ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

Speed Regulation of Switched Reluctance Motor

K.Pandiarajan, R.Goutham Govind Raju, K.Naveen Kumar, D.Balaji

Assistant Professor , Dept. of Electrical and Electronics Engg, Prist University, Puducherry, India,

Assistant Professor , Dept. of Electrical and Electronics Engg Christ college of Engg. & Tech., Puducherry, India,

Assistant Professor, Dept. of Electrical and Electronics Engg , C.K.College of Engg. & Tech, Cuddalore, India.

Assistant Professor, Dept. of Electrical and Electronics Engg, Manakular Vinayakar Institute of Tech. Puducherry, India,

ABSTRACT*:* Switched reluctance motor is the simplest of all electrical machines in constructional aspects. The Mainly advantage are structural simplicity, high reliability and low cost, However, the SRM has some limitations as it should be perfectly electronically commutated, minimum torque ripple, noisy effects and nonlinear magnetic characteristics, to mitigate this demerits the motor should have good speed regulation and it is overcome by enhancing the controller. In this paper various controller are used to mitigate this demerits and it is done by using MATLAB/Simulink software and finally the result are compared using waveforms

KEYWORD*:* torque ripple, controller, speed regulation.

I . INTRODUCTION

The switched reluctance machine motion is produced because of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. The direction of generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor poles; many different SRM geometries can be realized [1-2]. Generally, increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to insure the starting direction. The number of rotor poles and stator poles must also differ to insure starting. The torque-speed operation point of an SRM is essentially programmable and determined almost entirely by the control [3-4].

II . LITERATURE REVIEW

In the field of the switched reluctance motors (SRM) several ideas arose in order to improve the classical control system of a SRM given in [5]. The torque ripples of the motor can be reduced by using fuzzy techniques or adaptive intelligent speed control [6-13]. In some cases, two phase angles were used as inputs, and the two adjacent phase currents were outputs and using torque error, it was possible to produce the desired torque value. In other cases, speed error was used as input and the reference current as output, which was modulated by subtracting the output of the fuzzy system from the sum of four phase currents computed at the previous sampling period as given in [14-17]. The modulated current was then fed into the phase windings of the motor through a converter, thus maintaining the speed constant and reducing the torque ripples. But due to the fact that both torque and speed are independent mechanical variables, in real life this technique might have drawbacks. Other control techniques include using a neuro-fuzzy compensator such as in [18-20] where a compensating signal was added to the output of the proportional integral (PI) controller in the current regulated speed control loop. Although the practicality of the idea is questionable since the varying dynamic torque is difficult to measure.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

III. MODELING AND OPERATION

A 3-ϕ, 6/4 SR motor, a 2-switch per phase bridge converter topology and PID, Fuzzy-PID, Neural and Neuro-fuzzy controllers are chosen. A block diagram of this drive system is shown in Fig 3.1. The controller has an inner current control loop and an outer speed control loop. The speed controller generates a current command based on the error between the reference speed and the motor speed.

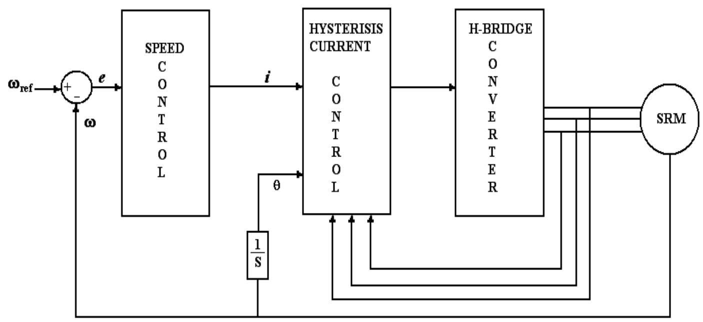


Fig 3.1: Block diagram of SR motor drive

A. Electromagnetic Equations

The instantaneous voltage across the terminals of a phase of an SR motor winding is related to the flux linked in the winding by faraday's law as

$$V = RI + \frac{d\Psi}{dt} \tag{3.1}$$

Where, V is the terminal voltage, I is the phase current, R is the phase resistance, and Ψ is the flux linked by the winding. Because of the double salience construction of the SR motor and the magnetic saturation effects, the flux linked in an SR motor phase varies as a function of rotor position θ and the phase current. Equation (1.1) can be expanded as

$$V = RI + \frac{\partial\Psi}{\partial I}\frac{dI}{dt} + \frac{\partial\Psi}{\partial\theta}\frac{d\theta}{dt} \tag{3.2}$$

Where, $\frac{\partial\Psi}{\partial I}$ is defined as the instantaneous inductance L (θ), and term $\frac{\partial\Psi}{\partial\theta}\frac{d\theta}{dt}$ is the instantaneous back e.m.f.

