10

Artificial Intelligence Techniques of Estimating of Torque for 8:6 Switched Reluctance Motor

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1. Introduction

Switched reluctance motor (SRM) is one of the best candidates for industrial and household applications. Owing to its superior abilities such as high torque to inertia ratio, easy cooling, high speed capability and ease of repair, SRM has been taken into consideration by researchers. one of the major difficulties is the nonlinear relation between current, rotor position and flux linkage. Due to the mentioned nonlinearity, it is essential to have an accurate model to deal with nonlinear characteristics of SRM. The essence of this research work is to develop the SRM model based on artificial techniques (AI) such as fuzzy logic, adaptive neuro-fuzzy. In the papers (Chancharoensook& Rahman,2002;Geldhof&Van den Bossche& Vyncke&Melkebeek,2008; Mirzaeian-Dehkordi& Moallem, 2006; Gobbi, Ramar;2008; Rajapakse& Gole& Muthumuni& Wilson& Perregaux,2004; Wai-Chuen Gan& Cheung& Li Qiu,2008) SRM models presented based on the look-up tables.

In this short communication, rule based system are considered in order to find a model to deal with nonlinear characteristics of SRM. We call it rule based due to have fixed data point. Fuzzy logic and adaptive neuro-fuzzy are employed to develop a comprehensive model for nonlinear characteristics of 8:6 SRM. Torque profile is simulated based on fuzzy logic, adaptive neuro-fuzzy techniques via MATLAB software. In the line above, error analysis is conducted for those models. Data is tabled and compared with the published data. The result of error analysis reflects the precision of the method and the capability of the approach for the further simulation.

2. Background theory

Switched reluctance motor (SRM) is a type of synchronous machine. Figure 1 shows the classification of the SRM. This initial classification is made by considering the method of movement.

Stator and rotor are two basic parts of SRM. One of the most important features of the SRM comes back to its simple structure. This type of electrical machine has no winding or magnet in rotor part. Both of stator and rotor have salient poles. Thus, it is named double salient machine. Figure 2 shows the typical structure of SRM.

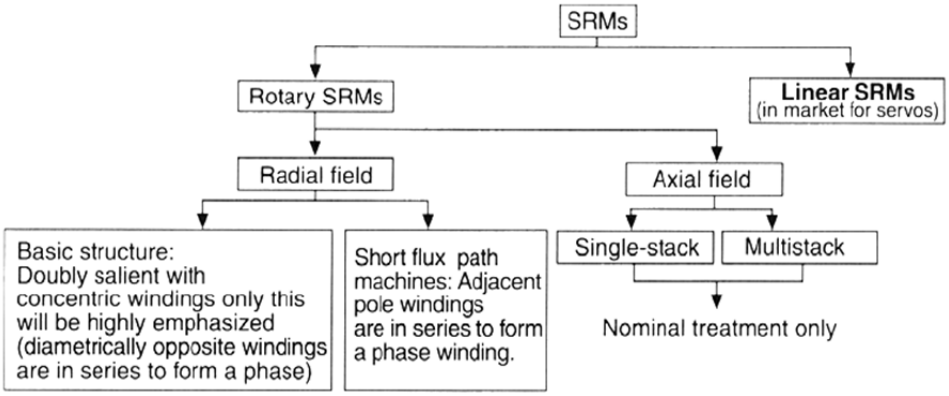

Fig. 1. Classification of the SRM

The number under the configuration (6/4 or 8/6) means SRM with 6 or 8 poles on stator and 4 or 6 poles on rotor.

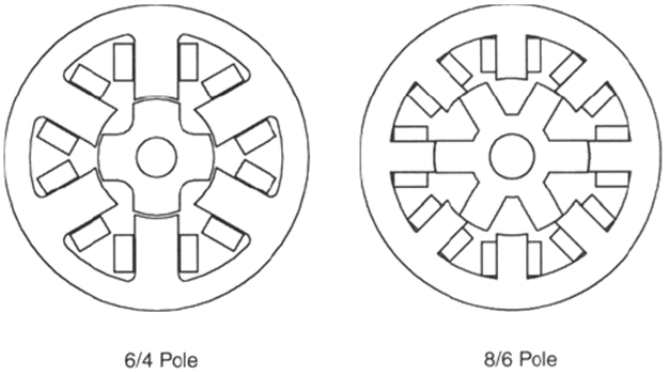

Fig. 2. SRM configuration

3. Operation of the SRMs

The key of understanding rotor movement is rising from the tendency of rotor to place in minimum reluctance position at the instance of excitation. While two rotor poles are in front of two stator poles, called align position. In align position; another set of rotor pole is out of alignment position there for another set of stator pole will be excited to move the rotor poles until the time to reach minimum reluctance. Figure 3 shows a 6:4 SRM. In the figure, at the first situation, suppose that r_1 and r_1' are two poles of rotor and in align position with c and c' which are the stator poles. When a is excited in the direction that is shown, stator poles tends to pull the rotor poles toward itself. Therefore, $r_2$and r_2' are in front of the a and a', respectively. After they are aligned, the stator current is turned off and the corresponding situation is shown in Figure 3(b). Now, b is excited and pulls the $r_1$and r_1' toward b' and b, respectively. Hence, the rotor is rotating in a clockwise direction.

