Design of GT-FLC Speed Controller and Position Sensorless Control Using ANN for 8/6 SRM

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Abstract— A mathematical model has been designed for a Switched Reluctance Machine (SRM) with Gain Tuning Fuzzy Logic Controller (GT-FLC) using Matlab/Simulink environment. The Tuning parameters in FLC gives better speed controller than conventional control. Both linear and nonlinear model are developed and simulation studies are performed for 8/6 SRM. The presence of position sensor is main disadvantage of SRM. Hence sensors have been replaced with Artificial Neural Network (ANN). ANN have unique feature to solve the non-linear characteristic model present in SRM. This model is developed efficiently and trained under supervised learning method in which flux-linkage and phase-current are given as input and rotor position is estimated as output. This paper shows a mathematical model with GTFLC of 8/6 SRM for simulation verification and an effective BPNN algorithm of artificial neural network for removal of position sensor of 8/6 switched reluctance machine.

***Keywords*- Switched Reluctance Machine, Linear model, Nonlinear Model, ANN,GT-FLC, speed controller,Simulation.**

I. INTRODUCTION

SRM's intrinsic simplicity and ruggedness make it superior to other electrical machines. Its high speed capability, high torque to inertia ratio, reliability and high robustness has been attracted by many researchers' interest all over the world [1]. They are known to have high peak torque-to-inertia ratios and the rotor mechanical structure is well suited for high speed applications. However, SRMs have been limited in their use due to the high ripple content of torque inherent in their doubly salient design. The new industrial applications necessitate position and speed variators having high dynamic performances, good precision in permanent regime. To meet this requirement needs a precious controller for SRM

The stator winding current commutation with respect to rotor position is the central subject of Switched Reluctance Motor (SRM) control. Therefore, detection of rotor position either directly or indirectly is essential for variable speed drive application. The elimination of the mechanical transducer increases reliability, reducing costs This paper describes the development of ANN based position sensor less closed-loop control of a 4-phase SRM with Gain tuning Fuzzy Logic controller for speed control as well as adaptive reference current fixing for the current controller. As well known the performance and operation of a SR motor depends on the knowledge of rotor position, in order to obtain the correct stator phases energization. As a matter of fact motoring torque is obtained during stator and rotor pole alignment, only if the related stator phase is energized. The converter provides a full four quadrant operation with independent energization and commutation of each phase winding [8].

In this paper, the mathematical model with an initialization program is made for the simulation of switched reluctance machine. The simulation verification has been done for both Linear as well as Non linear Model. Linear Model fully based on Mathematical equations and the Non linear model characteristics have been taken from MagNet Software and feed to Matlab as a lookup tables. The GT-FLC is a technique in controlling the speed of SRM efficiently in the full load range [9]-[13]. For Back Propagation Neural Network (BPNN) algorithm has been developed for sensor less operation and verified its output under supervised learning phase [8].

II. SRM MODELIZATION

Switched reluctance machine is a doubly salient electric machine shown in fig1. The rotor is aligned whenever diametrically opposite stator poles are excited. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation.

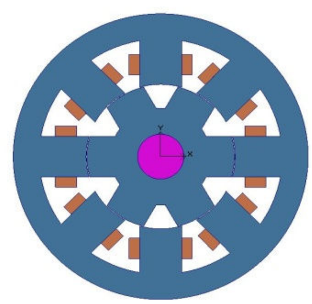

Figure 1. 8/6 SRM Model

All the four phases are assumed to be identical. Hence, all the equations are described with respect to the generic phase. Mutual inductances between the phases are neglected. The phase flux linkage is a nonlinear function of the rotor position and the phase current. The discrete mathematical model of the SRM is a set of controlled difference equations obtained by the use of standard SRM theory. The difference equations that describe the dynamics of SRM are approximated as follows

A. *Voltage Equation:*

If the mutual effect of phases is neglected, the voltage (1) applied to one phase of SRM can be expressed as follows.

$$V_j = R_j I_j + \frac{d\psi_j}{dt} \qquad j = 1, \dots, m \quad ----(1)$$

Where indicates the voltage applied on the phase windings, represents the phase current, shows the phase resistance and is the phase current while m is the motor phase number. In the SRM, flux is a function of both the current and the rotor position.

