NEURO-FUZZY COMPENSATION OF TORQUE RIPPLE IN A SWITCHED RELUCTANCE DRIVE

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Abstract: Simple power electronic drive circuit and fault tolerance of converter are specific advantages of SRM drives, but excessive torque ripple has limited its application. This paper presents a novel method of controlling the motor currents to minimize the torque ripple, using a neuro-fuzzy compensator. In the proposed control concept, a compensating signal is added to the output of a classical PI controller, in a current-regulated speed control loop. The compensating signal is learned prior to normal operation, in a self-comissioning run, but the neuro-fuzzy methodology is also suitable for on-line self-learning implementation, for continuous improvement of the compensating signal.

1.- INTRODUCTION

Many authors [1-4] have proposed the dynamic control of a SR drive using fuzzy logic and neural networks. This type of control is today well established in the area of motion control and particularly in drive systems. Artificial intelligence-based fuzzy, neural and fuzzy-neural controllers have a number of advantages over conventional controllers [5], and even helping to incorporate some "intelligence" into them [13-17]. The most remarkable advantages for SR Drives are: no requirement of an accurate model; possibility of design based exclusively on linguistic information derived from experts or from the use of clustering techniques and capacity of incorporation of new data and information as they become available by learning mechanisms.

Fuzzy logic control of a SR drive has been implemented with success in [2], and has shown to be effective for the speed control in applications where some degree of torque ripple is tolerated, as is the case in many industrial applications. Nevertheless, in servo control applications or when smooth control is required at low speeds, the elimination of the torque ripple becomes the main issue for an acceptable control strategy. In this case, even using a fuzzy PI-like control as the one described in [2] is not satisfactory, because the controller's output signal, which is used as a reference signal for the current control in the power converter, gives rise to sustained torque pulsations in steady-state. Furthermore, this torque ripple changes with the speed of the SR motor and with the load applied to it.

2.- TORQUE PULSATION

With a PI-like control alone, it is not possible to obtain a ripple-free output speed at any speed range, because it would also require a ripple-free output torque, for this purpose. If it is supposed that the output speed is constant and equal to the reference speed in steady-state, then the PI controller's output signal (i.e. the reference current) would be constant. However, a constant current reference would produce an oscillating torque (Fig. 1), rendering the ripple-free speed control unfeasible. The simulation results shown in Fig. 1 correspond to the current-regulated, full-load operation of a 750W SR motor, at rated speed (1800rpm).

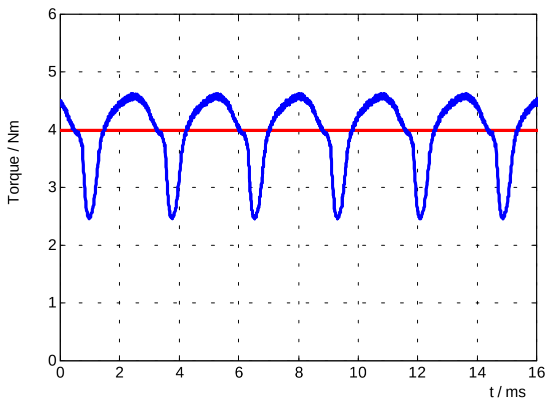


Figure 1 -Torque ripple produced by constant current reference signal (simulation).

At high speeds, the torque pulsations would occur at higher frequencies, thus causing less speed ripple, due to the natural filtering provided by the mechanical load inertia. Furthermore, SR drives are usually operated in single-pulse mode at high speeds, without current control. In this case, the most effective way of reducing vibrations caused by torque pulsation is by way of turn-off angle control.

At lower speeds, it is more convenient to compensate for the torque pulsations through phase current waveshaping. In this case, the current reference signal should vary as a function of position, speed and load torque, in order to produce the desired compensation. In fact, the optimum compensating signal is a highly non-linear function of position, speed and load. Several works [7-12] have been published, which use many different strategies to produce a compensating signal.. Some authors [8,10] use the inverse of the static torque-current-position relationship, which are tabulated previously and stored in memory. However, this method is quite laborious and sensitive to parameter variations.