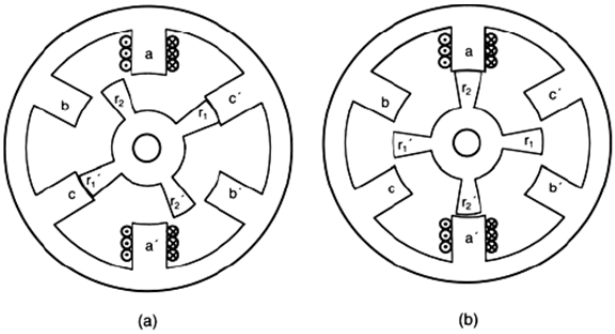

Fig. 3. Operation of switched reluctance motor a)Phase c aligned b) Phase a aligned

Following figure shows the lamination profile of 8:6 SRM in align position with magnetic potential contour.

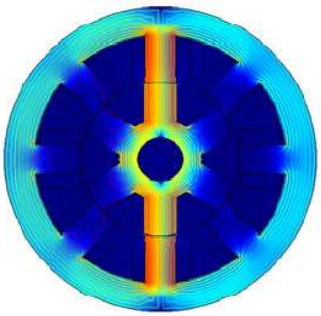

Fig. 4. Lamination profile of 8:6 SRM (Parvizi, Hassani, Mehbodnia, Makhilef, & Tamjis, 2009)

4. Single – Phase SRMs

During the past years, single-phase SRMs have attracted much attention due to resemblance to universal and single phase induction machines and also, single-phase SRMs are low-cost manufacture as well as induction and universal machines. Specific applications of single-phase SRMs come up in where high-speed motors are needed. When the stator and rotor poles are in front of each other which means the align position, the current that relevant to stator phase is turned off and the rotor keeps moving toward the adjacent stator pole due to kinetic energy which is stored. Adjacent stator phase is energized to attract the rotor pole toward itself. This process subsequently will be continued.

The major problem of single-phase SRMs operation come up when the rotor and stator are in align position at the instant of starting or the rotor at a position where the load torque at the starting is greater than the produced load. Permanent magnet has been used as a solution. It pulls the rotor away from the stator or at the right position in which motor can produce a torque greater than the load torque. As the figure 5 shows the rotor and stator are in unaligned position.

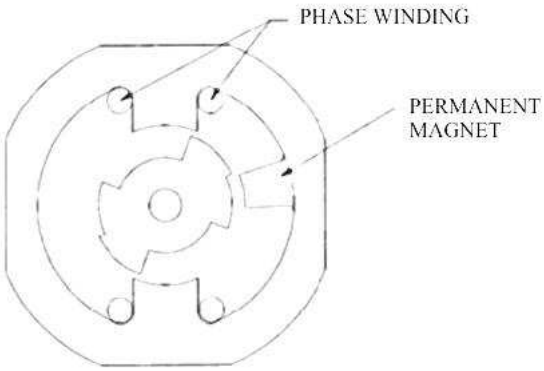

Fig. 5. Single-phase SRM with permanent magnet

Maximum duty cycle of single-phase SRM is 0.5, thus, noise and high ripple torque are deduced from a torque discontinuity which arises from duty cycle. Applications, in which torque ripple and noise are not important, are good for this machine such as home appliances and hand tool.

5. Magnetization characteristic of SRM

Due to saturation and varying reluctance with rotor position, there is no simple analytical solution to express the field which is produced by phase winding. Energy conversion approach that is presented in is used to analyze energy conversion.

Figure 6 shows a typical magnetization curve. Flux linkage is a function of both rotor position and excitation current and also, it is nonlinear function. One of the most important parameter which affects on flux linkage is air gap. As it can be seen clearly, in unaligned position, flux linkage is a linear function due to big air gap. In other words, the gap between stator pole and rotor pole is big. In contrast, in aligned position, due to small air gap, the magnetization curve is heavily saturated.

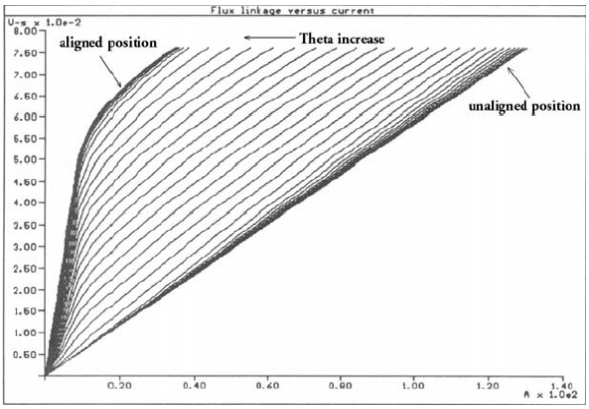

Fig. 6. Magnetization curve for SRM

Figure 7 shows a magnetization curve under specific condition. Rotor angle is locked in somewhere between aligned and unaligned position. Energy and co-energy are defined in any point of that respectively by:

$$W_f = \int_0^{\lambda_a} i d\lambda(i,\theta) \tag{1}$$

$$\acute{W} = \int_0^{i_a} \lambda(\theta,i) di \tag{2}$$

$\lambda(\theta,i)$ represents the flux linkage as a nonlinear function of rotor position and current. As figure 7 shows, the area behind the magnetization curve until $\lambda_a$called stored field energy (W_f) that this energy is stored in the iron core (rotor and stator) and in the air gap. The area under the magnetization curve until i_a called co-energy $(\acute{W})$.