$$V_j = R_j I_j + \frac{\partial\psi_j}{\partial I_j}\frac{dI_j}{dt} + \frac{\partial\psi_j}{\partial\theta_j}\frac{d\theta_j}{dt} ----(2)$$

B. *Torque equation:*

When each phase of the SRM is excited, it produces an instantaneous torque (3). When the instantaneous torques produced by the phases is added, the total torque induced in the motor is found. The instantaneous torque produced by one phase of the motor is as follows:

$$T_j = \left.\frac{\partial W_j'}{\partial\theta}\right|_{i=const} = \frac{\partial\int_0^{i_j}\psi_j(i_j,\theta)\,di_j}{\partial\theta} ----(3)$$

The total torque (4) is expressed as the sum of the m individual phase torques when the magnetic coupling between phases is not taken into account.

$$T_e = \sum_{j=1}^{m} T_j\,(i_j,\theta) ----(4)$$

C. *Mechanical equations:*

Mechanical equations can be expressed as below:

$$T_e - T_l = J.\frac{d\omega_r}{dt} + B.\omega_r ----(5)$$

Here is the load torque is the rotor speed, J and B are the moment of inertia and the coefficient of friction respectively. When the above equation is re-arranged in order to write the speed expression,

$$\frac{d\omega_r}{dt} = \frac{1}{J}.[T_e - T_l - B.\omega_r] ----(6)$$

For linear mathematical model, single phase winding is modeled using the basic equations in Matlab similar phases are grouped to form an 8/6 SRM shown in fig5. The subsystem of single phase linear model is shown in Fig2

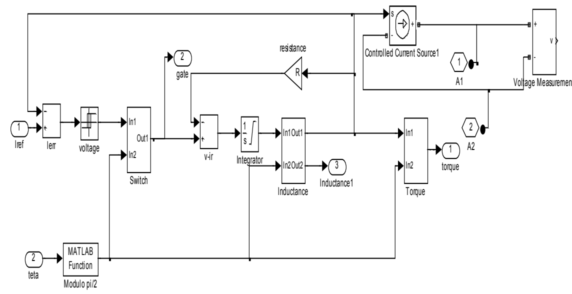

Figure 2. Single Phase Linear Model Subsystem

For nonlinear mathematical model, here 8/6 SRM is considered and their parameters such as flux-linkage, torque and inductance are obtained from the finite element analysis method. The subsystem of single phase nonlinear model is shown in Fig 3.

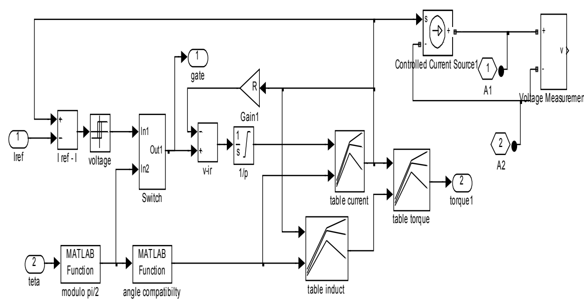

Figure 3. Single Phase Nonlinear Model Subsystem

The flux-linkage characteristics obtained for the nonlinear 8/6 SRM model is shown in Fig 4.