B. Torque Equation

The SR motor can be described by a convex function that only depends on the rotor position θ and currents in the 'n' phases $I = (I_1, I_2 \ldots I_n)^t$. This function is the co-energy W (I,θ). In a similar manner, the function energy W (Ψ,θ), whose variables are the fluxes of 'n' phases $\Psi = (\Psi_1, \Psi_2 \ldots \Psi_n)^t$ and the rotor position also permits to describe the SR motor. Whatever are the vectors Ψ and I the functions of co-energy, verify the following inequality condition:

$$\overline{W}(I,\theta) + W(\Psi,\theta) \geq \Psi^t I \tag{3.3}$$

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

Because of Doubly saliency the SR motor can have a variation of the magnetic energy and therefore torque production. The partial derivative of the energy function in relation to the rotor position gives the machine torque T,

$$T(\Psi_1 \ldots \Psi_n, \theta) = \frac{\partial W}{\partial \theta}(\Psi_1, \Psi_2 \ldots \Psi_n, \theta) \quad (3.4)$$

Applying this relation to 6/4 SR motor,

$$T(\Psi_1, \Psi_2, \Psi_3) = \frac{\partial W}{\partial \theta}(\Psi_1, \Psi_2, \Psi_3, \theta) \quad (3.5)$$

When energizes one phase, the torque appears so that the rotor evolves in the direction where the inductance increases. Therefore, the torque will be in the direction of the nearest aligned position. The Fig.3.2, shows the linear inductance profile L (θ) with each phase inductance displaced by an angle θ_S given by

$$\theta_S = 2\pi\left(\frac{1}{N_r} - \frac{1}{N_s}\right) \quad (3.6)$$

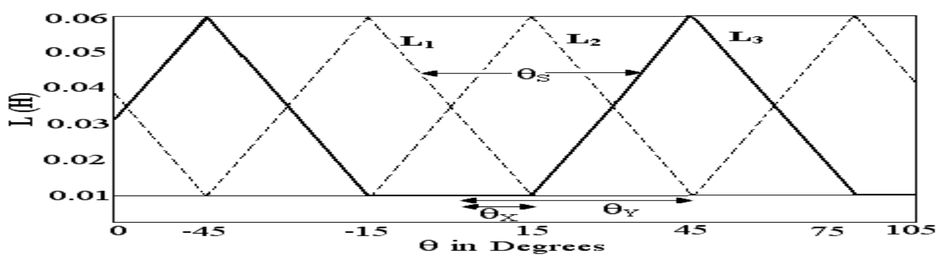


Fig.3.2: Linear phase Inductance profile of each phase

Where, N_r and N_s are the number of rotor and stator poles, respectively. When the motor has equal rotor and stator poles, $\beta_r = \beta_s$, one has the following angle relations.

$$\theta_X = \left(\frac{\pi}{N_r} - \beta_r\right), \quad \theta_Y = \left(\frac{\pi}{N_r}\right) \quad (3.7)$$

The parameters used for 6/4 SR motor are as follows: Three phase, 600 W, 150 V, 15 A, 187 rad/sec, 3 N-m, R = 1.3Ω, L_{max} = 60 mH, L_{min} = 8 mH, J= 0.0013, B= 0.0183 and $\beta_r = \beta_s = 30^o$. Thus, from electric equation of each phase is given by

$$\frac{d\psi_i(\theta, I_i)}{dt} + R\, I_i = V \qquad \text{with } i = \{1, 2, 3\} \quad (3.8)$$

While excluding saturation and mutual inductance effects, the flux in each phase is given by the linear equation

$$d\Psi_i(\theta, I_i) = L(\theta) I_i \quad (3.9)$$

The total energy associated with the three phase (n=3) is given by

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

$$W_{Total} = \frac{1}{2}\sum_{i=1}^{3} L\left(\theta + (n-i-1)\theta_S\right) I_i^{2}$$

(3.10)

The motor total torque is given by

$$T = \frac{1}{2}\sum_{i=1}^{3} \frac{dL\left(\theta + (n-i-1)\theta_S\right)}{d\theta} I_i^{2}$$

(3.11)

The mechanical equations are

$$J\frac{dw}{dt} = T - T_L - f\omega \quad \& \quad \frac{d\theta}{dt} = \omega$$

(3.12)

Where T_L represents the load torque and f is the machine friction coefficient.

C. H-Bridge Converter

A fault in one phase of the motor or in the converter generally affects only the flawed phase and other phase can continue to operate independently. Therefore, uninterrupted operation of the motor drive is possible with reduced power output. The maximum control and flexibility is obtained with the H-bridge asymmetric type converter shown in Fig.3.3. Each phase has two insulated gate bipolar transistors (IGBTs) and two diodes. The number of semiconductors is the same as for an inverter of a synchronous machine. However, the structure is completely different. One can also notice that it is not possible to short-circuit the source because the resistance of the coils limits the current.

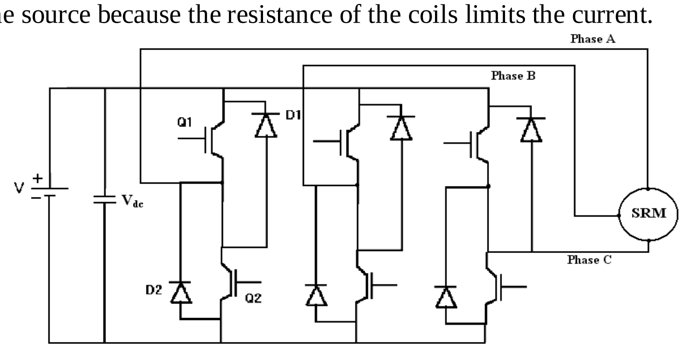


Fig.3.3: H-Bridge Asymmetric Converter

IV. CONTROLLER DESIGN

The speed control of switched reluctance motor is performed using conventional PID, fuzzy, fuzzy-PID, ANN, Neuro-Fuzzy controller. The speed of the motor can be controlled to any desired value at different loading conditions. The controller of the motor will work satisfactorily. Simulation results and performance of the system are obtained.

