REVIEW OF THE RIPPLE REDUCTION STRATEGIES IN SRM

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Abstract— A review of most important reduction torque oscillating techniques is shown. Some critiques and analysis, for advantages and disadvantages, are made about these works to qualify the techniques proposed in this article. This paper presents a concise new technique for minimizing the torque ripple in a switched reluctance motor.

Keywords— **Switched reluctance machine, Intelligent control, Neuro-fuzzy systems, Ripple compensation**

1 Introduction

Due to its non-linear nature, the switched reluctance motor has an intrinsic ripple torque oscillation in the rotor axis. There are many strategies and methods to reduce (or cancel) ripple torque in this type of machine. Essentially, we can present two initial approaches for the reduction of the oscillation: the first consists on improving the magnetic design of the machine, and another is based on the use of electronic control.

Electric machines designers take into consideration, during the design, its non-linear magnetic features, projecting the structure of the polar regions of the stator and the rotor, so that the machine can operate in a settled speed, without torque oscillation. Many papers have been written in this area. However, these strategies restrict excessively the speed band operation of the SR Motor (Miller, 1993).

(Kavanagh et al. 1991) present mechanical modifications in the polar regions for a smooth operation; in fact, they present a motor that possess a sinusoidal-like torque-angle characteristic. There are also solutions where designers project machines with optimized geometry to produce a smooth torque (Bryne et al, 1985). Articles like Radun (1995) present analytical equations designed for reluctance machines. These equations facilitate the design significantly. The designers of machines currently take advantage of the use of finite elements programs to simulate all the operation of motor (Cardoso et al. 1995) and (Nascimento et al. 1995).

The other study, concentrated in the converter design and in the control strategy, is based on selecting the best combination of parameters operation which include voltage, energization and desenergization angles, and current profile.

There are countless proposals for torque oscillation reduction using diverse types of control and modeling (Schramm et al. 1992), (Moreira 1992), Husain et al., 1996) and (Kavanagh et al. 1991). Some are based on the static system model, which means that the control uses a table which contains the magnetic characteristic for only one speed (Kavanagh et al. 1991), others have the advantage of being capable to adapt in real time to any change in the system characteristics, a past from others that possess the possibility to estimate some variables used for the machine control, like: speed, torque or position.

Additionally, there are papers that use linear model, although this model is not good for high performance applications, and therefore innumerable mathematical approaches are necessary.

In other types of work, a current profile is used to produce current peaks when in regions of low inductance variation. It can be concluded that there is a wide range of possibilities. The objective of this introduction is to argue the advantages and disadvantages of some of them. Moreover, we are considering a new approach of control for reduction of ripple, based in a hybrid technique of neural networks and logical fuzzy system.

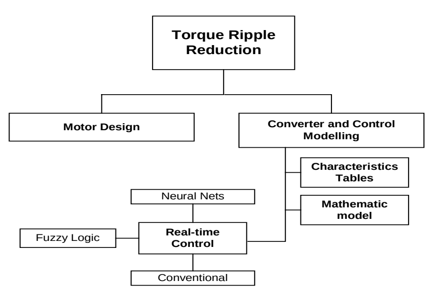

Figure 1. Oscillation reduction method diagram

To take into account a single criterion for all the strategies of control and minimization of torque oscillation in SRM is sufficiently complex. Therefore, we can divide them in some sub-groups, presented in the diagram of Figure 1.

2 Characteristic Table

This strategy of control was the first one implemented. It is based on the table which contains the magnetic characteristics of the motor, namely the relations: L(θ,I) and Γ(θ,I) (presented in Figure 2 and Figure 3)

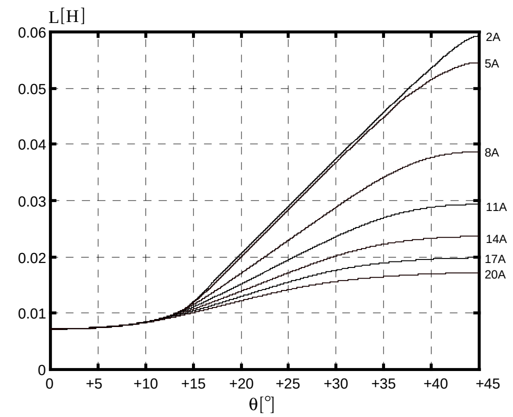

Figure 2. Inductance Profile $L(\theta, I)$.