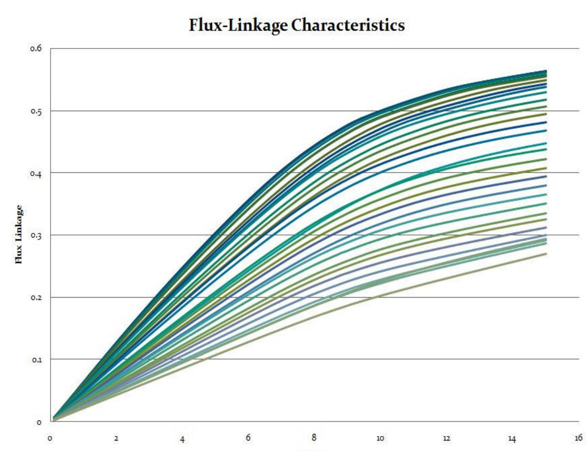

Figure 4. Flux-linkage characteristics

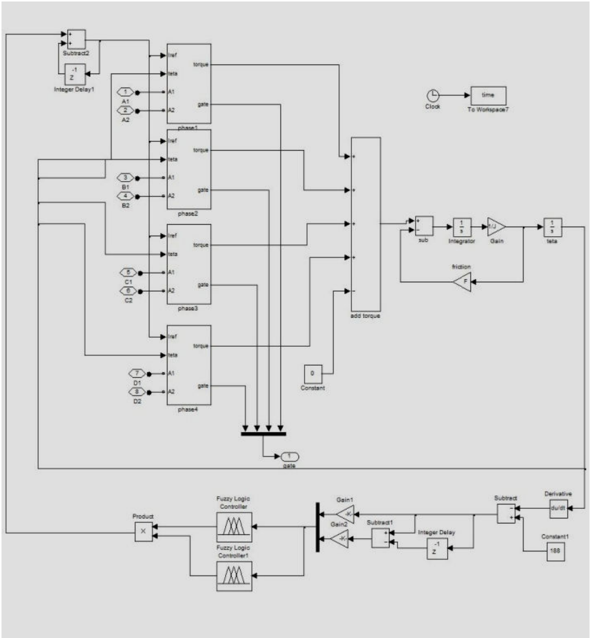

Figure 5. Four Phase SRM Model

III. Fuzzy Logic Controller

A fuzzy logic controller chooses the switching states based on a set of fuzzy variables. In this paper, the fuzzy logic controller is used to control the speed by the speed error signals (eN) and change in speed (Δe). Fuzzy logic controllers perform better than conventional model-based controllers, especially when applied to processes difficult to model, with nonlinearities, and with uncertainties. The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect.

The STFLC consists of a combined effect of PI-FLC and GT-FLC thereby a high logic performance control action can be achieved under transient and steady state. In conventional PI-FLC, the value of G is maintained constant throughout the entire operating conditions, then the controller is said to be PI type FLC. But, the gain of the proposed STPIFLC does not remain fixed while the controller is in operations; rather it is changed in each time step by the gain scaling factor, depending on the total torque of the SRM.

The Table 01 represents the rules of PI-FLC with linguistic variables and Table 02 represents the rules for GT-FLC. In the Fig.6 membership function for both FLC are shown for input and output. By implementing the Fuzzy interference system (FIS) into the mathematical model can control the speed efficiently when compared to conventional controller.

Δe_N / e_N	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NL	NM	Z
NM	NL	NL	NL	NL	NM	Z	PS
NS	NL	NL	NM	NM	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

Table01. RULES OF PI-FUZZY SYSTEM

Δe_N / e_N	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	VB	VB	VB	B	SB	S	Z
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
Z	S	SB	MB	Z	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PL	Z	S	SB	B	VB	VB	VB

Table02. RULES FOR GT-FUZZY SYSTEM

The meaning of the linguistic variables in Table I and Table II are as follows:

NL : Negative Large
NM : Negative Medium
NS : Negative Small
Z : Zero
MB : Medium Big
VS : Very Small
PS : Positive Small
PM : Positive Medium
PL : Positive Large
VB : Very Big
SB : Small Big
S : Small ; B : Big

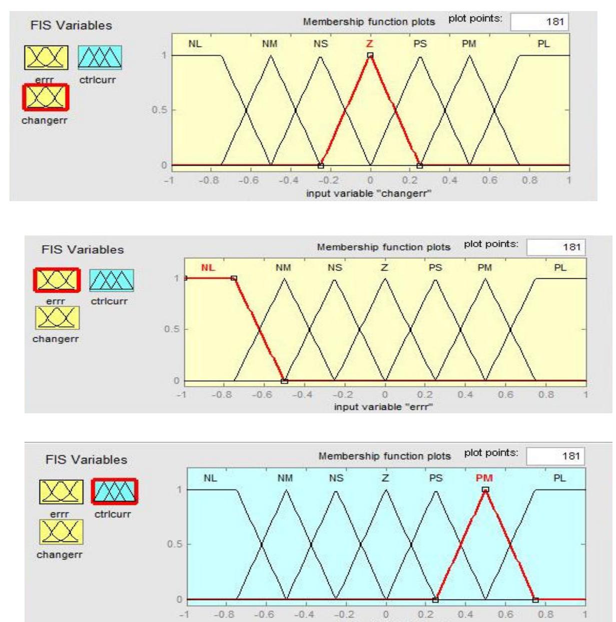

Figure 6. Membership functions of input and output variables

IV. Simulation Verification

A. Simulation result of Linear Model

To begin the SRM simulation using its linear model, it is necessary to take care of choosing an initial rotor position that is not in the zone where inductance had a constant value, since there is no torque produced. When the load torque is zero, variable TETA corresponding to rotor position would not evolve and the machine will be halted all the time. However, when the load torque is not zero, the rotor position will displace to establish a rotor speed where T_e=T_l. Thereby in this paper it considers the initial rotor position as (TETAON+1).