A. Performance of the Conventional PID Controller in SRM

The control performance of the SR motor drives is simulated with change in reference speed and load disturbance. The parameter of the PID controller are chosen as $K_P = 10$, $K_i = 8$ and $K_d = 0.5$ by trial and error, to give the best responses. The quantitative criteria for measuring the performance are chosen as Integral Absolute Error (IAE) and Integral of Time

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

Weighted Absolute Error (ITAE). The closed loop control of dc drive system is shown in Fig 4.1. The power circuit consists of a H-Bridge asymmetric converter that drives the switched reluctance motor. The circuit has an inner current control loop and an outer speed control loop. The speed controller is designed in such way to track the variation in load. The current loop is used to generate the control signal V_d to motor.

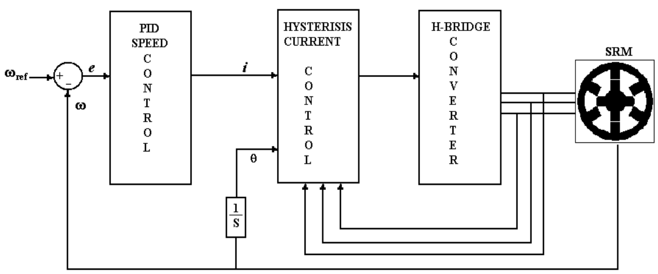


Fig 4.1 Block Diagram of Closed Loop Conventional Controller

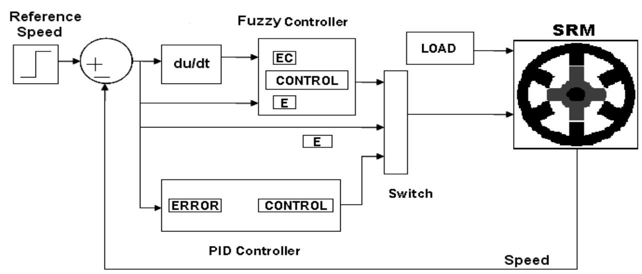


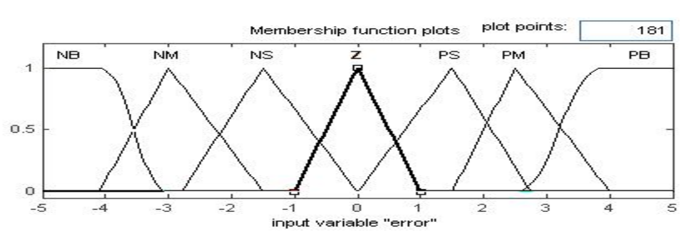
Fig 4.2 Block Diagram of the FUZZY_PID Compound Control

B. Design of FUZZY-PID for the Switched Reluctance Motor

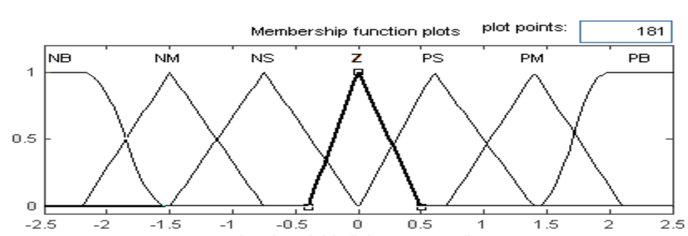
The objective is to design the FUZZY-PID controller to maintain the speed of the SR motor at the desired set points and to introduce step change and load disturbances in operating point, and observe the performance of the controller. The conventional controller is replaced by the FUZZY-PID compound controller for the satisfactory operation in maintaining the set points of speed in occurrences of system disturbance of more than 10%. The block diagram of the FUZZY-PID compound controller is shown in Fig 4.2.

i) FUZZY-PID compound control Simulation

One of the possibilities of rules of the fuzzy system for 7 X 7 Membership function (input/output) is shown in table. Figure shows the membership function for error, change in error and output of the FLC system design. The triangular with Z and S membership function are used for controller design. These rules are used to create the fuzzy logic controller for controlling the error to maintain speed at desired set point. Based on the rules given in table the fuzzy controller is created in MATLAB. Fig 4.3 shows the membership for error, change in error and output and Table 4.1 shows the fuzzy rule base matrix.