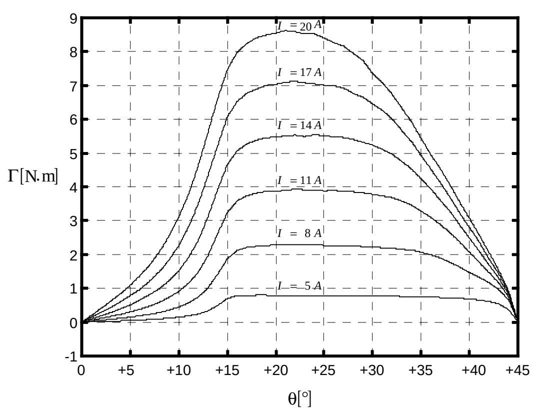

Figure 3 - Phase Torque - $\Gamma(\theta, I)$.

Using these relations, their reverse relation can be obtained, and to produce the desired torque, we can take ideal current. The production of these tables is not trivial, it demands much time and the step algorithm number is significant.

The method described by (Moreira 1992) is based on the instantaneous torque estimation of the switched reluctance motor through the flux/position/current characteristic curve. These curves are obtained through the experimental measurement of the voltage and current for different positions of the rotor and, later, the interpolation derives values using a method of bi-cubical interpolation. With this method, the torque estimation is obtained through 3rd order polynomial equations where the calculated coefficients are stored in the DSP memory used in the implementation (Figure 4). After that, the estimated torque is compared with a reference torque, and the result is then used in the current regulator that controls the phase current motor (Figure 5). The algorithm of this method involves a 3rd-order polynomials operation and it does not take into consideration the advantage of the overlapping of phases when the variation of the phase inductance is positive.

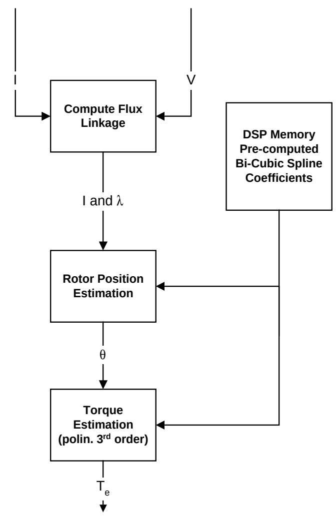

Figure 4 – Position and torque estimation

The torque ripple reduction method presented in (Schramm et al. 1992) is produced with current overlapping during switching. This method is based on defining a central point of switching, where two phases have equal currents, such that the torques generated for the both phases added are equal to the desired total torque.

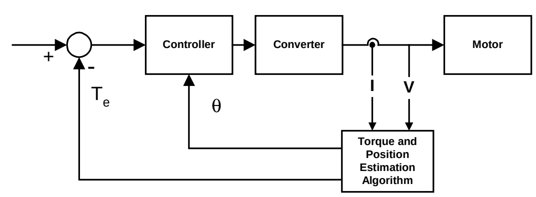

Figure 5 – Estimation and control of a SR Motor

3 Mathematical Model

The representation of the machine through its linear or non-linear mathematical model is a step forward in the switched reluctance motor control study. It allows us to take into account the machine speed and to use a real time approach, instead of using a static table (Russa et al. 1998).

However, some studies calculate the optimized torque function, before this operation, to minimize the oscillation (Kjaer et al. 1996), (Stankovic et al. 1999). This approach reduces the computational work of the controller significantly and more easily allows the operation of the control in real time. This method also allows the inclusion of secondary objectives of control, like the performance maximization. However, the off-line function calculation also leads to the loss of robustness in the system. Another problem is the necessity of great space of memory to store all information in the table for a wide band of speed and some levels of torque.

A possibility to implement an adaptative control was researched in (Amor et al. 1993), but the obtained controller has a complicated structure for online operation, and the realization and implementation become unfeasible.

The article (Rochford et al. 1993) shows a mathematical approach of the flux/current/position and torque/current/position relations for the achievement of the algebraic model that represents these characteristics. The use of this model allows a fast torque control in real time through speed and position loop control. The disadvantage of article (Rochford et al. 1993) is that a great part of the system is represented in a linear form.

