AUTOMATIC LEARNING OF PULSE CURRENT SHAPE FOR TORQUE RIPPLE MINIMISATION IN SWITCHED RELUCTANCE MACHINES

L. Henriques*, P.J. Costa Branco †, L. Rolim*, W. Suemitsu*

* *COPPE/ Federal University of Rio de Janeiro, p.o.box.60504, E-mail:suemitsu@coe.ufrj.br, Rio de Janeiro, RJ, Brazil*
† *Mechatronics Laboratory, Instituto Superior Técnico (I.S.T.), Av. Rovisco Pais, 1096 Lisboa Codex*
† *fax : +351-21-8417167. e-mail : pbranco@alfa.ist.utl.pt*

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Abstract

In servo control applications or when smooth control is required at low speeds, torque ripple reduction becomes the main issue for switched reluctance machines. In this paper, the design and experimental evaluation of a novel technique of adjusting the machine currents to minimize its torque ripple is shown. In the proposed technique, a compensating signal, which is based upon a self-tuning neuro-fuzzy system, is added to the PI speed-controller to minimize automatically the ripple. Experimental results are presented to show how the current is modulated reducing torque ripple for different motor speeds and load values.

1 Introduction

Fuzzy logic control of a switched reluctance motor (SRM) has been implemented with success in [1], and has shown to be effective for 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 [1] 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 pulsation in steady-state. Furthermore, its torque ripple changes with the speed of the SR motor and with the magnitude of the load applied to it.

In this paper, we show the experimental evaluation of the technique originally proposed in [3] and described in detail in [5], which presents our simulation study. In the technique proposed, a compensating signal is added to the output of a PI controller, in a current-regulated speed control-loop, which adjusts automatically the machine currents to minimize the torque ripple of the motor. Other techniques [8,9] have shown a similar approach but including the controller in the the compensator. The implementation and a set of tests are presented in this paper. The experimental results achieved show how the motor phase currents are shaped to reduce the torque ripple, also considering different load values.

2 The Switched Reluctance Machine

In a switched reluctance machine, only the stator presents windings, while the rotor is made of steel laminations without conductors or permanent magnets. Its motion is produced because of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. When a rotor pole is aligned with a stator pole (Fig. 1), there is no torque because field lines are orthogonal to the surfaces (considering a small gap). In this position, the inductance is maximal since reluctance is minimum (one neglects the reluctance of the magnetic circuit). If one displaces the rotor of its position, there will be torque production that will tend to bring back the rotor toward the aligned position. If current is injected in the phase when in the unaligned position (Fig. 2), there will not be torque production (or very little). If one displaces the rotor of the unaligned position, then a torque tends to displace the rotor toward the next aligned position.

2.1. SRM Magnetic Characteristic

The inductance profile $L(\theta, I)$ of the 6/4 SR motor was obtained by FEM analysis and it is displayed in Fig. 3 for different values of phase current and rotor position. The inductance curve is not linear and shows that for large currents there are large saturation effects. Fig. 3 admits two axes of symmetries in $\theta = 0°$ and in $\theta = +45°$, unaligned and aligned positions, respectively.

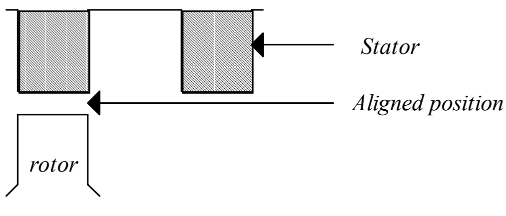


Fig. 1. Aligned position.

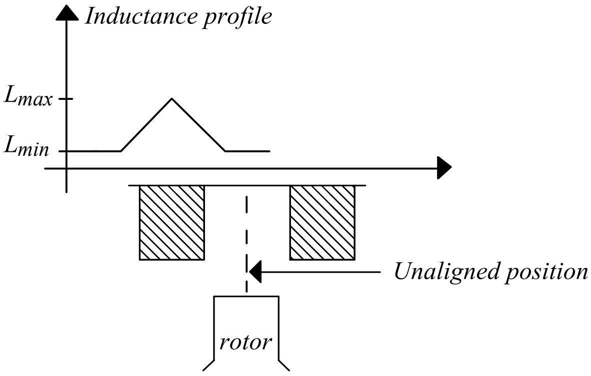


Fig. 2. Unaligned position.