(a)



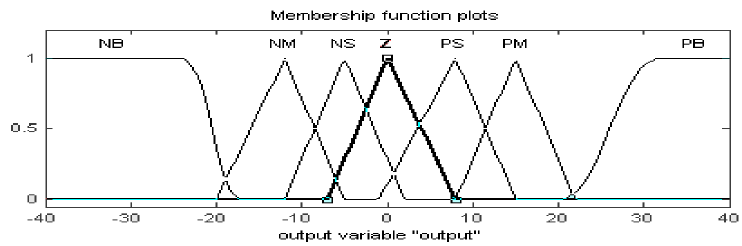
(b)

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014



(c)

Fig 4.3 Membership function for (a) error, (b) change in error and (c) Output

TABLE 3.1: Rule base

CE \ E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NM	NS	Z	PS	NB	NB
NS	NM	NS	Z	PS	PM	NB	NM
Z	NS	Z	PS	PM	PB	NB	NS
PS	Z	PS	PM	PB	PB	NS	Z
PM	PB	PM	PB	PB	PB	Z	PS
PB	PM	PB	PB	PB	PB	NB	NB

C. Design of Neural network controller for SR Motor

The control system of SR motor using ANNs is presented in the Fig 4.4, where Neural Speed controller ANN1 and Neural Current controller ANN2 are trained to emulate a function: ANN1 to estimate the speed, ANN2 to control terminal voltage.

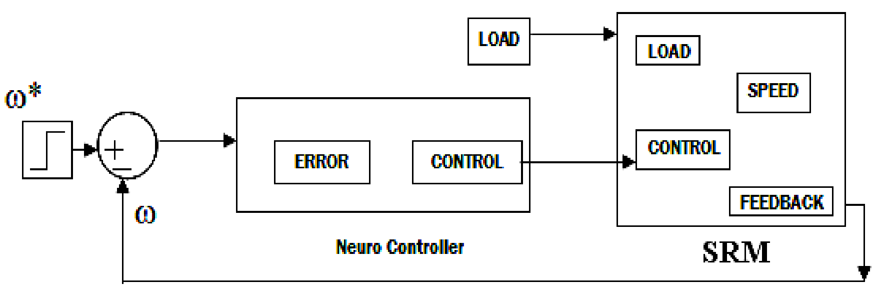


Fig 4.4 Block Diagram of SR Motor Using Neural Network Controller

D. Adaptive Neuro-Fuzzy Inference System (ANFIS)

The fuzzy logic provides an inference mechanism under cognitive uncertainty; computational neural networks offer exciting advantages, such as learning, adaptation, fault-tolerance, parallelism and generalization. This leads to the following three steps in a fuzzy neural computational process:

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

i) Development of fuzzy neural models motivated by biological neurons,
ii) Models of synaptic connections which incorporates fuzziness into neural network,
iii) Development of learning algorithms (that is the method of adjusting the synaptic weights).

V SIMULATION RESULTS

The step changes Speed from 140 rad/sec to 135 rad/sec is applied for PID Controller as shown in Fig 5.1 and 120 rad/sec to 130 rad/sec for FUZZY-PID Controller as shown in Fig 5.2 are introduced and the performance of both PID controller and FUZZY-PID are observed. The Simulation results demonstrate the comparable steady state performance. From the simulation results, it is clearly seen that the speed response of the FUZZY-PID compound control is slightly better than PID controller and FUZZY-PID response quickly even for a small change in speed and attains the set speed earlier than conventional PID controller.

Further for the comparable steady state performance, the simulation results are obtain from ANN and ANFIS, it is clearly seen that the speed response using ANFIS controller as shown in Fig 5.3 settles earlier than ANN control as shown in Fig 5.4. The error response of ANFIS control in Fig 5.5 is better than ANN control Fig 5.6 and also ANFIS settle earlier than ANN. Hence the ANFIS compound control is slightly better than ANN controller and ANFIS response quickly even for a small change in speed and attains the set speed earlier than ANN controller. Current Distribution and Inductance Distribution for PID Controller is shown in the Fig 5.7 which explains that the distortion increases at the initial stage and the Current Distribution and inductance distribution for FUZZY_PID Controller shown in Fig 5.8 which explains that the distortion decreases at the initial stage. Similarly for Current Response and Inductance Distribution of ANN Controller and Current Response and Inductance Distribution of ANFIS Controller are shown in Fig 5.9 and 5.10.