Inanç et al. (1996) is about reducing ripple of torque in the linear region and with the presence of mutual inductance. However, it neglects the losses due to eddy current and iron losses. The technique of reduction of the oscillation is based on the addition of the squares of currents, but this is only possible when machines like the 8/6 ones are used.

We can point out the necessity of having only 2 phases operating at the same time as critical to the method presented in this paper. This occurs because the strategy used in this study utilizes only 2 current sensors.

4 Online adaptive control

Real time techniques can be used to implement the motor control. Some techniques use complex algorithms that update the controller parameters in real time, others use intelligent techniques like neural networks, genetic algorithms and fuzzy logic.

4.1 Conventional

Using conventional control techniques, we can get the updated values of the controller parameters in real time using a recursive identification algorithm (Russa et al. 2000). During the operation, the control constants are adjusted online.

The only input required for the controller is phase resistance. The controller adjusts its parameters in real time to any change in the motor characteristics Self-tuning algorithms can ideally minimize the torque ripple in SRMs. The results indicate that this technique works well for low speeds. For the high speeds, it generates an invalid model for the estimation algorithm, caused by the necessarily long computational time to run the torque calculation and system identification in the same DSP.

The speed control is a conventional PI controller that generates a reference torque signal T^*. With the T^* signal, and after the torque motor estimation, the controller produces the reference currents for the hysteresis.

The great contribution of this work is in the system identification and not in the torque oscillation minimization. However, the better the system identification, the better the torque minimization will be.

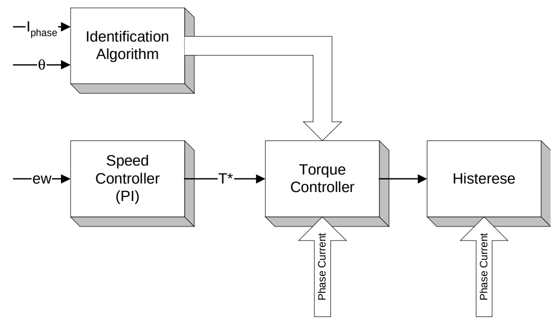

Figure 6 – Controller diagram with parameter adaptation.

Husain (1996) presents the optimization of the current curves in the phases, mainly at the switching moments, for the reduction of ripple. The strategy is based on generating the current shapes so that the addition of the torques generated for each phase is constant and equal to the desired torque. For this, the authors define a contour function $f_T(\theta)$.

Innumerable contour function sets exist that are fit for the reluctance motor. The functions shown in Figure 8 are an example of these.

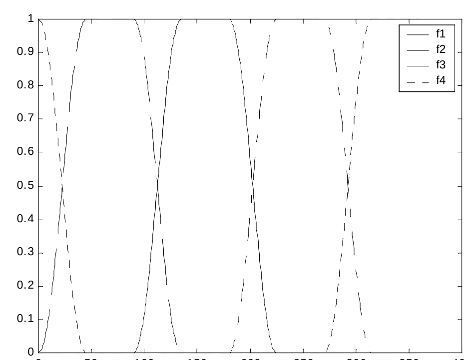

Figure 7 - Current membership functions

The corresponding function to phase 1 would be:

$$
\begin{aligned}
f_1(\theta) &= 0.5 - 0.5\cos 4(\theta - \theta_0), && \theta_0 \le \theta < \theta_1 \\
&= 1, && \theta_1 \le \theta < \theta_2 \\
&= 0.5 + 0.5\cos 4(\theta - \theta_2), && \theta_2 \le \theta < \theta_3 \\
&= 0, && \text{for other values}
\end{aligned}
$$

The control algorithm is made using the torque/current/position characteristic curves. First, $f(\theta_1)$ is calculated using the table and then one calculates the torque in each phase. This torque is inserted in the table and afterwards, it is possible to derive $I_{desired}$ currents. Later we regulate the currents to keep the desired values. The use of these contour functions has some restrictions:

- The sum of the functions for all the phases has to be a constant one,
- And the current has to be capable of following contour defined for the function.

Therefore, although it is possible to use diverse contour forms, there is necessary a criteria for the choice of the functions.

Moreover, the current switching between the phases is considered as instantaneous, which is not feasible because of the high di/dt in inductive winding of the phase.

4.2 Neural networks

Elmas et al. (1994) discuss the backpropagation learning technique. The advantages of this method are that it does not need a previous knowledge model or equation and that it has reduced mathematical complexity.

