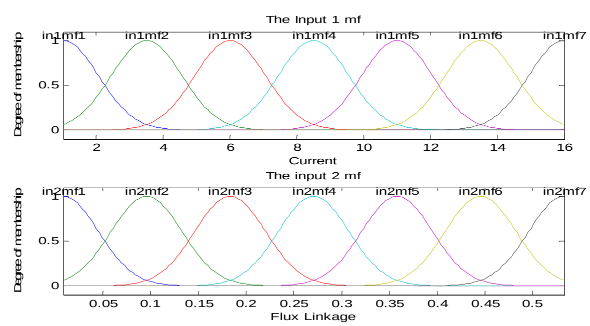

Figure-7. Gbell Membership function curve.

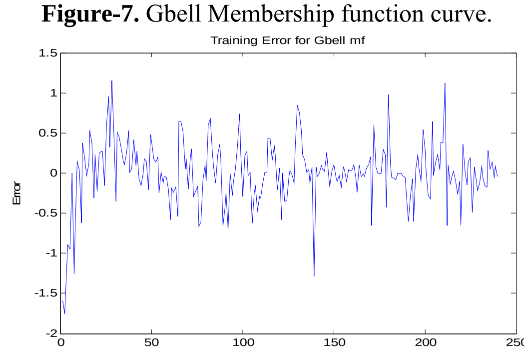

Figure-8. Error curve for training data for Gbell mf.

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B. Based on membership function

The comparison for the membership functions have been carried out using error, MSE, MAE, MSEREG and elapsed time are given in Table-III. For comparison the number of epochs taken is 100 and number of mfs allotted is 5. Hence there are 25 rules have been framed for the analysis. The triangular mf has least MSEREG value of 0.9879. Also it has lowest elapsed time of 28.2312 sec. Again the triangular mf has lowest MSE of 1.0976. The trapezoidal mf has largest MAE value of 0.7012.

Table-3. Comparison for mf is 5 and number of epochs is 100.

MF type	Parameters			
	Elapsed Time	**MAE**	**MSE**	**MSEREG**
Gbell	29.1721	0.5258	1.1476	1.0328
Triangular	28.2312	0.5272	1.0976	0.9879
Trapezoidal	29.3552	0.7012	1.4433	1.2990
Gauss	28.9456	0.5296	1.5998	1.4398

Table-4. Comparison of various number of mfs.

No. of Mfs.	Parameters for Gbell mf and number of Epochs is 500			
	Elapsed Time	***MAE***	***MSE***	***MSEREG***
9	374.0424	0.8857	5.5704	5.0134
7	143.6829	0.73	2.2143	1.9928
5	58.8415	0.4558	0.916	0.8244
3	29.9693	0.7792	2.6794	2.4115

C. Based on number of membership functions

Table-IV shows the comparison of ANFIS performance based on number of epochs. Here the number of epochs taken for comparison is 500. The number of 5 mfs has superior performance compared to number of mfs 9, 7 and 3. Since the ANFIS having number of 5 mfs has minimum values MAE, MSE and MSEREG. Those values are 0.4558, 0.916 and 0.8244. Number of mfs 9 requires more elapsed time. MAE is low for number of mfs is 5.

D. Based on Efficiency

Efficiency for various combinations has been given in Table V. Triangular mf has best performance for number of epochs is 100 and number of 3 mfs is used. Its efficiency is 99.58%. Number of mfs 5 has better efficiency compared to 3, 7 and 9. Its efficiency is 98.75% for Gbell type mf and number of epochs are 500. The efficiency is calculated based on error less than 3. The error is the difference between the target and the estimated rotor position by ANFIS. Using this error value the efficiency has been calculated.

Table-VI shows the efficiency calculation for various values of epochs. This is for Gbell mf and number of mfs is 7. The number of epochs 500 has least efficiency. The efficiency value is same for epochs up to 300 and its value is 97.9%.

Table-VII shows the efficiency calculation for various values of number of mfs. This is for Gbell mf and number of epochs is 500. The number of mfs 5 has highest efficiency. The efficiency value is 98.75%.

Table-5. Efficiency calculation for mfs 3 and 5.

Type of MF	Parameters		
	Number of epochs	**Efficiency for mf=3**	**Efficiency for mf=5**
Gbell	100	94.16	97.5
Triangular	100	99.58	97.9
Gauss	100	96.67	97.9
Trapezoidal	100	94.58	97.5

Table-6. Efficiency for various EPOCHS.

Type of Mf	Parameters		
	Number of Mfs	**Epochs**	**Efficiency**
Gbell	7	100	97.9
Gbell	7	200	97.9
Gbell	7	300	97.9
Gbell	7	500	95.4

Table-7. Efficiency calculation for number of EPOCHS 500.