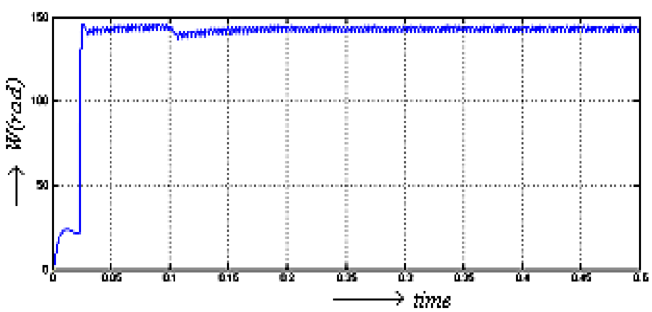


Fig 5.1 Speed Change Response of PID Controller

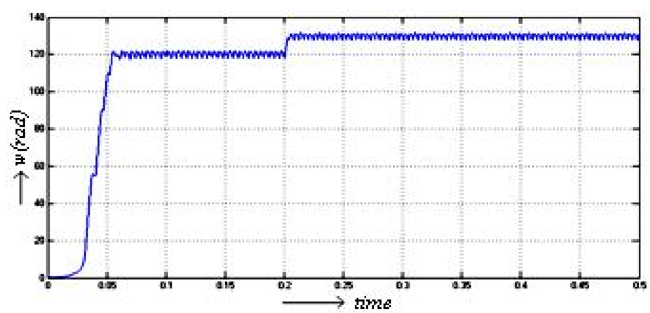


Fig 5.3 Speed Change Response of ANN Controller

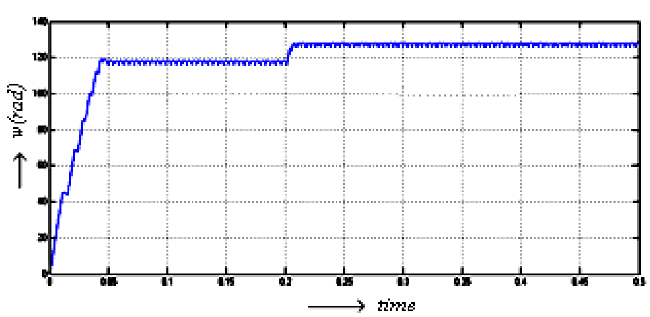


Fig 5.2 Speed Change Response of FUZZY_PID Controller

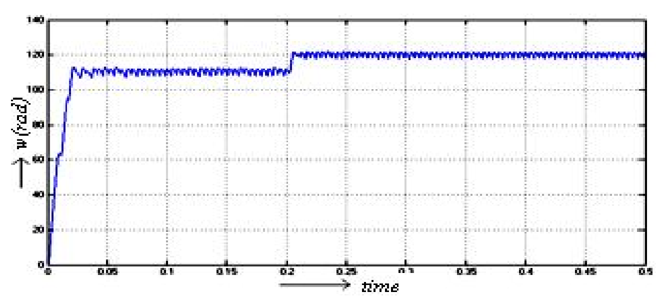


Fig 5.4 Speed Change Response of ANFIS Controller

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

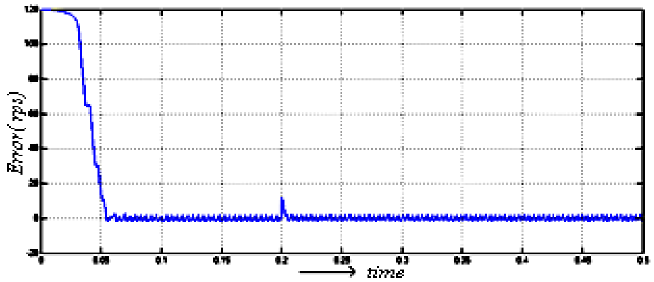


Fig 5.5 Error Response for ANN Controller

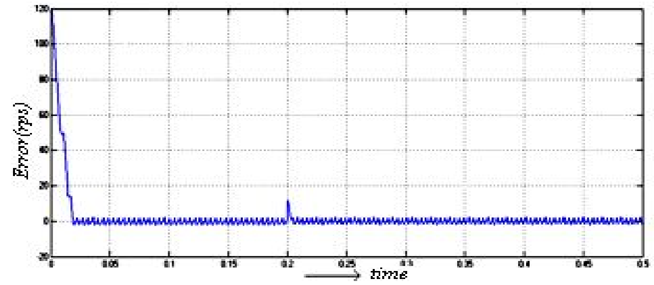
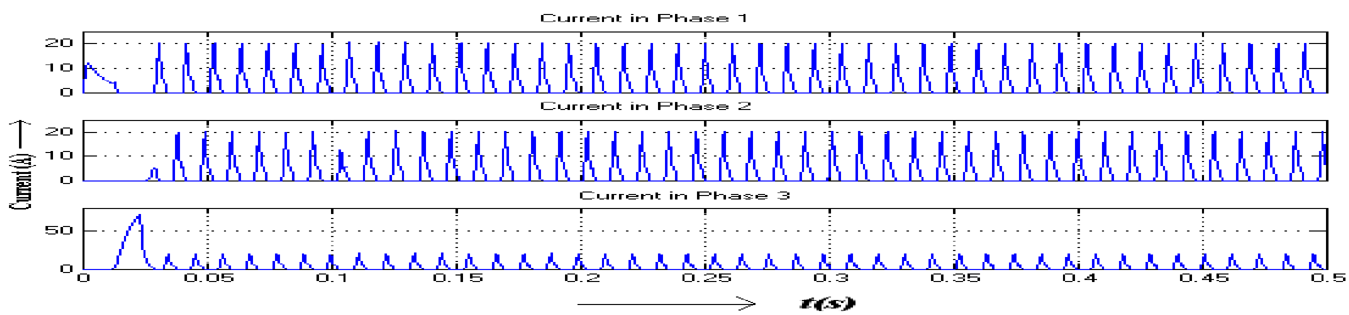
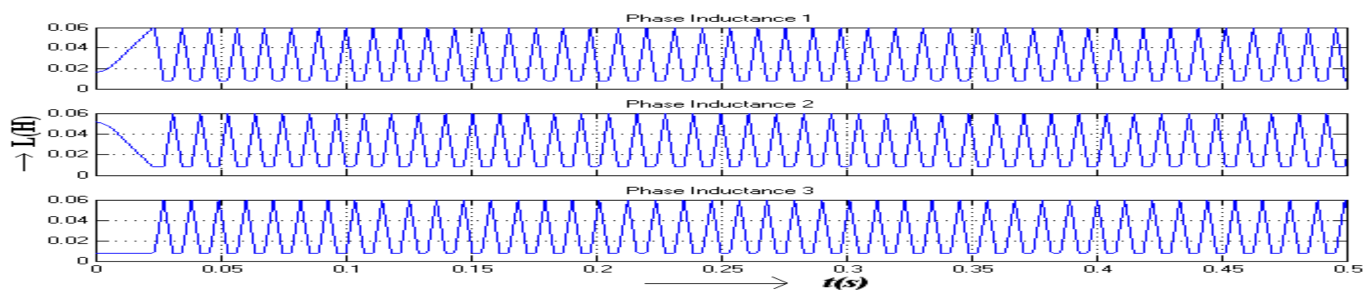