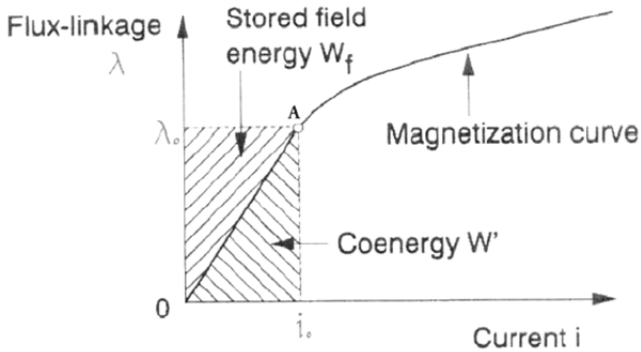

Fig. 7. Concept of stored field energy and co-energy

In the next step, suppose that rotor is released. In this situation, rotor moves toward the adjacent stator pole until place in align position. For an infinitesimal movement$\Delta\theta$, suppose that i_a is considered constant, thus the flux linkage changes from point A to point B as shown in figure 8. By considering the conservation of energy, the mechanical work Δw_m which has been done by rotor during the $\Delta\theta$ movement is equal to the change in the stored field energy (ΔW_f).

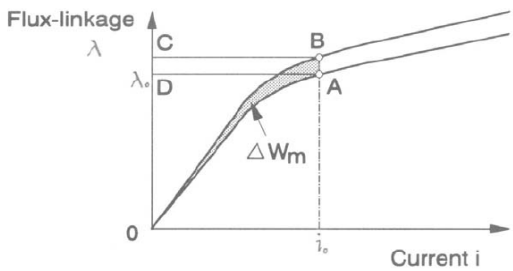

Fig. 8. Mechanical work area

The area ΔW_m equals to the change in co-energy because of the $\Delta\theta$ movement. Thus, the mechanical energy can be stated as following:

$$\Delta W_m = \Delta \acute{W} = \int_0^{i_a} \lambda(\theta_B, i)di - \int_0^{i_a} \lambda(\theta_A, i)di \tag{3}$$

And also

$$\Delta W_m = T\Delta\theta \tag{4}$$

There for, the mechanical torque can be expressed as:

$$T = \frac{\Delta W_m}{\Delta\theta} = \frac{\int_0^{i_a} \lambda(\theta_B, i)di - \int_0^{i_a} \lambda(\theta_A, i)di}{\Delta\theta} \tag{5}$$

By considering that the movement goes zero($\Delta\theta \to 0$) , for any current, the instantaneous torque can be written as following:

$$T = \frac{\partial}{\partial\theta}\int_0^i \lambda(\theta, \acute{i})d\acute{i} \tag{6}$$

For a linear flux model:

$$\lambda(\theta, i) = L(\theta)i \tag{7}$$

Therefore:

$$T = \int_0^i \frac{\partial\lambda(\theta,\acute{i})}{\partial\theta}d\acute{i} = \int_0^i \frac{dL}{d\theta}id\acute{i} = \frac{dL}{d\theta}\int_0^i i\, d\acute{i} = \frac{1}{2}i^2\frac{dL}{d\theta} \tag{8}$$

Therefore, the magnetization curve has been analyzed and instantaneous torque has been elaborated. Under specific condition such as being current in certain value (in linear flux region and no saturation effect), the relationship between the flux linkage and current can be assumed linear. As the current increases, the saturation effect occurs and the nonlinearity of the flux linkage will be appeared. Figure 9 shows the data of torque profile of 8:6 SRM published in (Bhiwapurkar& Jain& Mohan,2005).

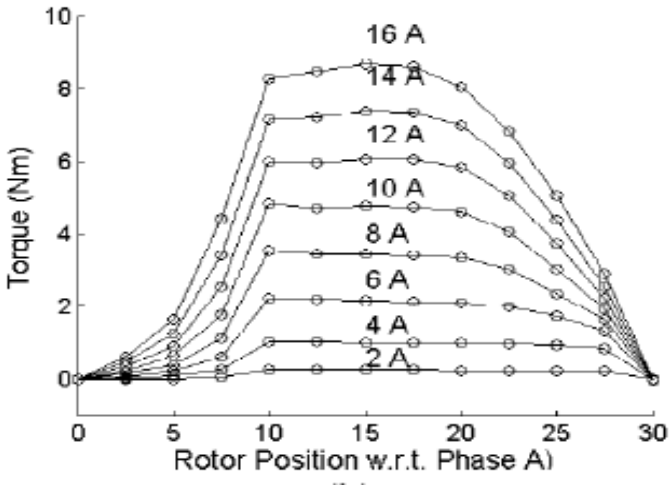

Fig. 9. Torque profile of SRM

6. Torque estimation model using fuzzy logic technique (FIS)

The modeling process for estimation of torque starts from analyzing data from plotted curve and will be continued by fuzzy rule base and FIS structure and ends in mapping surface. By considering 8:6 SRM's torque profile (Figure 10); Fuzzy Logic approach will be explained.