In this work, a novel compensation method is proposed, which is based upon a self-tuning neuro-fuzzy compensator. The proposed compensation scheme is described in the next section.

3.- PROPOSED METHOD

Figure 2 presents a simplified block diagram of the SR-drive speed control system, showing the proposed neuro-fuzzy compensating scheme. The basic idea of the proposed method is illustrated in Fig. 3. The output signal produced by the compensator, I_{comp}, is added to the PI controller's output signal, I_{ref}, which should be ideally constant in steady-state but producing significant ripple, as shown in Fig. 3(a). The resulting signal after the addition is used as a compensated reference signal for the current-controlled SR drive converter, as shown in Fig. 3(b). The compensating signal should then be adjusted in order to produce a ripple-free output torque.

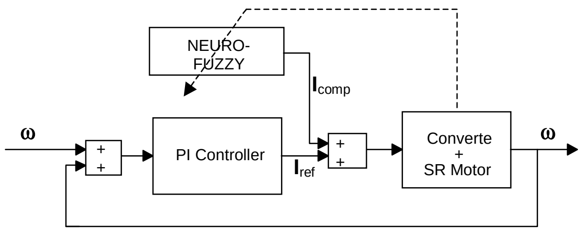
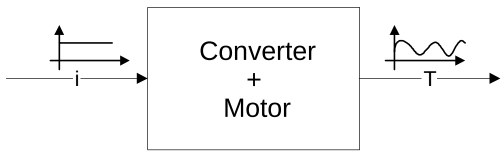
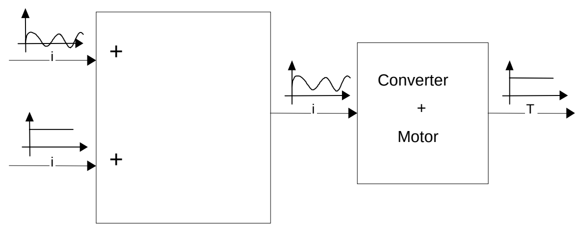


Figure 2 - Diagram of proposed compensation scheme.

The compensating signal is adjusted iteratively, through a neuro-fuzzy training algorithm, where the training error information is derived from some internal variable of the SR drive system. In the simulation tests, the torque ripple itself has been used as the training error variable, but this approach would not be very practical for on-line implementation in a real system, since the dynamic torque is a variable which is difficult to measure. For continuous on-line training, other variables could be more appropriate, such as acceleration or speed ripple. However, the torque could still be used directly in an off-line training system, e.g. for converter programming on a test rig at the factory.



(a)



(b)

Figure 3 - Basic idea of proposed compensation method: (a) torque ripple produced by constant current reference; (b) ripple-free torque produced by compensated reference.

3.- SIMULATION MODEL

The neuro-fuzzy compensator is a Sugeno-type fuzzy logic system with five fixed triangular membership functions for each input. The rotor angular position θ and the PI controller's output signal I_{ref}, are used as inputs to the compensator representing a relation as $\Delta I_{comp} = f(\theta, I_{ref})$.

The training procedure consists on whose adjusting the rule consequents by a hybrid training algorithm, which combines back-propagation and least-squares minimization . At each training iteration, the dc component is removed from the compensating signal, so that the ripple compensator does not try to change the mean value of the output torque. As a result, when the control system operates in steady-state, after the training, the PI controller will really produce a constant output signal, while the neuro-fuzzy compensator will produce a zero-mean-value compensating current reference, the ΔI_{comp} signal.

Training data are obtained from simulations of steady-state operation of the complete SR drive system. At each training iteration, the dc component is removed from the torque signal, so that just the ripple remains. This torque ripple data is then tabulated against the mean value of the PI output reference current, and against the rotor angular position. This data set is then passed to the training algorithm, so that the torque ripple is interpreted as error information for each current-angle pair. The output of the neuro-fuzzy compensator is then readjusted to reduce the error (which is in fact the torque ripple), being this process repeated until some minimum torque ripple limit is reached.

The choice of stopping criteria is very important for the stability of the method, since the converter may not be able to produce the required compensated currents at any speed or load. In this case, persisting on training may lead to output windup at the compensator.