Fig 5.6 Error Response for ANFIS Controller

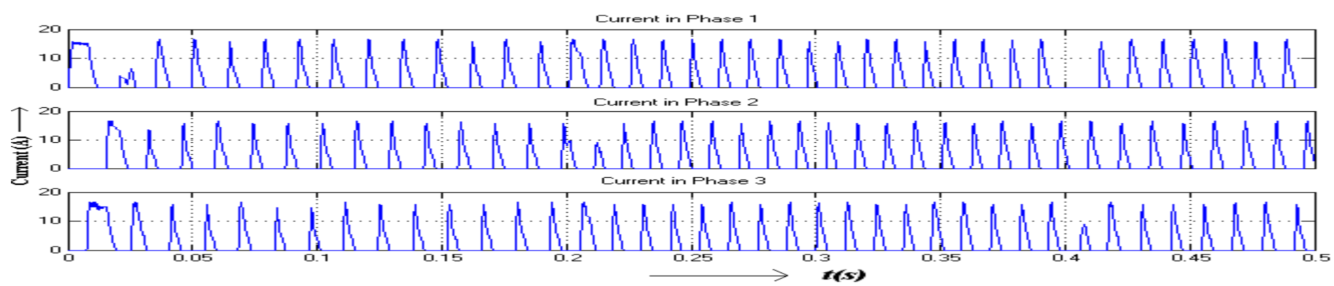


(a)



(b)

Fig 5.7 (a) Current Response and (b) Inductance Response of PID Controller



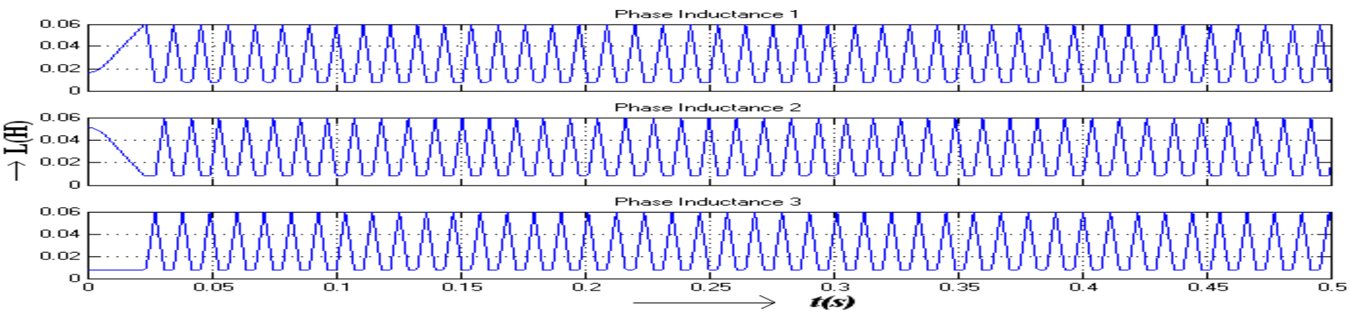
(a)

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

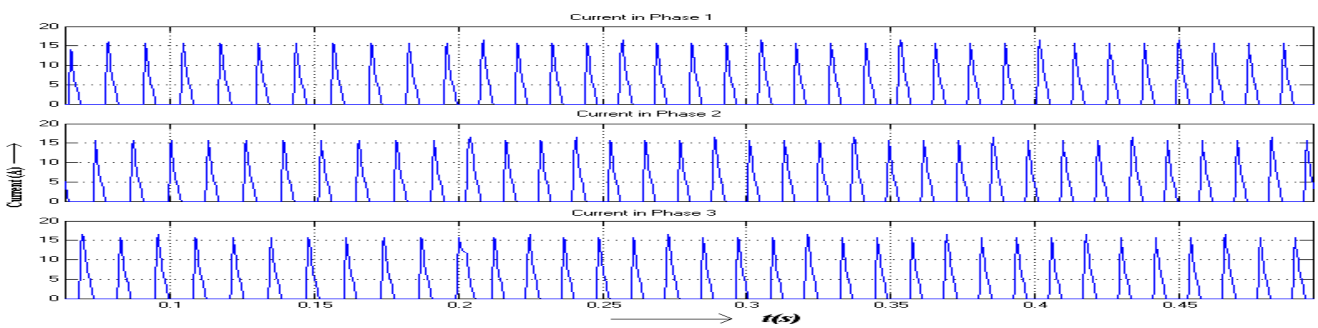
(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

