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Sliding mode angular position control for an 8/6 Switched Reluctance Machine: Theoretical concept, design and experimental results

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ABSTRACT

This paper presents a study about the angular position control of a regular four phases 8/6 Switched Reluctance Machine (SRM). The SRM has very interesting characteristics, however there is still not a comprehensive use of it as a position controlled system. Effectively there are many papers in the literature about position detection but still few about SRM position control. This work pretends to be a contribution to overcome this limitation. The theoretical development and design of a robust and accurate sliding mode controller (SMC) is presented, based on the machine torque characteristics, with the correspondent experimental implementation based on the construction of a prototype. It is a low cost system, which makes it very attractive and competitive in the market of drive systems for industrial processes. Experimental tests were done in order to validate the theoretical development. The performance and dynamic behaviour of the SRM system with angular position control is presented and discussed.

1. Introduction

The SRM has desirable features such as simple construction, high reliability, low cost production and maintenance. The designers' choice of this machine is based on its particular characteristics and how they are required by the process application. Some inherent advantages of this machine regarding motion control are: robust rotor structure, simple winding configuration, high power density and high torque. Some studies [1–4] suggest that the SRM presents better performance, efficiency and environmental cost life when compared with classical electrical machines for the same dimensions. However, the SRM presents some disadvantages such as noise, torque ripple and the requirement of an encoder or resolver. Researchers have presented diverse solutions for these problems [5–7]. Some studies demonstrate the good speed and torque behaviour [8–12], others with sensorless applications [13–15]. However, in the angular position control service, the SRM has not yet found its market place because there still exist few works that support and demonstrate its potential. Also some confusion is made between SRM and stepper motors, regarding the shaft position, but they are completely different when diverse intermediate positions between two poles alignment are intended. So, one question must be placed. Is the SRM motion drive suitable for position control in industrial applications? This paper intends to be a contribution to this field of knowledge. Recent papers on angular position control have control structures based only in PID controllers [16,17]. In these works the authors did not make the angular position error analysis in order to emphasize the system performance. Nor it is clear if the reference positions are coincident with a pole position alignment. In this last case the controller's task is simplified by the natural alignment of the poles when its phase is switched on. When comparing with the more recent angular position control for SRM, the following points show how this work contributes to the implementation of a SMC applied to the SRM angular position control. The first one is the SRM proposition of a new angular position control method based on the reaching law control approach. The second one is the implementation of a discrete time reaching law without the *sgn(.)* function for chattering attenuation. Finally, the third one, is the presentation of an angular position control system prototype without any analogue input either as current, voltage, speed or torque sensor, for low cost and good performance industrial motion drives. For this purpose, basically, it is necessary to understand the machine polar torque distribution, which is done in Sections 2 and 3. It is also necessary to develop one effective controller design, which is done in Section 4. Finally, it is required to implement the digital command

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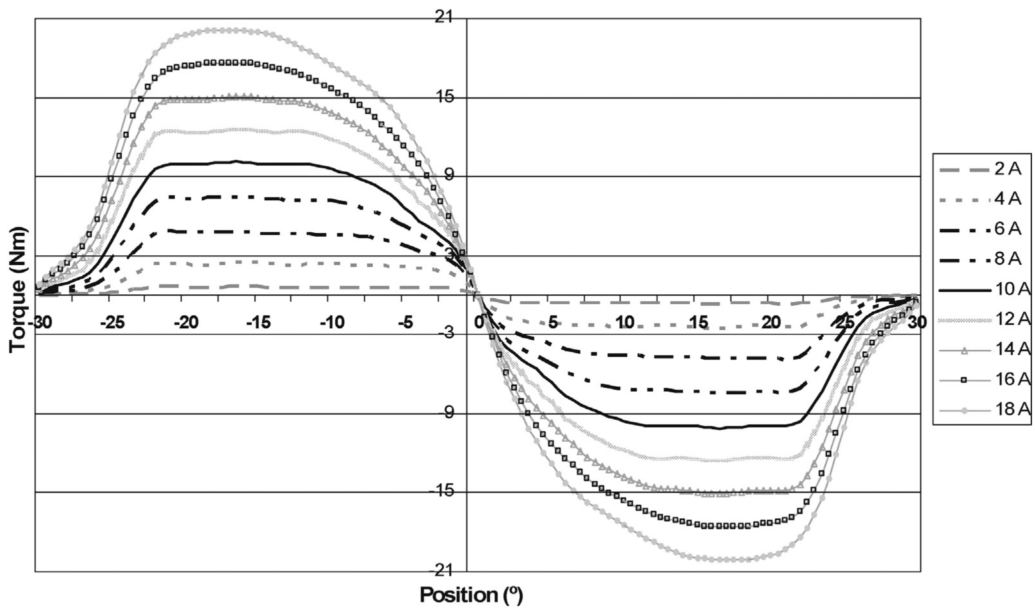