Fig. 4 shows the SRM torque as a function of rotor position and phase current values. The figure shows the influence of the non-linearity of the magnetic characteristic on the phase torque. One also notes in Fig. 4 that while approaching the aligned rotor position the phase torque decreases. This is caused by the saturation effect, which decreases the co-energy variation.

3 The Problem: Torque Ripple

With only a PI-speed controller, it is not possible to obtain a ripple-free motor speed at any speed range because it would require a ripple-free output torque for this purpose. If it is supposed that the speed is constant and equal to the reference one in steady state, then the PI controller's signal (i.e. the reference current) would be constant. Fig. 5 shows, however, that a constant current reference produces a pulsating torque, rendering the ripple-free speed control unfeasible. The results shown correspond to a simulation with full-load operation of the 750W SR motor, at speed of 1800 rpm.

For SR drives operating at lower speeds, it is more convenient to compensate for the torque pulsation through phase current wave shaping. In this case, the current reference signal should vary as a function of rotor position, motor speed, and load torque, to produce the desired ripple compensation.

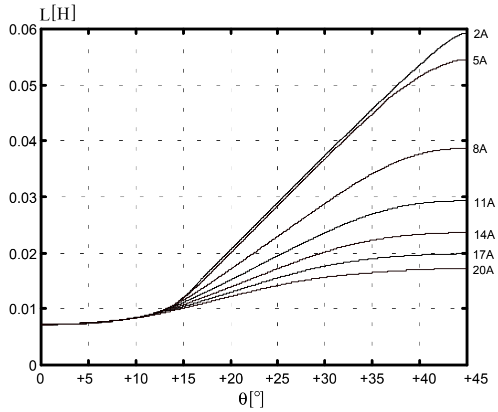


Fig. 3. Inductance profile $L(\theta, I)$.

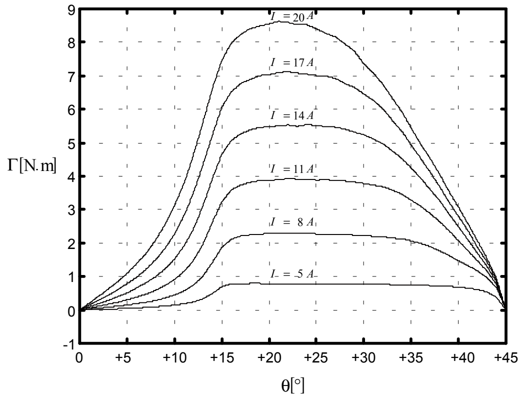


Fig. 4. Phase torque, $\Gamma(\theta, I)$.

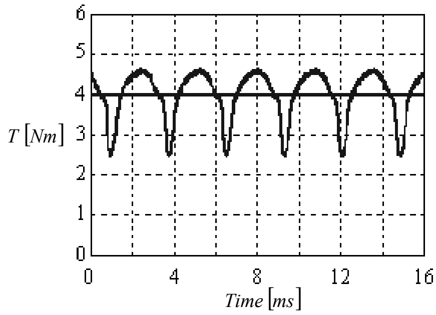


Fig. 5. Simulated result showing the torque ripple from a constant current reference.

4 The Compensator

To attenuate the torque ripple, a compensating signal has been added to the PI controller signal (Fig. 6). This signal is dependent of the rotor position, the motor speed, and the torque load value. In fact, it is a function that possesses high mathematical complexity and therefore the production of this signal is quite complicated. In this work, by the learning capabilities of the compensator, the control shows large operation flexibility. The learning mechanism makes the compensator more independent of the motor characteristics. If the system has some load modification and/or change of speed, the compensator will have the ability of to adapt itself to this new operating point, searching for the required torque ripple minimization. The strategy to produce the compensating signal is to insert in the PI speed controller some learning mechanism through "intelligent" methodologies as the neuro-fuzzy systems.