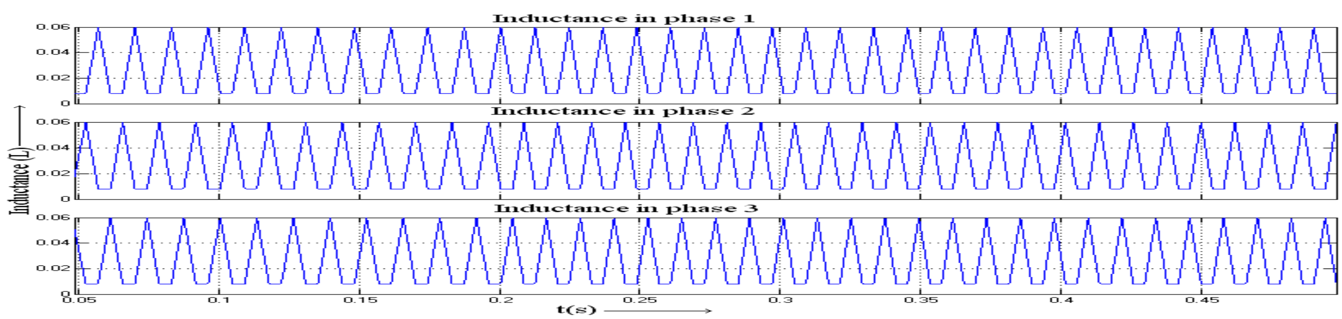


(b)

Fig 5.8. (a) Current Response and (b) Inductance Response of FUZZY_PID Controller



(a)



(b)

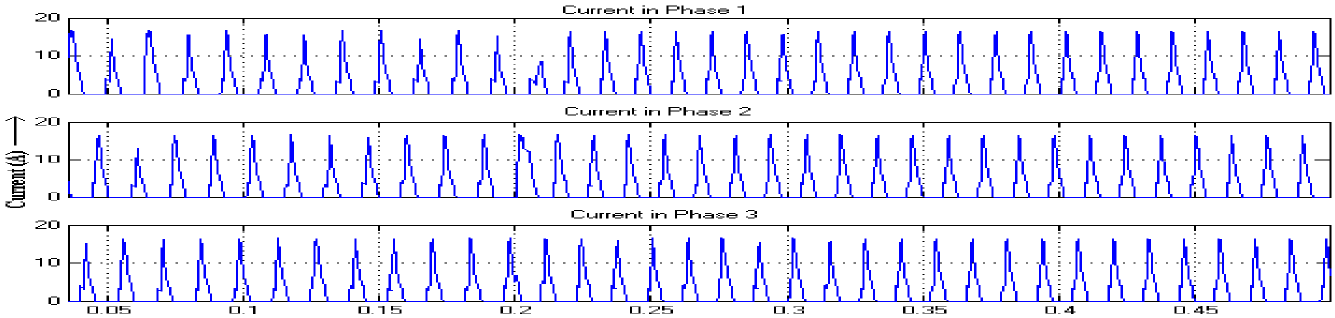
Fig 5.9: (a) Current Response and (b) Inductance Response of ANN Controller

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

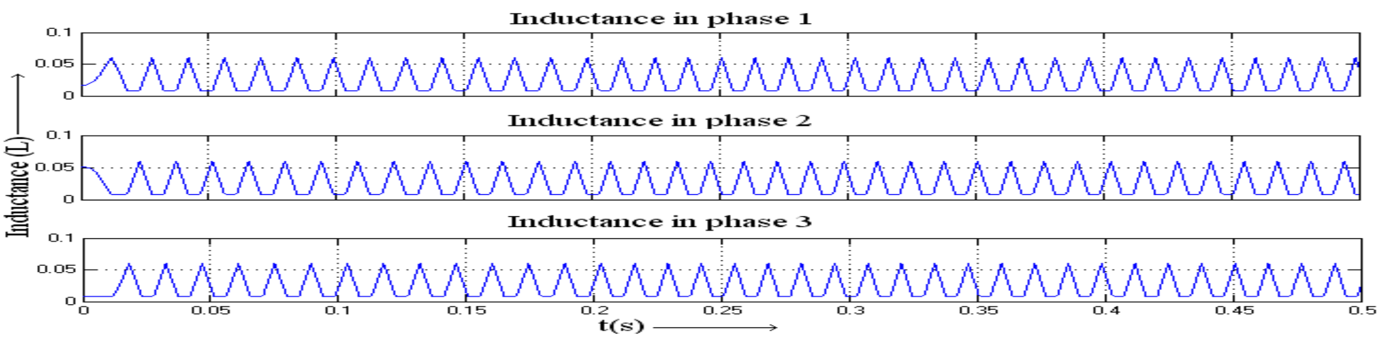
International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014



(a)



(b)