However, the collection of data for the training is critical for an efficient learning. Moreover, the period of training is very slow. This work simply shapes the motor; do not do the compensation, just replaces the tables that represent the motor.

Reay et al. (1995) present a neural network to control the switched reluctance motor. The technique is based on the specification of a reference torque profile. This profile is obtained from T(θ,I).

This paper argues the generation of the inverted torque/current/position relation table online. This perspective is interesting because it allows us to consider the magnetic iterations between conducting phases. This is not possible when we work with the static system.

The article presents a network with two inputs (torque and θ) and one output (current). It is important to know that the use of torque sensor is necessary during all the running time. And if the network initial conditions are favorable, this will strongly influence the network learning. Figure 9 shows how the implemented system.

A disadvantage of this method is that if the initial parameters of the neural-network were bad, the learning time of the network will be affected, even causing perturbations in the torque, which can be critical to the process where the machine is operating.

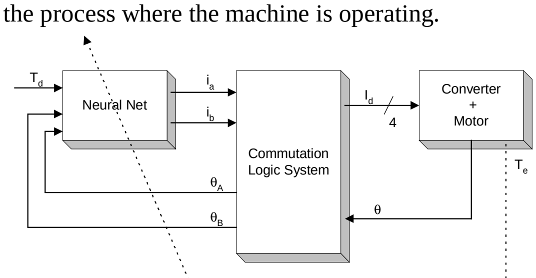

Figure 8 - Proposed System

4.3 Fuzzy Logic

Elmas (1995) shows a fuzzy logic application that replace a Conventional PI controller. The SRM presents a multi-variable, non-linear control structure that needs a complex control design to reach a high dynamic performance. However, controls based on the linear approach, near the operating point, do not produce this desired performance.

The article is divided in 2 parts:

1st - Magnetic non-linearities are modeled using fuzzy logic.

2nd - A speed control is made with fuzzy logic.

As inputs of the speed controller we have ew and cew (speed error and variation of the speed error) and the output will be ΔI. The rules were obtained by trial and error. The restrictions to this work are the necessity to know the fuzzy rules previously and also the incapacity to modify these rules online.

Mir et al. (1999) present an adaptive fuzzy control. The initial parameters are chosen randomly and later they are adjusted to optimize the control. This article is not dependent on predetermined properties of the machine, and is capable of adapting itself to any change of these properties. It is robust in relation to the position error, and prevents negative torque production during the switching.

However, the proposed method is based on the assumption that there is a torque sensor permanently connected to the machine, which is not practical neither reliable and very expensive.

The controller uses as input the rotor position and as output the I_{phases}. It is based on a knowledge base that uses the error between the desired torque and the real torque as an adaptation method. The desired torque is estimated using a technique proposed in Sayeer et al. (1995).

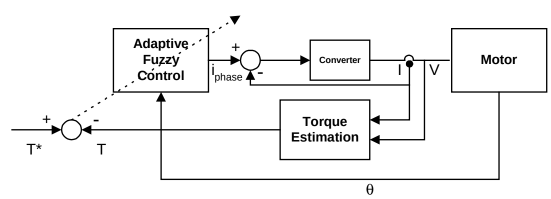

Figure 9 – Fuzzy adaptive control for torque ripple in SR motor

The torque error (T^*-T) is used to make the adaptation and in the output we have references for the phase currents. The commutation is normally made near the aligning position between stator and rotor, where phase inductance is high and demagnetization inductance is low.

The method presented in Bolognani et al. (1996) is an effort to reduce the torque oscillations through a fuzzy modeling, where the torque oscillation signal is obtained indirectly from the acceleration motor signal. The strategy is based on rules that activate different functions in according to the phase that must be energized. These functions are formulated in reference to the sliding mode speed control.

The operation inputs in sliding mode are speed error and acceleration. This way to search the oscillation torque information through the acceleration signal is interesting but this estimation method can fail. Moreover, the fuzzy logic system presented here is static; therefore, the control will be not modified if there are changes in the load, or in any machine parameter. That is undesirable, because the FLS (fuzzy logic system) can be tuned to a given excellent operation condition, but for other situations, this tuning is not satisfactory.