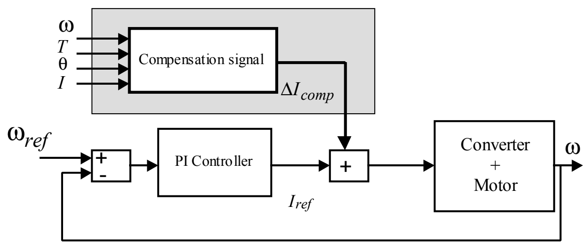


Fig. 6. SR drive with the compensating signal.

The ripple minimization scheme consists in use a neuro-fuzzy compensator where its output is employed together with the output of the PI controller.

The importance of our approach is in its possibility of to be trained by the signals not correlated directly linked with the input signals. The torque ripple signal is used to train the neuro-fuzzy controller to have an oscillating current and thus compensate torque oscillations. The use of a torque sensor is only economically viable if an offline system's training is possible. In addition, the torque sensor is too much expensive to be always connected to each SR drive system.

4.1 The Neuro-Fuzzy Compensator: Operation and Training.

Fig. 7. shows the neuro-fuzzy system employed in the compensator. It considers two inputs: rotor position θ and the PI controller's reference current I_{ref}. These are used by the network learning mechanism to generate the compensating signal $\Delta I_{comp} = f(\theta, I_{ref})$ added to I_{ref}. A second phase corresponds to the iterative training of the compensator. The presence of this iteration comes from our capacity in to obtain a previous simulation of the drive system and, after a pre-defined simulation time, to obtain the simulation results and use them to the compensator training.

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

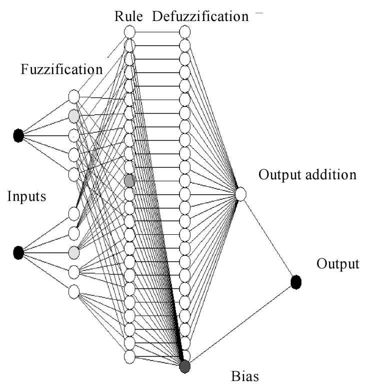
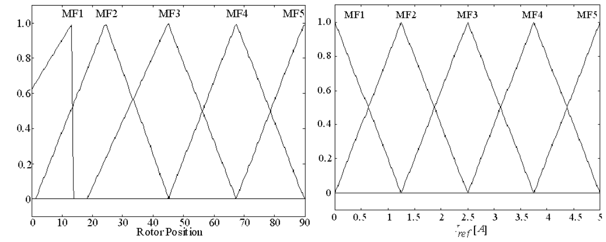


Fig. 7. Neuro-fuzzy structure of the compensator.

Using the fuzzy c-means clustering algorithm in the training data, the membership functions of the rotor position and the current reference were first computed, as shown in Fig. 8. Follow, with the neuro-fuzzy system structure based on obtained input fuzzy sets, it was trained by the back-propagation technique. Varying the values of the reference current and rotor position, for a constant motor speed operation and using the torque ripple as our error information, the compensating function $\Delta I_{comp} = f(I_{ref}, \theta)$ was obtained, as shown in Fig. 9.

5 Experimental Results

A SR drive prototype was used for experimental tests. It consisted of a 6/4 SR motor (Fig. 10) and a H-bridge power converter (Fig. 11). The converter used IGBTs with freewheeling diodes, and the continuous voltage V_d was obtained from a diode rectifier. A hysteresis current controller was used with the microcomputer establishing the energizing θ_{on} and desenergizing θ_{off} angles, and the reference current signal I_{ref}. Fig. 12 shows the SR motor phase current measured when the machine operated for a current reference of 2A, nominal DC voltage, using the θ_{on} and θ_{off} parameters listed in Table I.



(a) (b)

Fig. 8. Rotor position (a) and reference current (b).

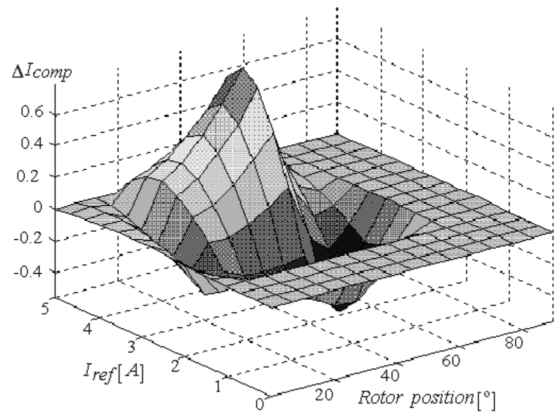


Fig. 9. Compensating function.