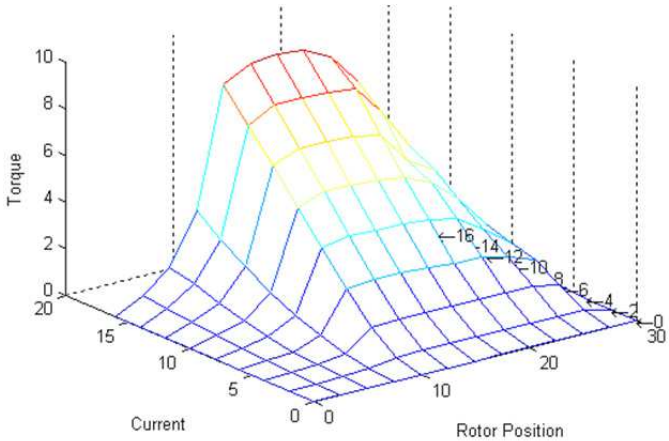

Fig. 10. Simulated Torque profile Via MATLAB

6.1 Establishing the fuzzy rules table

In the first step, from plotted curve, exact data should be extracted. For the torque estimation model, current and rotor angle are defined as inputs and torque is output. Based on analyzing the findings data from plotted curve minimum and maximum of each those inputs and output should be determined. Based on the division each of those inputs and output which is called fuzzy region, number of regions will determine and also, related linguistic variable will be assigned in order to settle the obstacle in establishing the fuzzy rule table. Table 1 show the input and output domain for 8:6 SRM. This table shows the inputs and output variable with their respective number of region and linguistic variable assigned for the region.

Input/output	Range	No. of regions	Variable
Current I(A)	2-16	8	s4-m-b3
Rotor position,(θ°)	0-30	13	s6-m-b6
Torque	0-9.54	21	s10-m-b10

Table 1. Input and output domains for 8:6 SRM

Once domains are determined, forming fuzzy rule base table starts. To convert the torque profile characteristics to fuzzy rule base table, right interpret from the extracted data to linguistic variable is very important. Table 2 shows the fuzzy rule base table for 8:6 SRM. According to the number of the fuzzy region and the linguistic variable, this table is established.

	s4	s3	s2	s1	M	b1	b2	b3
s6	s10	s10	s10	s10	s10	s10	s10	s10
s5	s10	s10	s10	s9	s9	s8	s8	s8
s4	s10	s9	s9	s8	s8	s7	s7	s6
s3	s9	s8	s8	s7	s6	s5	s3	s2
s2	s8	s7	s5	s2	b1	b3	b6	b9
s1	s8	s7	s4	s1	b2	b5	b7	b10
M	s8	s7	s4	s1	b2	b5	b7	b10
b1	s8	s7	s4	s1	b1	b4	b7	b10
b2	s8	s7	s5	s2	b1	b4	b6	b8
b3	s8	s7	s5	s2	M	b2	b4	b6
b4	s8	s7	s5	s4	s2	M	b1	b2
b5	s9	s8	s6	s5	s5	s4	s3	s3
b6	s10	s10	s10	s10	s10	s10	s10	s10

Table 2. Fuzzy rule base table for 8:6 SRM

It should be noted that wrong interpretation of each of rules will influence on overall output and as a result, wrong model will come up. Therefore, this part of work should be done carefully and without any wrong rule.

6.2 Formation of Fuzzy Inference System (FIS)

For the formation of the fuzzy inference system, fuzzy logic toolbox of MATLAB is used. Figure 11 shows the FIS structure that current and rotor angle are the inputs and torque is the output.

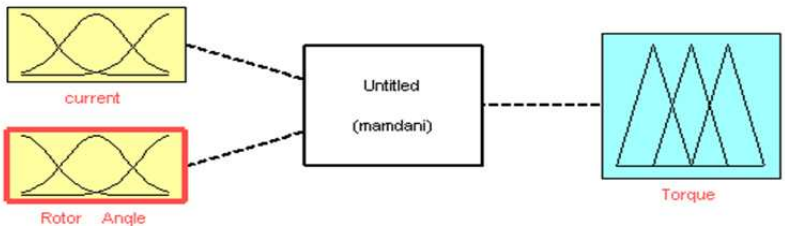

Fig. 11. Fuzzy SRM FIS structure

6.3 Assigning the FIS membership functions

Once the FIS structure is completed, membership functions for each of the inputs and the output will be formed. Toolbox of MATLAB has 11 built-in membership functions (MFs) which some of those are trimf, gbellmf, gaussmf, gauss2mf, sigmf, psigmf. One of these MFs that are formed by straight lines is called triangular MFs. These MFs are used here in account of simple structure and well suited for the modeling.