The parameters considered for four phase 8/6 switched reluctance machine is as follows: LMIN=0.018 Henry (H), LMAX=0.06 Henry (H), stator pole arc BETAS=19 degree (deg), rotor pole arc BETAR= 22 degree (deg), *overlapping angle* TETAX=9.5 degree and TETAY=28.5 degree.

Considering again motoring region assume that TETAON=18 degree (deg) and TETAOFF=25 degree (deg). The obtained profile characteristics are shown in Fig.7, Fig.8, Fig.9, Fig.10 and Fig.11.

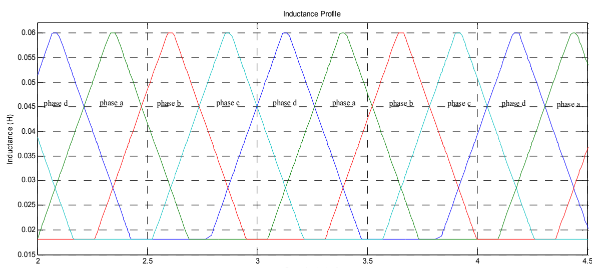

Figure 7. Inductance profile

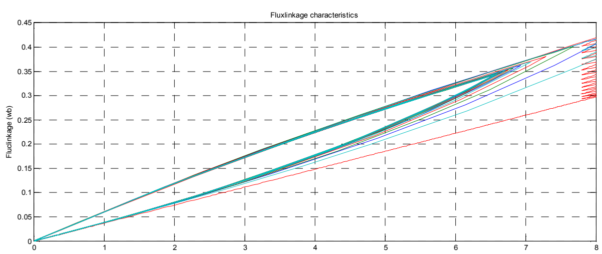

Figure 8. Flux characteristics

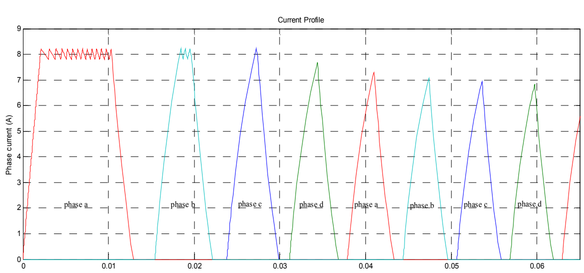

Figure 9. Current characteristics

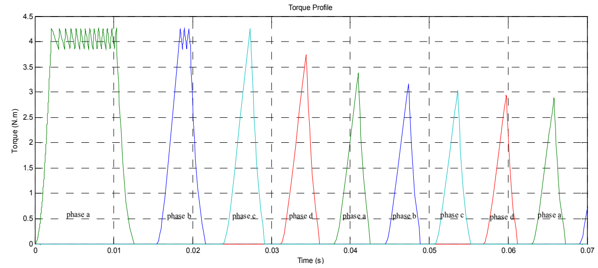

Figure 10. Torque Characteristics

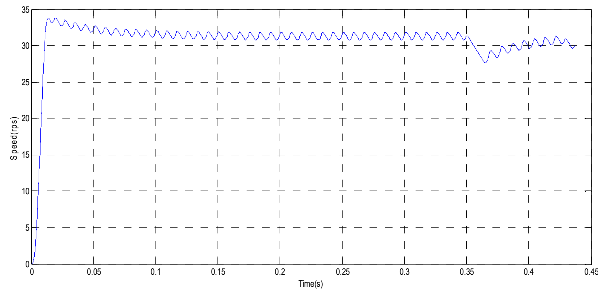

Figure 11. Speed characteristics

B. Simulation result for nonlinear Model

The 8/6 SRM model shown in Fig.1 is designed using Magnet tool and the look-up table is used for nonlinear model analysis. The parameters considered for nonlinear model are as follows: LMIN=0.018 Henry, LMAX=0.06 Henry, BETAS=19 degree, BETAR= 20 degree, overlapping angle TETAX=9.5 degree, TETAY=29.5 degree .