4.- SIMULATION RESULTS

For comparison purposes, the drive system has been simulated without compensation, at full-load torque (approximately 4 Nm mean value), 500 rpm. The rated speed is 1800 rpm. The output torque signal is plotted in Fig. 4, and its harmonic components are shown in Fig. 5. The torque signal shown in Fig. 4 is produced by a constant current reference. As a result, the phase current pulses are flat-topped.

As the motor has a 6/4 structure, the converter produces 12 current pulses per rotor turn. So, the torque pulsations occur at a frequency 12 times higher than the frequency of rotation. For this reason, the harmonic spectrum shown in Fig. 5 exhibits non-zero components only for orders multiple of 12. The magnitudes of the harmonics are expressed as percentage of the mean value. It should be noticed that the first non-zero harmonic (12th) exhibits a quite high magnitude (approximately 13%).

After one training iteration, the harmonic content of the output torque is already significantly lower, as shown in Figures. 6 and 7. The 12th harmonic has a relative magnitude of only 3% approximately. In this situation, the compensated current reference produces phase current pulses which are no longer flat-topped, as will be shown afterwards.

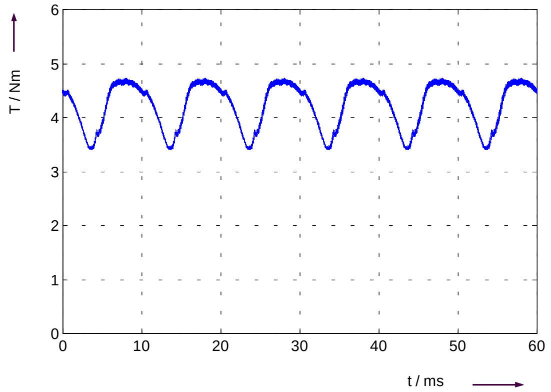


Figure 4 – Output torque for non-compensated (constant current reference) operation at 500 rpm.

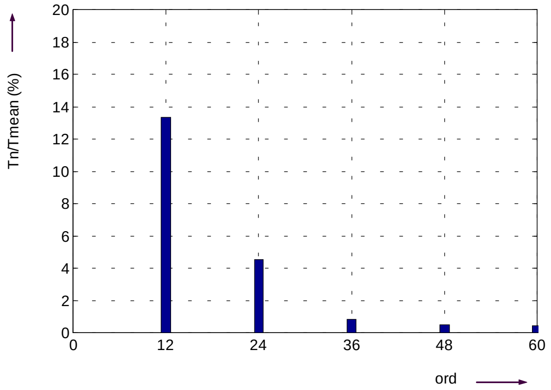


Figure 5 – Harmonic content of non-compensated torque signal of Fig. 4.

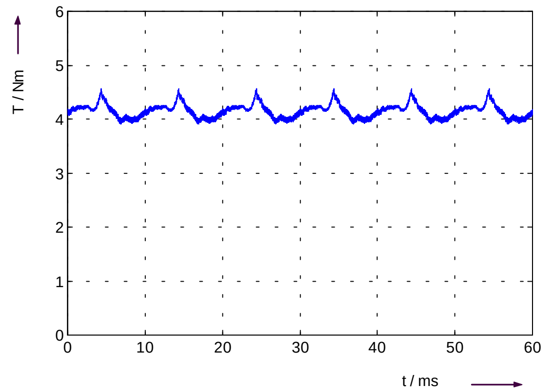


Figure 6 – Compensated torque after first iteration.

Figures 8 and 9 show the output torque waveform and its harmonic content for a compensated current reference after 10 training iterations. It can be seen that the total harmonic content is very low, and the 12th harmonic is lower than 0.5% of the mean torque.