Fig. 1. Torque versus angular position versus phase current curves in one phase.

system and algorithm controller in a low cost hardware platform, and analysing the behaviour of the system in order to place the machine shaft at an intended angular position, which is done in Section 5. An Appendix A with the *SRM ratings and parameters* is presented at the end of the paper.

2. SRM characterization

The functioning principle of this machine is based on the reluctance variations of its magnetic circuit that depends on the rotor position [16]. In fact, this magnetic reluctance circuit is dependent on its geometry and also on some constructive parameters, like the dimension of the magnetic circuit, the type of ferromagnetic material that is used on its structure, its thickness and lamination factor that form the magnetic circuit, etc.

The SRM in study is composed by 8 stator poles, 6 rotor poles and 4 phases.

The SRM mathematical model is considered complex due to the non-linearity of its magnetic circuit. The SRM electrical equations of one phase can be expressed as:

$$V_j = R_j i_j + \frac{d\lambda_j(\theta_r, i_j)}{dt} \tag{1}$$

where V_j is the phase voltage, i_j is the phase current, R_j is the phase resistance, θ_r is the rotor position, j is the active phase and $\lambda_j(\theta_r, i_j)$ is the phase linkage flux. Using the chain rule, (1) can be rewritten as:

$$V_j = R_j i_j + \frac{\partial\lambda_j(\theta_r, i_j)}{\partial i_j}\frac{di_j}{dt} + \frac{\partial\lambda_j(\theta_r, i_j)}{\partial\theta_r}\frac{d\theta_r}{dt} \tag{2}$$

The torque (T) developed by one switched on phase is determined by the variation of the magnetic coenergy (W') produced in its magnetic circuit in relation to the variation of the position and it is expressed in the following equation:

$$T\left(\theta_r, i_j\right) = \left.\frac{\partial W'\left(\theta_r, i_j\right)}{\partial\theta_r}\right|_{i=\text{const}} \tag{3}$$

The magnetic coenergy is characterized by the following expression:

$$W'\left(\theta_r, i_j\right) = \left.\int_0^i \lambda_j\left(\theta_r, i_j\right) di\right|_{\theta=\text{const}} \tag{4}$$

To analyse the SRM behaviour and to define the necessary conditions for the rotor position operation, it is important to know its torque characteristic expressed by (3).

The torque curves characterize the SRM. These can be obtained with different techniques [18–21]. In this study, the SRM static torque was measured. A metallic arm system linked with the shaft structure was carefully balanced and was used to measure the static torque. The torque was calculated based on the measure of the distance from the shaft to a known weight that was placed in order to balance the torque produced for particular current and shaft position values. This procedure was repeated every one degree position between -30° and $+30^\circ$ and, in each position, various current steps were applied (2A to 18A), allowing to obtain the curves shown in Fig. 1.

In Fig. 1, the 0° position corresponds to the aligned pole position of phase 1. Now, one knows the static torque curves developed by one phase. Considering that the other three phases have identical static torque curves, the 4 phases static torque curves can be obtained only by taking into account the 15° angular shift position of each phase. This shift position is imposed by the geometry of the SRM.

In Fig. 2, the phase torque overlapping is observed in two near pole phases. One angular speed direction is produced by a set of positive torque values when the phase sequence is 1, 4, 3 and 2. For a reverse angular speed, a set of negative torque values is needed and so the phase sequence is 1, 2, 3 and 4. The activation phase current must be limited between two appropriate turn-on and turn-off angular positions, usually denoted as θ_{on} and θ_{off}, respectively.

3. Rotor position control—Theoretical concept

The difficulty increases when one tries to position the rotor without load, because this machine, with concentrated polar flux, tends to align the poles when excited. In an 8/6 SRM, these main