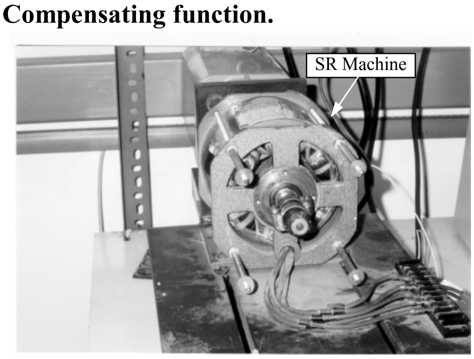


Fig. 10. Stator and rotor elements of the 6/4 SR machine.

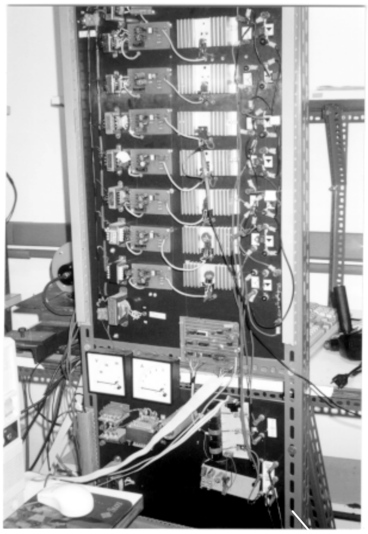


Fig. 11. H-bridge power converter.

TABLE I
OPERATING PARAMETERS

$V_d = 150$ V	$I_{ref} = 2$ A	$\theta_{on} = 0°$	$\theta_{off} = 22°$

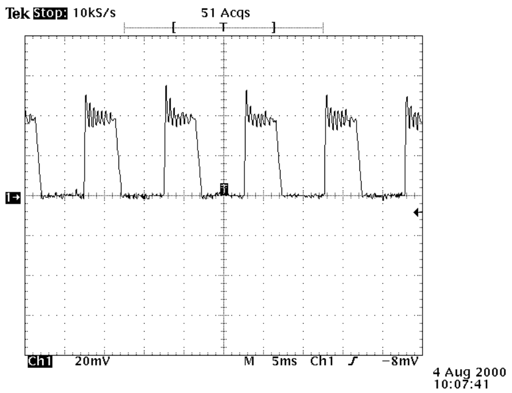


Fig. 12. Currents regulated by the hysteresis controller. (Vert.: 1A/div and Hor.: 25ms/div ≅ 20 mech. degrees)

5.1 Open-Loop Compensation

The first test was effectuated with the SR drive operating in the open-loop mode, without the PI controller, and with a constant reference current of 2A and without load applied. The reason of this test was to verify the pulse current modulation and the consequent ripple redution first without influency of the PI controller dynamics on the speed control-loop.

Two situations were considered: one without compensation and other when the neuro-fuzzy compensator is inserted into the SR drive system. Fig. 13 shows the phase current signal when there is no compensation, and Fig. 14 shows the current when the neuro-fuzzy compensator is inserted in the SR drive system. One can notice that when the compensator is inserted, the current shape is slightly modified, following the curve previously learned and stored in the compensating function in Fig. 9. The current correction follows the shape of the compensation curve in Fig. 15 between 45° and 90°, which are the necessary increments to be added in the reference current of 2A to minimize the torque ripple. Note that all current pulse shapes will follow the left side of the compensation curve since the motor during the tests had its speed reversed.

The procedure used to evaluate the torque smoothness when the compensator is included was the frequency spectrum of the speed error. This procedure is effective in show torque ripple reduction if the speed reference signal and the external motor load are made constant, as demonstrated in [7]. Fig. 16 shows the frequency spectrum of the speed error signal before (a) and after (b) the compensator was inserted revealing the ripple reduction.