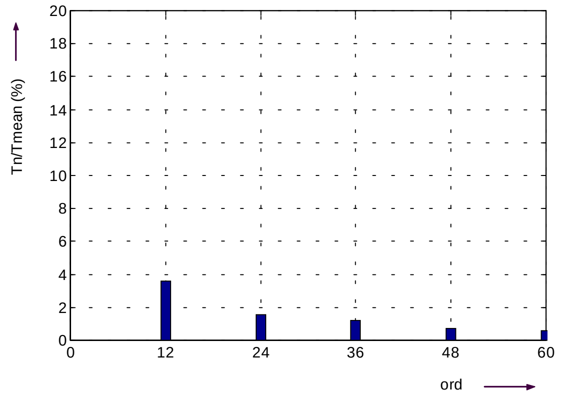


Figure 7 – Harmonic content in torque signal of Fig. 6.

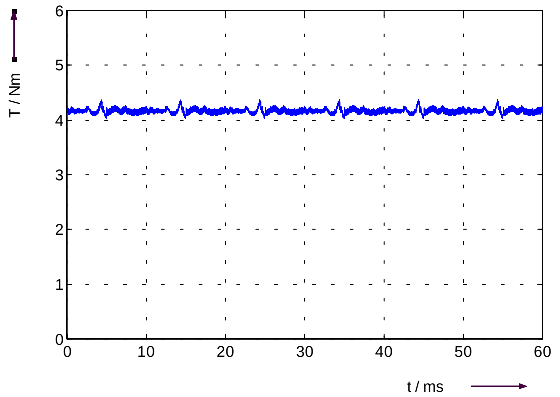


Figure 8 – Compensated torque after 10 iterations.

After 10 training iterations, the compensated current reference produces phase current pulses like those shown in Fig. 10. As expected, the current values are higher at the beginning and at the end of the current pulse. This pulse shape is consistent with the torque characteristics of te SR motor, which produces less torque at the beginning of pole overlapping and just before the aligned position.

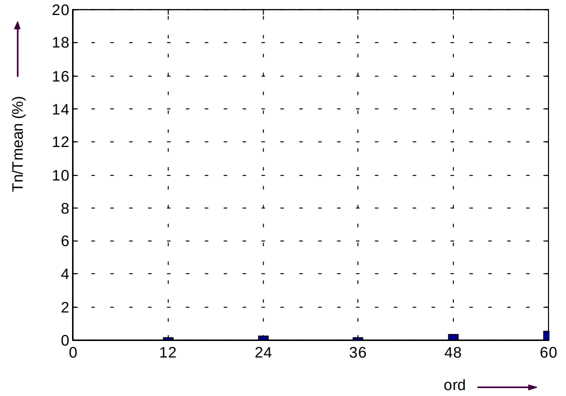


Figure 9 – Harmonic content in torque signal of Fig. 8.

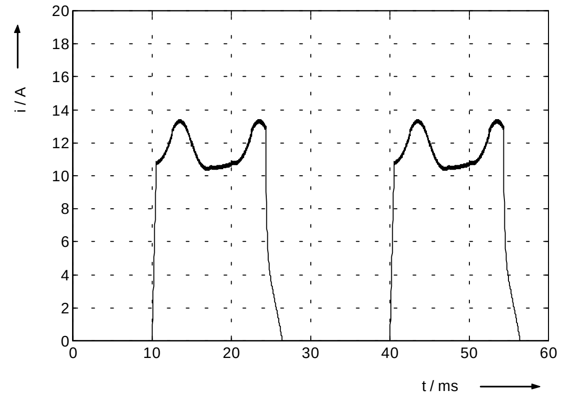


Figure 10 – Harmonic content in torque signal of Fig. 8.

5.- CONCLUSIONS

The Neuro-fuzzy modeling and the learning mechanism to ripple reduction in SR motor were investigated. The simulations of the switched reluctance drive show that is possible to incorporate a compensating signal in the current waveform to minimize the torque ripple. Next steps are using this concept in an experimental drive and incorporate another signal to be trained.

6.- REFERENCES

[1] D.S.Reay, M.M.Moud, T.C.Green, B.W.Williams; "Switched Reluctance Motor Control Via Fuzzy Adaptive Systems", IEEE Control Systems, June 1995.

[2] M.G.Rodrigues, W.I.Suemitsu, P.Branco, J.A.Dente, L.G.B.Rolim; "Fuzzy Logic Control of a Switched Reluctance Motor", IEEE International Symposium on Industrial Electronics, pp. 527-531, Guimarães, Portugal, July 1997.