Assume that TETAON=18 degree (deg) and TETAOFF=28 degree (deg). The obtained profile characteristics are shown in Fig.12, Fig.13, Fig.14, Fig.15 and Fig.16.

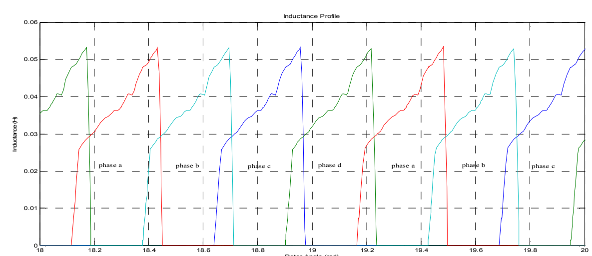

Figure 12. Inductance profile

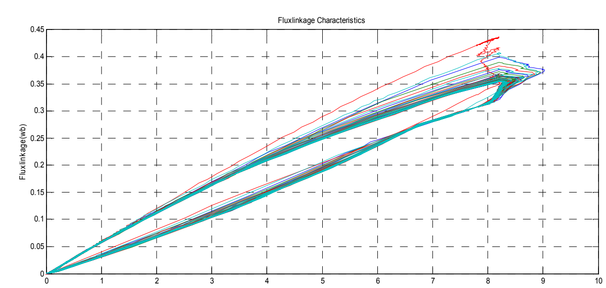

Figure 13. Flux characteristics

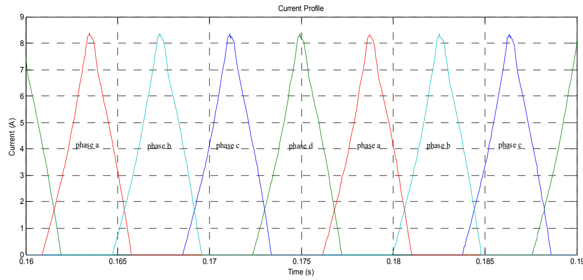

Figure 14. Current profile

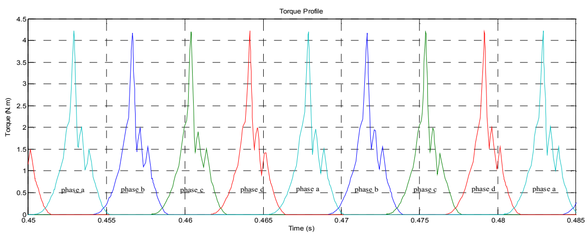

Figure 15. Torque profile

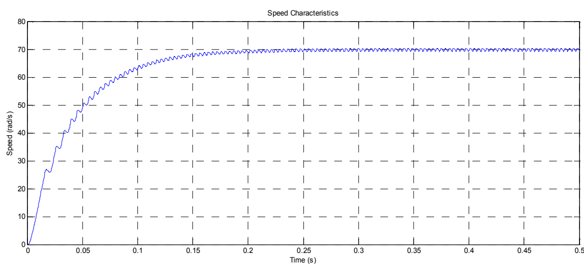

Figure 16. Speed characteristics

V. DYNAMIC SYSTEM IDENTIFICATION USING ARTIFICIAL NEURAL NETWORKS

An artificial neural network is a mathematical model or computational model that is inspired by the structure and/or functional aspects of biological neural networks. A neural network consists of an interconnected group of artificial neurons shown in fig 17, and it processes information using a connectionist approach to computation.

In most cases, an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. Modern neural networks are non-linear statistical data modeling tools.

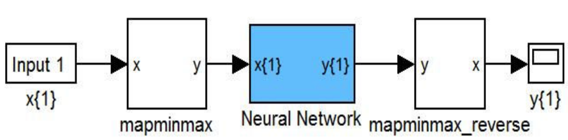

Figure 17. NN Model

Neural Network inputs are flux linkage and phase current which are preprocessed using map minmax function and trained under supervised learning phase i.e., target values are given in respective to their inputs. The data sets which are obtained from MagNet machine model are trained using Back-Propagation Algorithm (BPA).