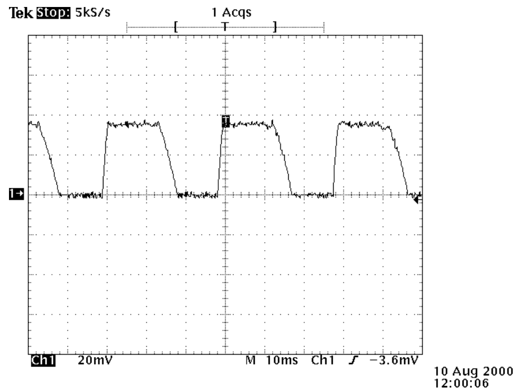


Fig. 13. Phase current without compensation. (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

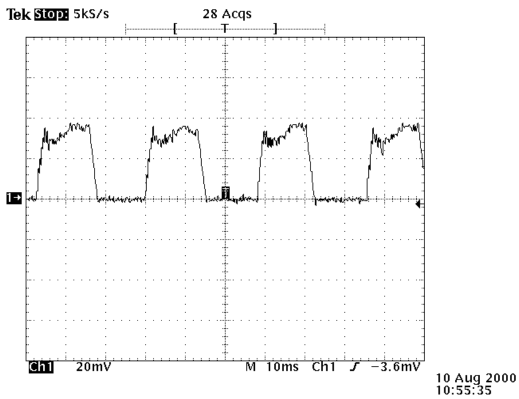


Fig. 14. Phase current with compensation. (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

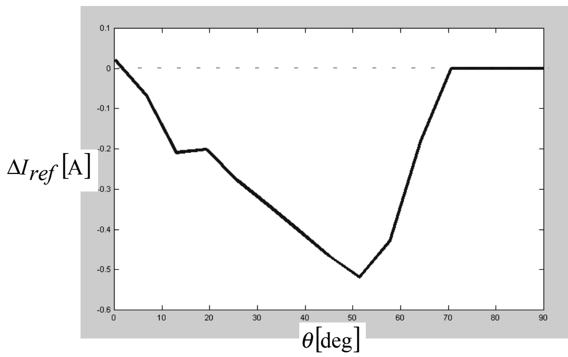


Fig. 15. Compensation curve for $I_{ref} = 2$A .

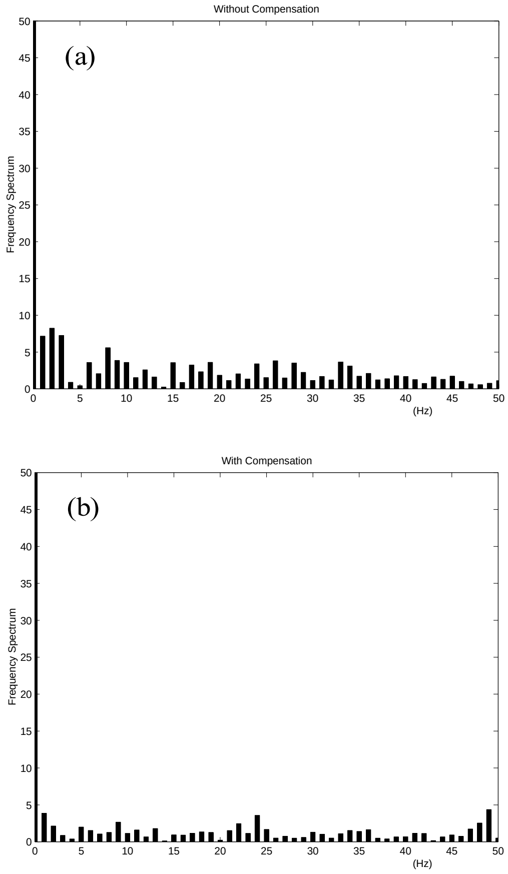


Fig. 16. Frequency spectrum (a) before and (b) after compensation.

5.2 Closed-Loop Compensation

In this second test, the PI speed controller was inserted in the SR drive system. The essay was effectuated for a motor speed reference of $\omega_{ref} = 800\,\text{rpm}$, equal to that reached in the previous test and thus to achieve a current reference about 2A, as before, since no external load was applied. Again two situations have to be observed: before and after the neuro-fuzzy compensation. Fig. 17 shows the current signal when there is no compensation and Fig. 18 shows the current when the compensator was inserted.