Type of Mf	Parameters	
	Number of Mfs	**Efficiency**
Gbell	3	95.4
Gbell	5	98.75
Gbell	7	95.4
Gbell	9	94.8

CONCLUSIONS

The SRM rotor position is estimated using ANFIS based hybrid technique. The ANFIS is created and the data have been trained and tested. Error between the estimated and target has been calculated. The performance is analyzed by comparing the 240 training data and 240 testing data. The comparison is done based on number of epochs, type of mf and number of mfs. Various parameters taken for the comparison are elapsed time, MAE, MSE and MSEREG. The error between target and estimated rotor position is calculated. The error value not exceeding 3 is included for comparison. The efficiency value is highest for triangular mf 99.58%. This is for number of mf is 3 and number of epochs is 100. This proves the superior performance of ANFIS.

In future the implementation of Fuzzy based ASIC chip is utilized for predicting the rotor position in real time. Further in special applications like aero the prediction accuracy can be improved. For this application the error degree may be considered as 1.

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REFERENCES

[1] T.J.E. Miller., M. Mc Gilp. Nonlinear theory of the Switched Reluctance motor for rapid computer aided design. IEE proceedings. Vol. 137, pp. 337–347, 1990.

[2] D.A. Torrey. and J.H. Lang. Modelling a nonlinear variable reluctance motor drive. IEE proceedings. Vol. 137, pp. 314–326, 1990.

[3] H.J. Guo., M. Takahashi., T. Watanabe. and O. Ichinokura. A new sensorless drive method of Switched Reluctance motors on motor magnetic characteristics. IEEE Trans. Power Electronics. Vol. 37, pp. 2831–2841, 2001.

[4] Duck-Shick Shin., Hyong-Yeol Yang., Young-Cheal Lim, Peter Freere. and Krishna Gurung. Rotor position sensing method for Switched reluctance Motors using an Indirect Sensor. Journal of Power Electronics. Vol. 5, No. 3, pp. 173–179, July 2005.

[5] Wendyam F. Traore. and Roy A. Mc Cann. Flux estimation in Switched Reluctance motors using a two dimensional least square method approximation. IEEE region 5 Technical Conference, 2007.

[6] Liviu E. Somesan., Emil Padurariu. and Ioan A. Viorel. Two simple analytical models, direct and inverse for Switched Reluctance Motors. Progress in Electromagnetics Research M. Vol. 29, pp. 279–291, 2013.

[7] A. Peniak., J. Makarovic., P. Rafajdus. and P. Dubravka. Optimization of Switched Reluctance Motor for drive system in Automotive Applications. International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering. Vol. 8, No.9, pp. 1515–1522, 2014.

[8] P. Srinivas. and P.V.N. Prasad. Comparative analysis of DTC based Switched Reluctance motor drive using torque estimation and FEA models. International Journal of Electrical, Robotics, Electronics and Communication Engineering. Vol. 8, No. 3, pp. 498-503, 2014.

[9] Erkan Mese. and David A. Torrey. An approach for sensorless position estimation for Switched Reluctance motor using Artificial Neural Networks. IEEE Trans. Power Electronics. Vol. 17, pp. 66–75, January 2002.

[10] T. Lachman., T. R. Mohamad. and C. H. Fong. Sensorless Position estimation of Switched Reluctance motor using Artificial Neural Network. IEEE International Conference on Robotics. 2003.

[11] Estislao Echenique., Juan Dixon., Roberto Cardenas. and Ruben Pena. Sensorless Control for a Switched Reluctance Wind Generator based on current slopes and Neural Networks. IEEE Trans. Ind. Electronics. Vol. 56, pp. 817–825, 2009.

[12] M. Marsaline beno., L. Rajaji., V.M. Varatharaj. and Arnold Nolasco Santos. Rotor position estimation of Switched Reluctance motor using a Novel Neural Network algorithm. IEEE GCC Conference and Exhibition, pp. 77–80, 2011.

[13] R.A. Gupta, S.K. Bishnoi and Rajesh Kumar, “Sensorless Control of Switched Reluctance drive with fuzzy logic based rotor position estimation,” International Journal of Computer applications, vol. 1,No. 22, pp. 72–79, 2010.

[14] S.Kanagavalli and A.Rajendran, “Sensorless rotor position estimation of Switched Reluctance motor drive using computational Intelligence Techniques,” International Journal of Soft Computing, vol. 3, No. 2, pp. 83-87, May 2013.

[15] S.Paramasivam, S. Vijayan, M. Vasudevan, R. Arumugam and Ramu Krishnan, “Real time verification of AI based rotor position estimation techniques for a 6/4 pole Switched Reluctance motor.

IEEE Trans. Magnetics. Vol. 43, No. 7, pp. 3207–3222, July 2007.

[16] T. Lachman., T.R Mohamad. and C.H. Fong. Nonlinear modeling of the Switched Reluctance motor for rapid computer aided design. IEE Proceedings Electrical Power applications. Vol. 151, pp. 53-60, 2004.

[17] S.N.Sivanandam. and S.N. Deepa. Principles of Soft Computing, 2nd ed., Wiley, 2011.

[18] Jyh-Shing Roger Jang. ANFIS : Adaptive-Network-Based Fuzzy Inference System. IEEE Transactions on Systems, Man and Cybernetics. Vol.23, No. 3, pp. 665-685, May1993.