Speed Control of Switched Reluctance Motor Using an Adaptive Neuro-fuzzy Controller

Hany M. Hasanien

Abstract—**This paper presents an adaptive neuro-fuzzy controller (ANFC) for the switched reluctance motors (SRM). The proposed controller is used for speed control of this type of motors. The dynamic response of the SRM with the proposed controller is studied during the starting process and under different disturbances. The effectiveness of the proposed ANFC is then compared with that of the conventional proportional-integral (PI) controller.**

***Index Terms*—Adaptive neuro-fuzzy controller, speed control, switched reluctance motor.**

I. Introduction

The switched reluctance motor (SRM) drives are considered to be attractive solutions for variable speed applications with high power density. The SRM possesses many inherent advantages such as simplicity, robustness, low manufacturing cost, high starting torque, high speed, and high efficiency [1]-[7]. On the other hand, the stator winding is concentrated and no winding, no brushes on the rotor, as shown in Fig. 1. The rotor has segments which constitute flux guides that serve to bend the flux produced by current flowing in a coil winding in a stator slot around the slot and back towards the periphery of the rotor. Maximum inductance is realized when a flux guide of the rotor is aligned with each such slot. Minimum inductance occurs when the flux guides are out of alignment with the slot conducting current and aligned with an adjacent slot. In addition to this, only simple converter circuits with reduced number of switches due to unidirectional current requirements are needed.

These advantages make this type of motors a competitive choice to both the dc series motor and the squirrel cage induction motor. The SRM can be used for general purpose industrial drives. The motor ability to operate in the four quadrants and its suitability for hazardous areas open a wide range of applications for switched reluctance motor drives including mining, explosion proof machinery, traction and domestic applications. Recently, a good deal of the research work focus on the SRM control and torque smoothness in order to make it a competitor to both fully controlled dc and ac drives. In this paper an adaptive neuro-fuzzy controller is presented for speed control of that motor.

The author is with the Saudi Aramco Chair of Electrical Power, Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia, 11421, (e-mail: hanyhasanien@ieee.org).

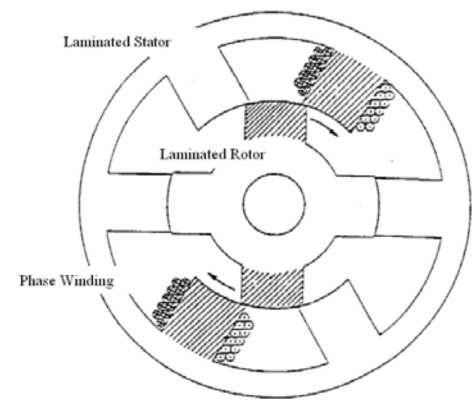

Fig. 1. Construction of a 3 phase, 6/4 SRM.

II. Dynamic Model of SRM

The mathematical model of the SRM consists of three basic groups of equations:-

1- The motor phase equations.
2- The mechanical equation.
3- The angular speed equation.

The motor phase equations which describe the electrical behavior of the SRM are defined as follows:

$$\frac{d\psi_k(\theta_k, i_k)}{dt} = \pm V - R.i_k \tag{1}$$

where ψ_k is the phase k flux linkage as a function of the current and the rotor position, V is the supply voltage, R is the winding resistance per phase, and i is the phase current.

The mechanical equation which describes the mechanical motion of the motor is defined as follows:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{k=1}^{q} T_k(\theta_k, i_k) - T_l\right) \tag{2}$$

where ω is the rotor speed, J is the moment of inertia of both the rotor and load, T_l is the load torque, q is the number of phases, $T_k(\theta_k, i_k)$ is the torque produced by the K^{th} phase and θ_k is the rotor position as seen by the K^{th} phase. The angular speed equation is defined as follows:

$$\omega = \frac{d\theta}{dt} \tag{3}$$

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

The equations representing the dynamic model of SRM are solved simultaneously using a Numerical integration technique with the aid of the motor look up tables.

III. SPEED CONTROL WITH THE PROPOSED CONTROLLER

The system under study is shown in Fig. 2. It consists of the SRM provided with its controlled power supply. The data of the motor is given in the appendix. The drive is tested under the following condition. First the motor is started against its full load torque until the motor reaches rated steady state speed (2000 rpm). Then, the motor is subjected to a speed reference disturbance where the reference speed is suddenly increased to 2250 rpm, followed by another suddenly increase of the reference speed disturbance to 2500 rpm.