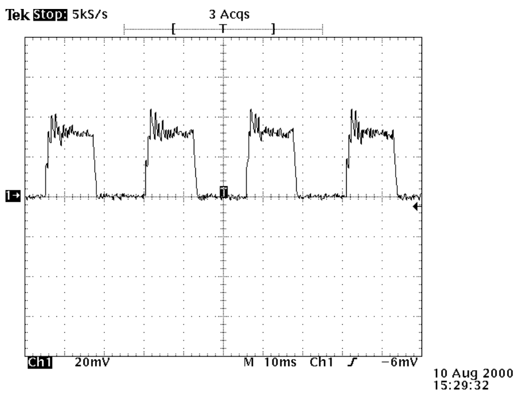


Fig. 17. PI closed-loop without compensation. (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

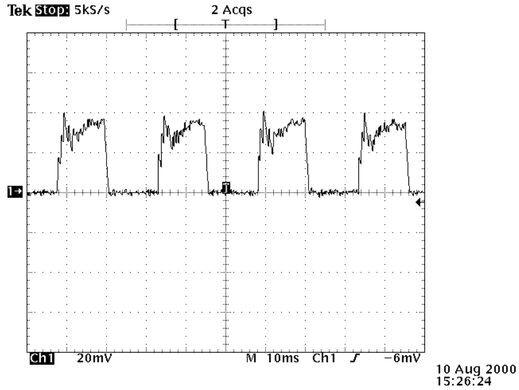


Fig. 18. PI closed-loop with compensation. (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

5.3 Closed-Loop Compensation + external load

This test was effectuated with a load applied to the SR motor by a PM synchronous generator, which was connected to an external resistance of 500W through a three-phase diode bridge. Fig. 19 and Fig. 20 show the phase current before and after compensation, respectively.

When the compensator was inserted, the current shape was changed to follow the learned compensating curve shown in Fig. 21, which shows the necessary increment to be added to the new reference current of about 3A. Fig. 22 shows the frequency spectrum before (a) and after (b) the compensator was inserted, revealing a torque ripple reduction in the motor operation.

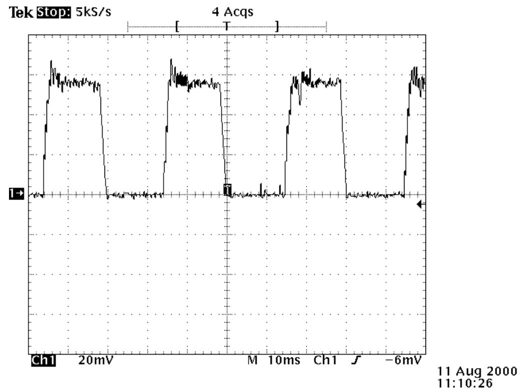


Fig. 19. PI cont. + external load (no compensation). (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

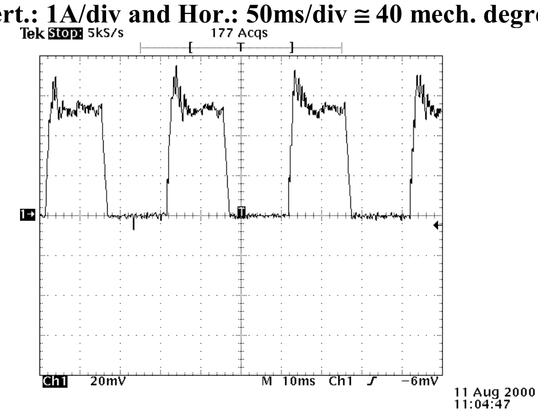


Fig. 20. PI cont. + external load (compensation). (Vert.: 1A/div and Hor.: 50ms/div ≅ 40 mech. degrees)

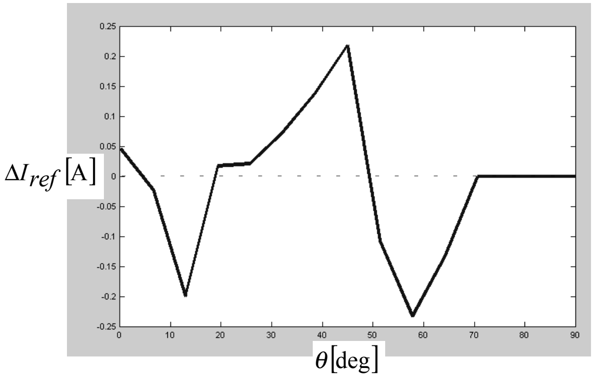


Fig. 21. Compensation curve for $I_{ref} = 3\text{A}$.