[3] S. Bolognani, M. Zigliotto; "Fuzzy Logic Control of a Switched Reluctance Motor Drive", IEEE Transactions on Industry Applications, pp. 1063-1068, Vol.32, Number 5, September/October 1996.

[4] Ç. Elmas, S.Sagiroglu, I.Çolak, G.Bal; "Modeling of a Nonlinear Switched Reluctance Drive Based on Artificial neural Networks", Power Electronics and Variable Speed Drives Conference Proceeding, pp.7-12, 1994.

[5] A.F.Stronach, P.Vas; "Design of Fuzzy-Neural Controllers for Variable-Speed Drives", ICEM96, Vol.III, pp.266-271, 1996.

[6] Kavanagh, R.C., Murphy, J.M.D. and Egan, M.; "Torque Ripple Minimization in Switched Reluctance Drives using Self-Learning Techniques", *Proc. of IECON'91*, pp. 289-294, Vol. 1, Japan, 1991.

[7] Iqbal Husain, M. Ehsani; "Torque Ripple Minimization in Switched Reluctance Motor Drives by PWM Current Control", IEEE Transactions on Power Electronics, Vol. 11, Number 1, pp. 83-88, January 1996.

[8] H. C. Lovatt, J. M. Stephenson; "Computer-optimized Current Waveforms for Switched Reluctance Motor" IEE Proceedings, Vol. 141, Part B, Number 2, pp. 45-51, March 1994

[9] D. S. Shramm, B. W. Williams, T.C. Green; "Optimum Commutation-Current Profile on Torque Linearization of Switched Reluctance Motors" ICEM '92 Manchester Conference Proceedings, pp. 484-488, September 1992

[10] Ulrich Steiert, H. Spath; "Torque Control of the Doubly-Salient Reluctance Motor" ETEP Vol.3, Number 4, July/August 1993

[11] Manfred Stiert, Jie Ge; "A Low Voltage Switched Reluctance Motor with Experimentally Optimized Control" ICEM '92 Manchester Conference Proceedings, pp. 532-536, September 1992

[12] Richard S. Wallace, David G. Taylor;" A Balanced Commutator for Switched Reluctance Motors to Reduce Toque Ripple" ", IEEE Transactions on Power Electronics, Vol. 7, Number 4, pp. 617-626, October 1992.

[13] Costa Branco, P.J.; Dente, J.A., "An Experiment in Automatic Modelling an Electrical Drive System Using Fuzzy Logic," *IEEE Transactions on System, Man, and Cybernetics - Part C: Applications and Reviews*, Vol. 28, No. 2., May.

[14] Costa Branco, P.J.; Dente, J.A., "The Application of Fuzzy Logic in Automatic Modelling Electromechanical Systems". *Fuzzy Sets and Systems*, Vol. 95, No. 3, pp. 273-293, 1998.

[15] Costa Branco, P.J.; Dente, J.A., "Design of an Electro-Hydraulic System Using Neuro-Fuzzy Techniques", In *Fusion of Neural Networks, Fuzzy Sets & Genetic Algorithms: Industrial Applications*, Chapter 4, Ed. L.C. Jain, CRC PRESS, 1998.

[16] Costa Branco, P.J.; Dente, J.A., "Control of an Electro-Hydraulic System Using Neuro-Fuzzy Modelling and Real-Time Learning Approaches". *Invited paper in the Int. Journal of Knowledge-Based Intelligent Engineering Systems*, Vol. 1, No. 4, pp. 190-206, October, EASA, Australia, 1997.

[17] Costa Branco, P.J. and Dente, J.A., "Inverse-Model Compensation Using Fuzzy Modelling and Fuzzy Learning Schemes". *In Intelligent Engineering Systems Through Artificial Neural Networks, Smart Engineering Systems: Neural Networks, Fuzzy Logic and Evolutionary Programming*, Eds. C.H. Dagli, M. Akay, C.L. Philip Chen, B. Fernández, and J. Ghosh, Vol.6, pp. 237-242, ASME Press, New York, U.S.A., 1996.