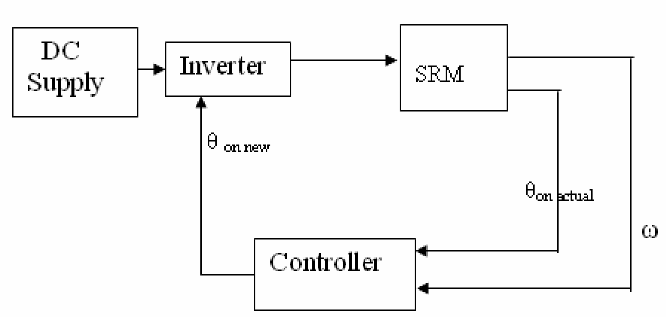

Fig. 2. Block diagram for speed control of SRM using ANFC.

IV. THE PROPOSED ANFC

The combination of neural networks and fuzzy logic control plays very important role in the advanced control techniques. However, it adheres with many advantages such as flexible, accurate and robust controller.

In this study, the proposed neuro-fuzzy controller presents a fuzzy logic controller with self tuning scaling factors based on artificial neural network structure as shown in Fig. 3. Firstly the fuzzy logic control rules are described then NN architecture is represented to self tune the output scaling factor of the controller.

The actual speed v or ω is compared with the reference speed v_{ref} to yield the speed error e(t). The incremental change of speed error Δe(t) can be expressed as follows:

$$\Delta e(t) = e(t) - e(t-1) \tag{4}$$

The proposed controller has two input scaling factors of gains G_e and $G_{\Delta e}$ and also one output scaling factor of gain $G_{\Delta u}$. The output signal of the input scaling factors can be written as follows:

$$\Delta e_N(t) = \Delta e(t).G_{\Delta e} \tag{5}$$

$$e_N(t) = e(t).G_e \tag{6}$$

The output signal of the input scaling factors e_N and Δe_N are considered to be the inputs of the fuzzy logic controller (FLC). The output signal of FLC Δu_N is the input of the output scaling factor. The neural network (NN) structure has two inputs e(t) and Δe(t). The output signal α of NN controller is used to fine tune the output scaling factor. The output signal of output scaling factor can be represented by the following equation:

$$\Delta u(t) = \Delta u_N(t).\alpha.G_{\Delta u} \tag{7}$$

The only output signal of neuro-fuzzy controller u(t) can be written as follows:

$$u(t) = \Delta u(t) + u(t-1) \tag{8}$$

For the FLC, the membership functions were defined off-line, and the values of the variables are selected according to the behavior of the variables observed during simulations. The selected fuzzy sets for FLC are shown in Fig. 4. The control rules of the FLC are represented by a set of chosen fuzzy rules. The designed fuzzy rules used in this work are given in Table 1. The fuzzy sets have been defined as: NL, negative large, NM, negative medium, NS, negative small, ZR, zero, PS, positive small, PM, positive medium and PL, positive large respectively.

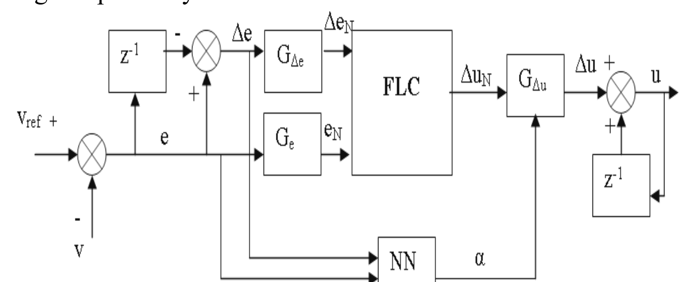

Fig. 3. Block diagram of adaptive neuro-fuzzy controller.