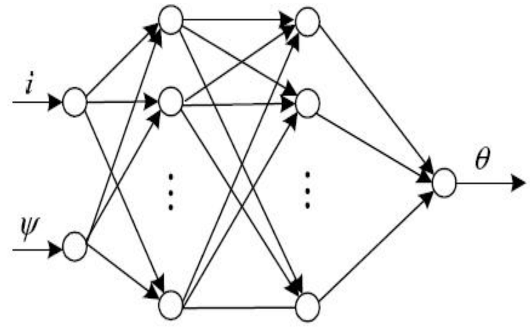

Figure 18. ANN Topology

They are usually used to model complex relationships between inputs and outputs or to find patterns in data.Layer1 is input layer and layer 3 is output layer whereas middle layer is a hidden layer which has no contact directly to user. Input layer has 2 neurons that represents flux-linkage and current which given in Fig.18 as ANN topology. One of the layers the subsystem with five neurons is shown in below Fig.19.

The trained output values from NN are compared with the target value and find the error. The iteration is repeated until the convergence made efficiently. The trained regression plot best fits the targeted line and make the ANN as efficient system to estimate rotor position efficiently.

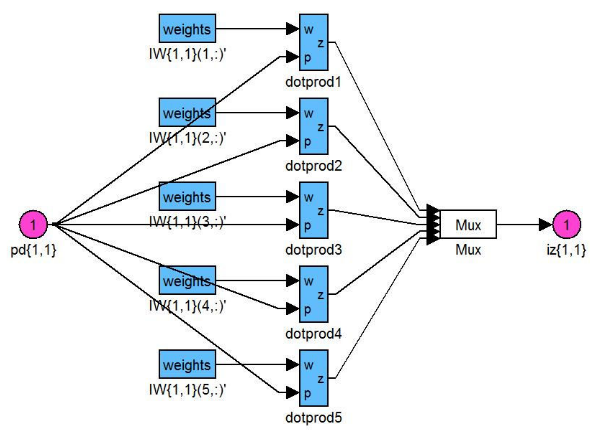

Figure 19. Five Neurons in H- Layer

The iteration are repeated until convergence made least mean square error above 10^{-4} from the epochs get best fitted in Fig.20 .This shows the estimation of rotor position from almost made an accuracy. Fig 21 shows the ANN flux and actual flux.

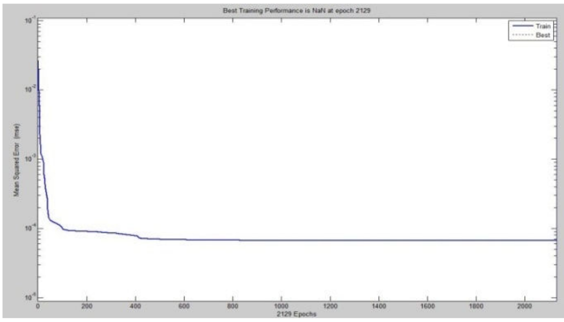

Figure 20. Epoch Plot

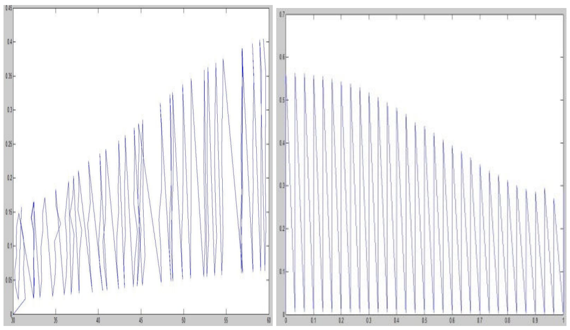

Figure 21. ANN Flux and Actual Flux

VI. CONCLUSION

Thus in this Paper it presents a mathematical model for Switched Reluctance Machine with Gain-Tuning Fuzzy Logic Controller (GT-FLC) for speed controller and studied their performance profile for linear and nonlinear model.. Using Artificial Neural Network (ANN) the disadvantage of rotor position in SRM has been removed and operated in sensor less mode. Due the accuracy of the estimated rotor position make it wide implementation in real time application. The effective improvement in BPNN algorithm and their training has been shown in this paper.

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