Fig 5.10: (a) Current Response and (b) Inductance Response of ANFIS Controller

VI. CONCLUSION

The various speed control of SRM with conventional PID, Fuzzy, Neural network and Neuro-fuzzy controllers are used and compared. Since PID controller is linear control its parameters not only need to be turned according to frequency characteristic curves of the controlled device. To overcome this demerit, Fuzzy-PID controller is proposed. When the error is big, fuzzy controller is used to accelerate the speed of dynamic response, and when the error is small, PID controller is used to enhance the steady-state accuracy of the system. It is observed that the Neuro-fuzzy controller is more flexible and also its response is comparatively faster. Hence it may be concluded that with Neuro-fuzzy controller, speed settles faster, having smooth response and the dynamic behavior of the motor has been improved, with no overshoot and a good rejection of impact load disturbance, thus leading to a better performance and higher robustness

REFERENCES

[1] R. Krishnan: Switched reluctance motor drives modeling, simulation, analysis, design and applications, London, CRC Press, 2001.
[2] T.J.E. Miller: Switched reluctance motors and their control, Oxford University Press, 1993.
[3] F. Soares and P.J. Costa Branco : "Simulation of a 6/4 Switched Reluctance Motor based on Matlab/Simulink Environment, Aerospace and electronic system", *IEEE* Transactions, Vol.37, pp. 989-1009, July 2001.
[4] Weiguo Liu, Shoujun Song, "Application of Fuzzy Control in Switched Reluctance motor Speed Regulating System" *IEEE* Conference on Control and Automation, 2006
[5] L. Szabó, M. Ruba, "On fault tolerance increase of switched reluctance machines", Proceedings of the IEEE Region 8 EUROCON Conference (EUROCON '2009), St. Petersburg (Russia), 2009, pp. 734-739.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 5, May 2014

[6] M. Hajatipour, M. Farrokhi, "Adaptive intelligent speed control of switched reluctance motors with torque ripple reduction", Energy Conversion and Management, vol. 49 (2008), pp. 1028–1038.
[7] R.Gobbi, K. Ramar, N.C. Sahoo, "Fuzzy Iterative Technique for Torque Ripple Minimisation in Switched Reluctance Motors", Electric Power Components and Systems, vol. 37, pp. 982–1004, 2009.
[8] A.Tahour, H. Abid, A.G.Aissaoui, "Adaptative Neuro-Fuzzy Controller of Switched Reluctance Motor", Serbian Journal of Electrical Engineering, vol. 4, no. 1 (June 2007), pp. 23-34.
[9] N.C. Sahoo, J.K. Xu, S.K. Panda, "Low torque ripple control of switched reluctance motors using iterative learning," IEEE Trans. Energy Conversion, vol. 16, no. 4, pp. 318–326, 2001.
[10] D.S. Reay, M. Mirkazemi, "On the appropriate uses of fuzzy systems: fuzzy sliding mode position control of a switched reluctance machine", Proc IEEE Conf. Ind. Appl., Monterey, pp. 371–376, 1995.
[11] S.G.Cao and N.M.Rees, "Analysis and design of Fuzzy Control Systems", IEEE conference on Fuzzy Systems, 1995, pp.317-324.
[12] S.Bolognani and M. Zigliotto, "Fuzzy logic control of a switched reluctance motor drive," *IEEE Trans.* Industry Applicat., vol. 32, pp. 1063–1068, Sept./Oct.1996.
[13] Simoes M.G, Suemitsu W.I, Costa Branco P.J, Dente J.A, Rolim L.G (1997), "Fuzzy Logic control for a Switched Reluctance Motor", *IEEE Transactions* on Aerospace and Electronic System, vol.37, No.3, 2001, pp.989-1009.
[14] D.S. Reay, M. Mirkazemi - Mous, T.C. Green, B.W. Williams, "Switched Reluctance Motor Control via Fuzzy Adaptive Systems", IEE Control Syst. Mag., vol. 15, no. 3, pp. 8-15, 1995.
[15] Virendra Kumar Sharma, Bhim Sing, S.Murthy, A. Chandra, K.Al-Haddad, "Performance Analysis of Fuzzy Logic Based Speed Controller for Switched Reluctance Motor Drive", *IEEE* Transaction on Industry Application, 1997, pp.373-379.
[16] C.T. Lin, C.S.G. Lee: Neural fuzzy systems: A neuro-fuzzy synergism to intelligent systems, Upper Saddle River, Prentice-Hall, 1996.
[17] Kelvin self (1990), "Designing with Fuzzy Logic", *IEEE* spectrum, Vol.42, No- 44,105.
[18] A. Derdiyok, N. Inanc, V. Ozbulur, Y. Ozoglu, "Optimal phase current profiling of SRM by fuzzy logic controller to minimize torque ripple," Proceedings of the 1997 IEEE International Symposium on Intelligent Control, vol. 1, pp. 77–82, Istanbul (Turkey), 1997.
[19] J.S.R. Jang ANFIS: Adaptive-network-based fuzzy inference system, *IEEE* Trans Syst. Man. Cybernet, 1993; 23(3), pp. 665-85.
[20] Radun.A.V (1995), "Design Considerations for the Switched Reluctance Motor", *IEEE* Trans. On Industry Applications, vol. 31, no. 5, pp.1079-1087.