Current and rotor angle as the inputs have 8 MFs and 13 MFs respectively for itself and torque as the output has 21 MFs for 8:6 SRM. Figure 12 , figure 13 and figure 14 show the MF for current, rotor angle and torque, respectively.

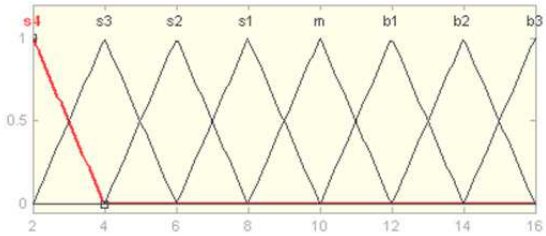

Fig. 12. Membership functions for current

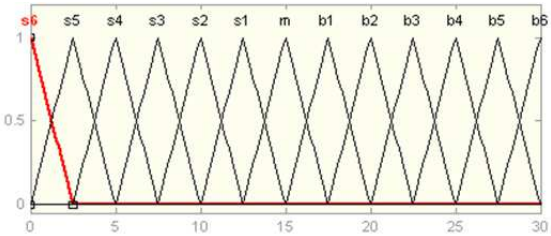

Fig. 13. Membership functions for rotor angle

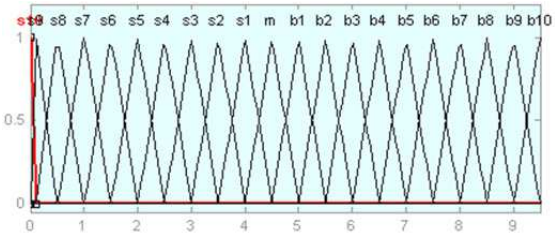

Fig. 14. Membership functions for torque

6.4 Constructing FIS rule

The most important part of the modeling is the constructing FIS rules because of the outcome of this part will define output fuzzy set. In other words, torque as the output is a fuzzy set that basically are formed by the results of the constructing FIS rules. Table 2 is used to constructing FIS rules. In Mamdani's type a set of if-then called rules. Thus, the conditional statements are formulated by if-then form. For instance,

Rule 1: If current is s6 and rotor angle is s4 then torque is s10

Degree of membership function is a value between 0 and 1 which is the output of the membership function. Now, degree of a rule can be defined the multiple of the degree of the inputs and output. For example, degree of the mentioned rule can be as following:

Degree (Rule 1) = μ (s6).μ (s4).μ (s10)

FIS editor is used to produce the rules which are shown in figure 15. Also, figure 15 shows a part of rules for 8:6 SRM and the number of total rules are 80.

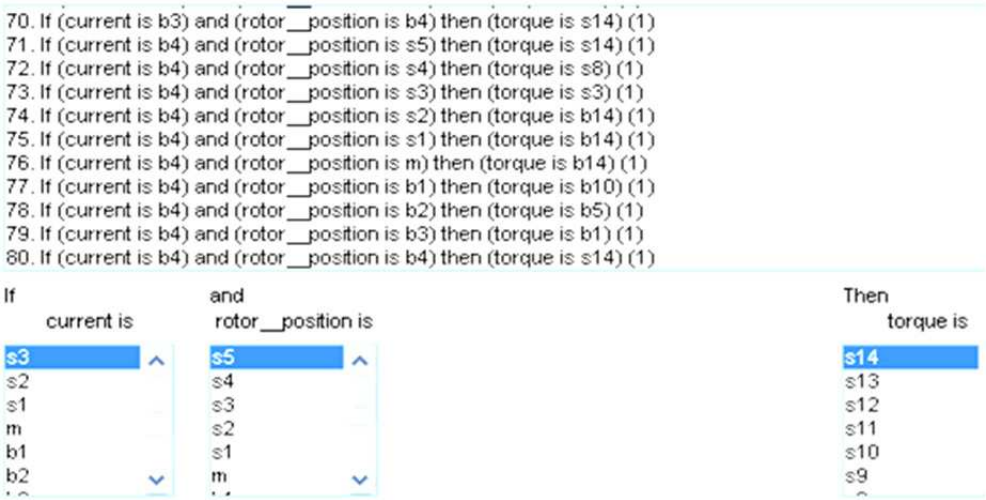

Fig. 15. Constructing rules using rule editor

The surface viewer is used to show the dependency of the output to both of inputs. There for, it generates torque surface map. Figure 16 shows the torque for 8:6.