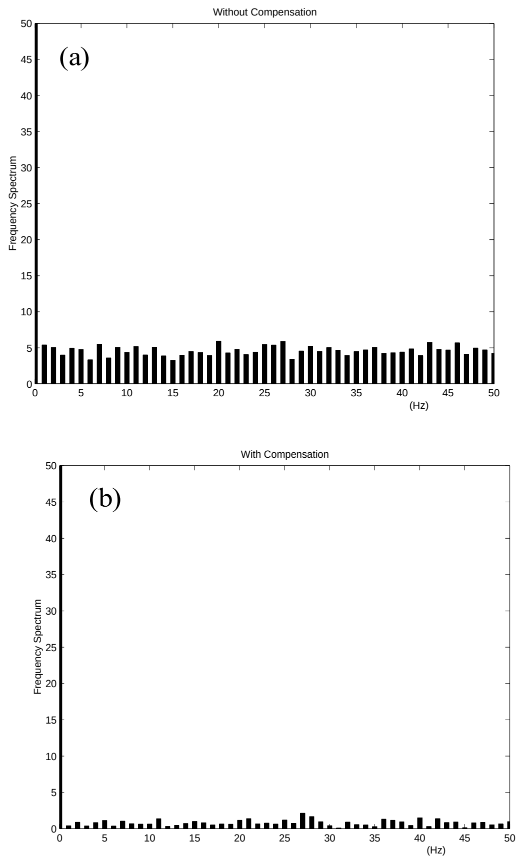


Fig. 22. Frequency spectrum (a) before and (b) after compensation.

6. Conclusion

The neuro-fuzzy modeling and the learning mechanism to ripple reduction in SR motor were investigated. The experimental results of the switched reluctance drive showed that it is possible to incorporate a compensating signal in the current waveform to minimize the torque ripple.

References

[1] Rodrigues, M., Costa Branco, P.J. and J.A. Dente., "Fuzzy-logic speed control for a switched reluctance motor: design, implementation and experimental verification," *European Control Conference (ECC2001)*, Porto, (2001).

[2] Stankocic, A., Tadmor, G. Coric, Z.J. "On Torque Ripple Reduction in Current-fed Switched Reluctance Motors" *IEEE Trans. on Ind. Electronics*, v. 46, n. 1, pp. 177- 183,Fev (1999)

[3] Henriques, L., Rolim, L., Suemitsu, W., Costa. Branco, P. J. and Dente, J. A., "Torque Ripple Minimization in a Switched Reluctance Drive by Neuro-Fuzzy Compensation"; *IEEE Trans. on Magnetics*,. Vol. 36, no. 5, pp 3592-3594, Sep (2000).

[4] Mir, S., Elbuluk, M., Hussain, I. "Torque-Ripple Minimization in Switched Reluctance Motors Using Adaptative Fuzzy Control." *IEEE Trans. on Ind. Applications* vol. 35, no. 2, pp 461-468 Mar/Apr (1999)

[5] Henriques, L., Rolim, L., Suemitsu, W., Costa. Branco, P. J. and Dente, J. A., " Neuro-Fuzzy Compensation Strategy to Minimize Torque Ripple in Switched Reluctance Drives "; *Preprints of the 1ª IFAC-Conf. on MECHATRONIC SYSTEMS*, 1, pp. 209-214, (2000).

[7] Rodrigues, M.; Costa Branco, P.J.; Suemitsu, W.;. "Fuzzy Logic Torque Ripple Reduction by Turn-off Angle Compensation for Switched Reluctance Motors", *IEEE Trans. on Ind. Electronics*, vol. 48, no. 3, June. (2001)

[8] Kavanagh, R.C., Murphy, J.M.D., Egan, M.: "Torque Ripple Minimization in Switched Reluctance Drives using Self-Learning Techniques". *Proc. of IEEE IECON91*, pp. 289-294. (1991)

[9] Reay, D.S., Moud, M.M., et al.; "Switched reluctance motor control via fuzzy adaptive systems", *IEEE Cont. Syst. Mag.*, pp. 200-206. (1995)