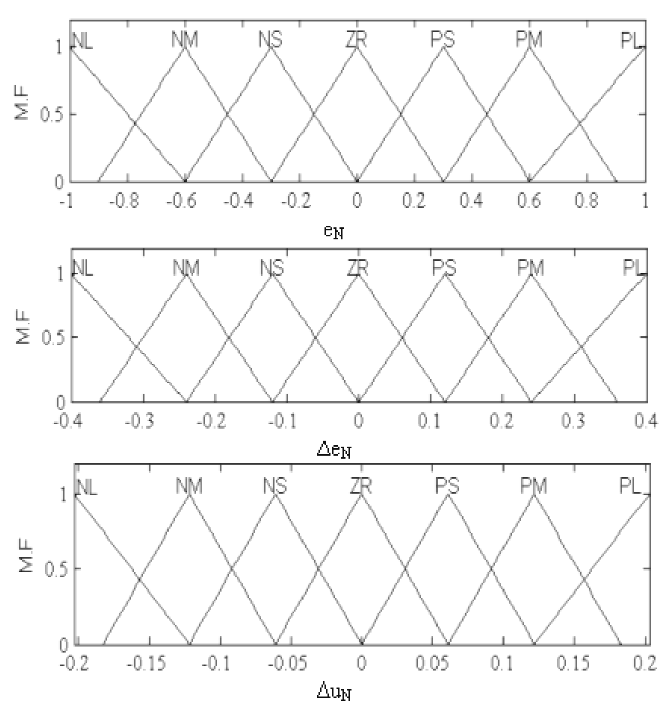

Fig. 4. The membership functions of FLC.

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE 1. RULES OF FLC.

		e_N						
		NL	NM	NS	ZR	PS	PM	PL
Δe_N	NL	PL	PL	PM	PM	PS	PS	ZR
	NM	PL	PM	PM	PS	PS	ZR	NS
	NS	PM	PM	PS	PS	ZR	NS	NS
	ZR	PM	PS	PS	ZR	NS	NS	NM
	PS	PS	PS	ZR	NS	NS	NM	NM
	PM	PS	ZR	NS	NS	NM	NM	NL
	PL	ZR	NS	NS	NM	NM	NL	NL

On the other hand, for NN structure, a three layer feed forward neural structure with 2 × 3 × 1 (2 inputs, 3 hidden, and 1 output) is used in our study as shown in Fig. 5. The input nodes were selected as equal to the number of input signals and the output nodes as equal to the number of output signals. The number of hidden layer neurons is generally taken as the mean of the input and output nodes. In this NN structure, 3 hidden neurons were selected. The inputs are consisted of the speed error e(t), and the change in speed error Δe(t). The output of the NN is the signal α, which has certain value between -1 and +1 [8].
The activation function of the nodes in the hidden layer is:

$$f(x) = \frac{1-e^{-x}}{1+e^{-x}} \tag{9}$$

The activation function of the output layer neuron is chosen to be as follows:

$$h(x) = \frac{1}{1+e^{-x}} \tag{10}$$

The output signal of the neuro-fuzzy controller *u(t)* after being rescaled is used to modulate the motor phase switching on angle. The advanced switching-on angle θ_{onnew} can be written as follows:

$$\theta_{onnew} = \theta_{oninitial} - k.u \tag{11}$$

where $\theta_{oninitial}$ is the initial switching on angle, and k is a constant.
In addition, the NN structure can be established to fine tune the input scaling factors but the controller will be very complex and also its effect on transient stability is low. Therefore, in this study, one NN structure is used to fine tune the output scaling factor.

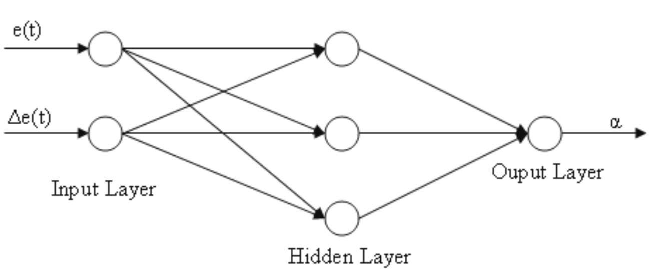

Fig. 5. Block diagram of NN structure.

V. PERFORMANCE EVALUATION

The SRM is tested with the same conditions stated before in section 3. For a good motor performance, the design requirements will be as follows:
The maximum overshooting is very small and tends to zero, the rise time is less than or equal to 0.02 sec, and the settling time is less than or equal to 0.04 sec. Therefore, according to these requirements the damping ratio ζ equals 0.6, the undamped natural frequency ω_n is 180 rad/sec, the damped frequency ω_d is 144 rad/sec.