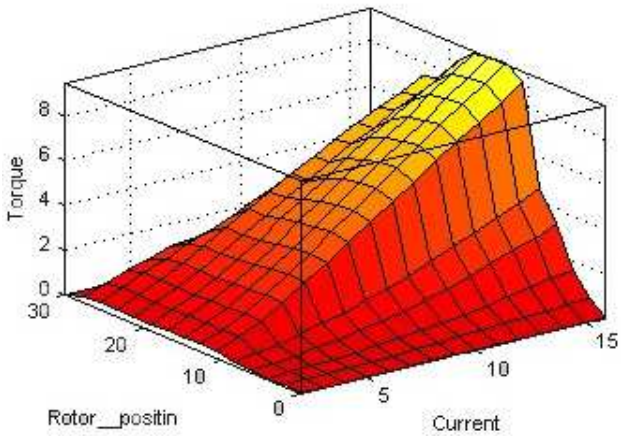

Fig. 16. Surface viewer of the FIS for 8:6 SRM

7. Torque estimation model using Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS is an acronym of Adaptive Neuro-Fuzzy Inference System. Adaptive Neuro-Fuzzy is a technique which provides a learning method from the desired input and output to adjust the MFs parameters. During this process, back propagation and hybrid are two algorithms that are used so that the best parameters for the MFs will be achieved.

7.1 Forming ANFIS

By considering the graphical representative of torque (figure 9), rotor angle and current are defined as inputs and torque as output. Figure 17 shows the FIS editor for ANFIS that two inputs and one output has been shown clearly.

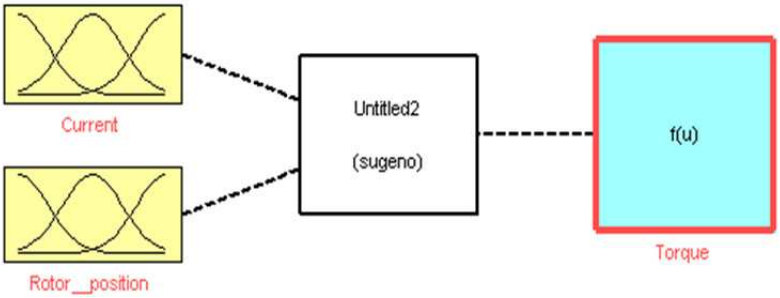

Fig. 17. Neuro-Fuzzy SRM FIS structure

7.2 Training scheme of FIS

Once the data set are obtained from the torque curve, loading data starts. The loaded data set should be in three columns matrix format. First and second belong to the inputs and the third one present the torque data.

The training data appears in the plot in center of the ANFIS editor as a set of circle as shown in figure 18 for 8:6 SRM.

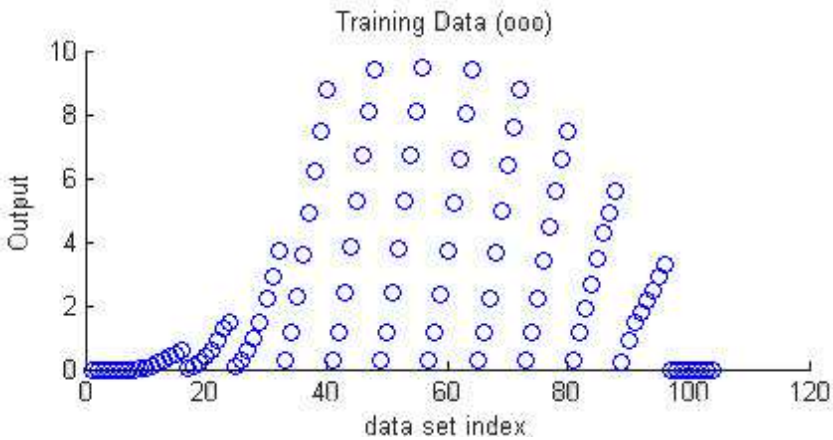

Fig. 18. ANFIS editor with training data loaded for 8:6 SRM

7.3 Initializing and generating FIS

Once data set is loaded, next step is initializing the MFs. There are two partitioning method for initializing the MFs:

1. Grid partition
2. Subtractive clustering

Second method is employed in account of having one-pass algorithm which estimates the number of clusters.

Figure 19 shows the cluster parameters which are:

1. Range of influence
2. Squash factor
3. Accept ratio
4. Reject ratio

For varying both of inputs "range of influence" is set to 0.15. Other parameters remain in their previous value because those values are acceptable for training scheme. Once the parameters are set, the outcome FIS generates 104 numbers of MFs for both of the inputs, and output.

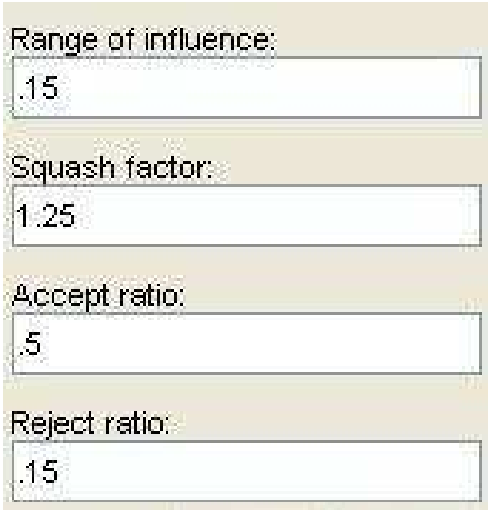

Fig. 19. Parameters set for subtractive clustering

7.4 ANFIS training

In order to optimize the obtained parameters, two methods are available:

1. Hybrid method: this method is a combination of least squares and back propagation method.
2. Back propagation: this method consists of steepest descend method for MFs.