Another fuzzy-logic-based technique to minimize torque is turn-off angle compensator. The turn-off angle, as a complex function of speed and current, is automatically changed for a motor speed range to reduce torque ripple. Changing the angle, it is possible to change current profile (Rodrigues et al 2001)

4.4 Neuro-Fuzzy Compensator

In this work (Henriques et al. 2002), the control possesses a greater flexibility of operation, since learning in the compensator is present. This learning makes the compensator more independent of the machine characteristics. If the system has some modification in load, voltage supply, or operation speed, the compensator has the ability to customize the function in this new operation point, and it searches for the desired reduction of the torque oscillation. The strategy proposed to produce this compensation signal is to incorporate in the traditional PI control system, mechanisms of learning, for example, in this paper, a neuro-fuzzy system (NFS). The control mentioned consists in using a neuro-fuzzy controller, whose output is used together with the output of the traditional PI, as it is seen in Figure 10.

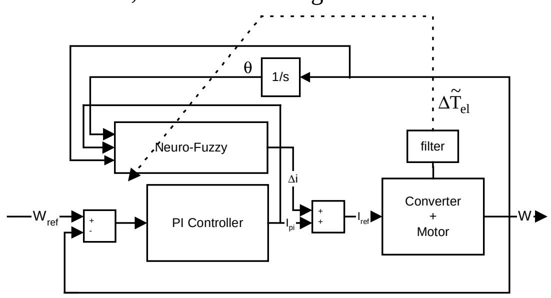

Figure 10 – Simplified diagram with the PI controller and "neuro-fuzzy" compensator

As input of the compensator, the motor speed, the rotor position, the reference current or the speed error can be used. This flexibility is very relevant for situations where all the signals for the training were available from sensors. This controller is important because it makes its training possible through signals indirectly correlated with the input signals. For example, we can use the proper oscillation of the torque to train the neuro-fuzzy net with the objective of producing a new current shape. Or we can use the speed error like an indirect training signal, making the elimination of the torque sensor possible.

In the work developed previously by the authors (Henriques et. al 2000), it was presented an offline compensation of the phase currents using the neuro-fuzzy algorithm developed by Jang (1993). Due to this approach (offline training), it is always necessary to retrain the system compensation after any change in the parameters of the machine or in the load (Henriques et. al 2001).

In this article, a new step forward is proposed. Using the same conditions, an online compensation for the reduction of the torque ripple in the machine is considered for two distinct approaches: with the torque signal and without this signal. In the first approach, the oscillating part of the torque (total torque - average torque) is used and, in the second, the error signal of speed is used as means to acquire information about the machine's torque ripple. They are in fact two different inputs for the compensator, but only one strategy of compensation. A disadvantage of the first approach is the necessity to use a torque sensor. However, this approach can be used before the second one as a first step in the acquisition of the compensator rules. The use of torque sensor in this case is only economically viable if we are able to make an offline training of the system. The torque sensor is sufficiently expensive to keep it constantly connected to a single system.

Most of the research on this subject presents the use of a sensor or a torque observer; the second approach is designed to prevent the use of any (Islan et al 2000). This second approach has the advantage of eliminating the torque sensor. However, the update signal got indirectly from the speed error does not possess as much information on the torque oscillation as that of the proper signal of torque, and then more training time and a too small learning rate are needed to keep the system stable.

The compensation strategy incorporates a learning mechanism in the system of traditional PI control. This compensator consists in using a neuro-fuzzy system whose output is used together with the output of the traditional PI, as it is shown in Figure 10. As inputs to the compensator, the speed signal, the rotor position, the phase current, or the speed error signal can be used. This flexibility presents a lot of interest for the circumstances where all the required learning signals are not available through the sensors.

Note the importance of a controller of this type that makes possible it's training through signals indirectly linked with the input signals. For example, the ripple torque oscillation can be used to train the neuro-fuzzy compensator with the objective of producing an oscillating current, and a speed error that gives indirect information about the torque ripple can be used, eliminating the need of the torque sensor.

5 Conclusion

In this work, a review of the ripple reduction strategies in SRM and a new methodology of compensation of torque oscillations are presented. This methodology possesses a greater flexibility of operation due to the presence of learning in the compensator. This learning becomes the compensator more independent of the characteristics of the motor. If the system suffers some modification in the load, in the source, or the speed of operation, the compensator will possess auto regulation ability for customizing the function shape in this new operation point, searching the desired reduction of the torque oscillation. More details about this methodology can be obtained in the cited article (Henriques et. al 2002)

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