Fig. 6, shows the speed response of the motor during the starting process and disturbances when provided with the ANFC as compared with the PI controller of gains $k_p = 10$ and $k_i = 0.5$, where these values represent the optimal values of the PI controller parameters. By inspection of the dynamic response, it can be realized that the dynamic response of the SRM when provided with the ANFC is improved compared with that obtained when the motor is provided with the PI controller. The response is fast with minimum overshoots.

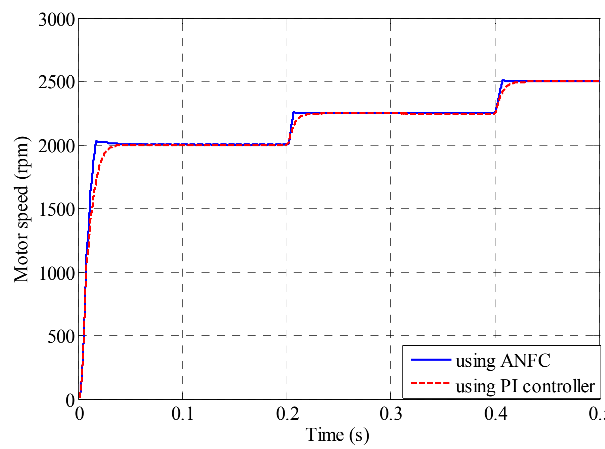

Fig. 6. The dynamic response of the motor during the starting and disturbances driven by the ANFC as compared with the PI controller.

VI. CONCLUSION

This paper had presented a novel adaptive neuro-fuzzy controller to ensure excellent reference tracking of the switched reluctance motor drives. The proposed controller is found to enhance the speed regulation of this type of drives over both starting and reference speed disturbance periods. The response is found to be superior to that corresponding to the conventional PI controller.

ACKNOWLDGEMENT

The author would like to thank the Saudi Aramco Chair of Electrical Power, Electrical Engineering Department, College of Engineering, King Saud University for their support.

APPENDIX

The motor under study is a three phase, SRM, the rated power is 4 kW at 2000 rpm. The phase resistance is 0.1 Ω, the motor inertia is 0.0012 kg.m^2 and the DC supply voltage = 360 V.

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

REFERENCES

[1] Hassan Moghbelli, Gayle E.Adams and Richard G. Hoft, "Performance of a 10-HP switched reluctance motor and comparison with induction motors", *IEEE Transactions on Industry Applications*, vol. 27, no. 3, May/June 1991.

[2] Nicholas J. Nagel and Robert D. Loranz, " Rotating vector method for torque control of switched reluctance motor drive," *IEEE Transaction of Industry Applications* vol. 36, no. 2, March/April 2000.

[3] Hany M. Hasanien, and S. M. Muyeen, "Speed control of grid-connected switched reluctance generator driven by variable speed wind turbine using adaptive neural network controller", *Electric Power Systems Research, Elsevier,* vol. 84, no. 1, pp. 206-213, March 2012.

[4] Eyhab El-Kharashi, and Hany M. Hasanien, "Reconstruction of the switched reluctance motor stator", *Journal of Electrical Engineering, Slovakia,* vol. 63. no. 1, pp. 1-10, January 2012.

[5] Hany M. Hasanien, S. M. Muyeen, and Junji Tamura, "Torque ripple minimization of axial laminations switched reluctance motor provided with digital lead controller", *Energy Conversion and Management, Elsevier,* vol. 51, issue 12, pp. 2402-2406, Dec. 2010.

[6] Hany M. Hasanien, S. M. Muyeen, and Junji Tamura, "Switched Reluctance Machine", Praise Worthy Prize Press, Napoli, Italy, ISBN 978-88-96329-02-3, Feb. 2010.

[7] Hany M. Hasanien, S. M. Muyeen, and Junji Tamura, "Speed Control of Permanent Magnet Excitation Transverse Flux Linear Motor by Using Adaptive Neuro-Fuzzy Controller", *Energy Conversion and Management, Elsevier,* vol. 51, issue 12, pp. 2762-2768, Dec. 2010.

[8] Hany M. Hasanien, N. H. Saad, M. A. Mostfa, and M. A. Badr, "Steady state performance of axial laminations switched reluctance motor" *in proceeding of the 11th international middle east power system conference (MEPCON 2006)*, El Minia University, Egypt.

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)