The first method is considered for data training. Error tolerance is established to create halt criterion. The error training will stop after certain epoch which is set. The number of epochs for both of 8:6 is 150.

The final error training is 3.014e -7 which is shown in figure 18 after 150 epochs.

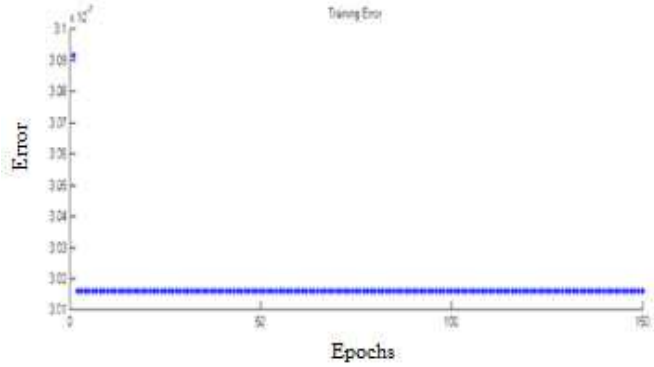

Fig. 20. ANFIS training with hybrid method

7.5 Viewing ANFIS structure

Figure 21 shows the ANFIS model structure for 8:6 SRM. There are two inputs (rotor angle and current) and one output (torque). There are total 104 MFs for each of inputs.

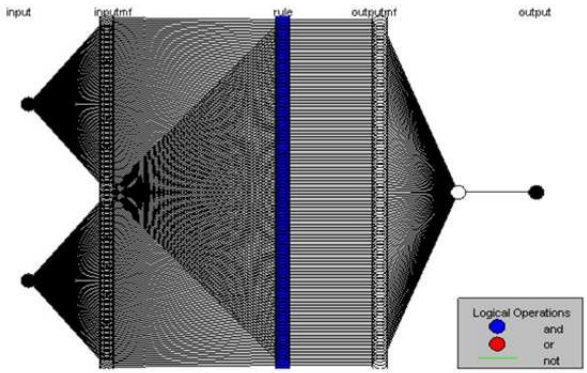

Fig. 21. ANFIS model structure for 8:6 SRM

The summarized modeling description is shown in table 3 for 8:6 SRM.

Modeling Description	Setting
Number of Inputs	2
Number of Output	1
Method	Subtractive Clustering
Number of MFs	104
Optimized Method	Hybrid
Epochs	150

Table 3. Fuzzy rule base table for 8:6 SRM

The mapping surface of 8:6 SRM using neuro-fuzzy technique is shown in figure 19.

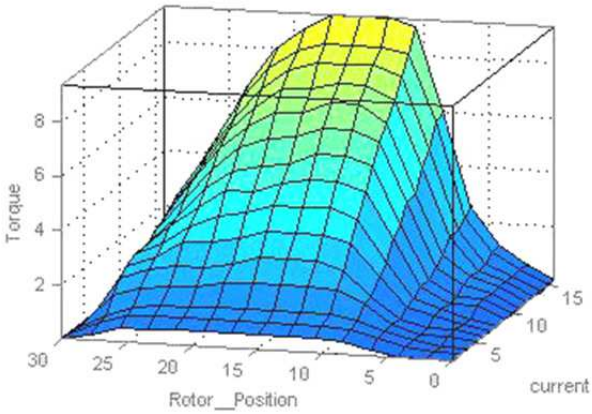

Fig. 22. Surface view of 8:6 SRM

8. Result and discussion

8.1 Error analysis for torque estimation model using fuzzy logic technique

Torque estimation based on fuzzy logic technique has been presented. Thus, 8 and 13 membership functions were formed for the inputs and 21 for the torque as the output for 8:6 RM. Error analysis is conducted to obtain the accuracy of the model. Appendix D shows the computed torque values in term of comparison with the desired measured values.

From the results in appendix A:

- N = Number of data points= 104
- I = phase current(A)
- θ = Rotor angle in mechanical degree
- T_m = Measured torque in Newton-meter
- T_f = Computed torque in Newton-meter
- $\sum(T_m)$ = Sum of the measured torque T_m=270.95
- $\sum(T_f)$ = Sum of the computed torque T_f=282.4614
- $\sum(|\varepsilon|)$ = Calculated total absolute error=16.2222

Thus,

Mean $T_f = \frac{282.4614}{104} = 2.716$

Average% error = $\left[\frac{\sum|\varepsilon|}{Mean\ T_f * N}\right] * 100\%$

$$= \frac{16.2222}{2.716 * 104} * 100\% = 5.7431$$

8.2 Error analysis for torque estimation model using adaptive neuro-fuzzy inference system technique

ANFIS is one the best approaches due to the capability of learning without dependency to human knowledge. In other worlds, in fuzzy logic approach, membership functions have been formed by the human knowledge but ANFIS because of having training algorithm and independency to human knowledge is more capable to produce accurate data. In this section, error analysis shows the preciseness of the mode:

From the results in appendix B:

- N = Number of data points= 104
- I = phase current(A)
- θ = Rotor angle in mechanical degree
- T_m = Measured torque in Newton-meter
- T_f = Computed torque in Newton-meter
- $\sum(T_f)$ = Sum of the computed torque =2.71E+02
- $\sum(T_m)$ = Sum of the measured torque =270.95
- $\sum(|\varepsilon|)$ = Calculated total absolute error= 4.61 e-011

Thus,

Mean T_f= $\frac{2.71\text{E}+02}{104}$ =2.6058

Average% error= $\left[\frac{\sum|\varepsilon|}{Mean\ T_f * N}\right] * 100\%$

$$= \frac{4.61e-011}{2.6058 * 104} * 100 = 1.7011e-011$$

9. Conclusion

Error analysis is conducted for the two approaches. Table 4 reflects the average percentage error of each models.

	FIS	ANFIS
Average Percentage Error	5.7431%	$1.701e-011\%$

Table 4. Error analysis result

As it can been seen clearly, table above shows the ANFIS model is the best among those. ANFIS technique is used in order to develop predictive model for obtaining precision outcome. This approach can be used for any nonlinear function with arbitrary accuracy.

Torque profile of switched reluctance motor is a nonlinear function and the inherent nonlinear characteristics lead us toward artificial intelligence approaches. Due to the mentioned nonlinearity a predictive model is needed. ANFIS model owing to its abilities to predict is opted. The reason being is due to the ANFIS modeling approach possessing

learning characteristic capability that allows it to learn from the data values through the training scheme, thus avoids on the dependency of human knowledge with regard to the systems(Parvizi.A&Hassani&Mehbodnia&Makhilef&Tamjis,2009) . Besides, ANFIS method dose not have the complexity of FIS method which makes it much easier to understand and utilize. Average percentage error shows that the outcome is in good agreement with the published data. Torque profile is simulated and results reveals that ANFIS modeling method is a trustable model for further research. In addition, this approch can be used in order to control the turn-off angle of the SRM which leades to a SRM with low torque ripples.

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11. Appendix A

Error analysis for torque Using Fuzzy logic Technique

Current	Rotor Angle	Measured torque	Computed torque	$\lvert\varepsilon\rvert$
2	0	0	0.1723	0.1723
4	0	0	0.1723	0.1723
6	0	0	0.1723	0.1723
8	0	0	0.1723	0.1723
10	0	0	0.1723	0.1723
12	0	0	0.1723	0.1723
14	0	0	0.1723	0.1723
16	0	0	0.1723	0.1723
.	.	.	.	.
.	.	.	.	.
2	30	0	0.1723	0.1723
4	30	0	0.1723	0.1723
6	30	0	0.1723	0.1723
8	30	0	0.1723	0.1723
10	30	0	0.1723	0.1723
12	30	0	0.1723	0.1723
14	30	0	0.1723	0.1723
16	30	0	0.1723	0.1723
936	1560	270.95	282.4614	16.2222

12. Appendix B

Error analysis for the ANFIS model of 8:6 SRM

Current	Rotor Angle	Measured Torque	Computed Torque	|ε|
2	0	0	7.99e-014	7.99E-14
4	0	0	6.49e-014	6.49E-14
6	0	0	6.61e-014	6.61E-14
8	0	0	3.72e-14	3.72E-14
10	0	0	2.14e-13	2.14E-13
12	0	0	2.36e-13	2.36E-13
14	0	0	3.11e-13	3.11E-13
16	0	0	3.08e-014	3.08E-14
.	.	.	.	.
.	.	.	.	.
2	30	0	-1.18e-013	1.18E-13
4	30	0	-4.62e-012	4.62E-12
6	30	0	-6.92e-012	6.92E-12
8	30	0	3.25e-012	3.25E-12
10	30	0	1.15e-012	1.15E-12
12	30	0	3.34e-012	3.34E-12
14	30	0	1.36e-012	1.36E-12
16	30	0	2.43e-011	2.43E-11
936	1560	270.95	2.71E+02	4.61E-11

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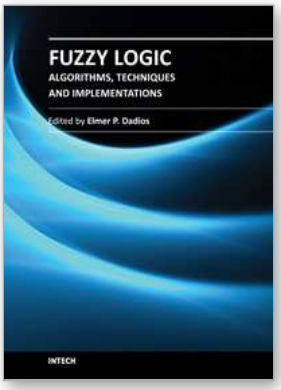

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Fuzzy Logic is becoming an essential method of solving problems in all domains. It gives tremendous impact on the design of autonomous intelligent systems. The purpose of this book is to introduce Hybrid Algorithms, Techniques, and Implementations of Fuzzy Logic. The book consists of thirteen chapters highlighting models and principles of fuzzy logic and issues on its techniques and implementations. The intended readers of this book are engineers, researchers, and graduate students interested in fuzzy logic systems.

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