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High Speed Range Enhancement of Switched Reluctance Motor with Continuous Mode for Automotive Applications

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Abstract: *This paper describes an original method for the elaboration of control laws for Switched Reluctance Motor for high speed operation. In this case, the control optimization relies on the choice of optimal turn-on and turn-off angles to ensure, in general, high global efficiency, in classical supply mode with full wave voltage. Then, after showing the influence of number of turns, a new supply mode called the continuous mode is described. This mode, used with a higher number of turns, allows to reduce the inverter current rating and hence silicon requirements without compromising performance at high speed. This make SRM competitive compared to other technologies (synchronous and induction motors). The simulation results for a 12/8 SRM are presented and compared to those for an induction motor.*

Keywords: Switched reluctance machine, control, number of turns, continuous mode, competitiveness

1. Introduction

The switched reluctance motors (SRM) are being used in a growing number of applications, which range from mass-production low cost-drives [1,2] (domestic appliances, automotive industry...) to high efficiency drives [3,4] (aeronautics). They offer attractive characteristics, from the point of view of manufacturing cost and performances including:

- Simple construction
- Robust structure
- Low cost

Indeed, stator and rotor have salient poles and are constituted solely by a stack of laminations (Fig.1a). Rotor does not contain conductors or magnet, which allows working in extreme atmospheres (high and low temperatures) and achieving very high speeds. Furthermore, if well

designed and controlled, this motor works well in flux weakening operation [5], which is particularly interesting in automotive applications.

The SRM converter used for this study is an asymmetrical half-bridge converter (Fig. 1b). SRM controllers are designed to ensure the lowest torque ripple (especially at low speed), maximum efficiency, minimum acoustic noise... These objectives can be targeted together or individually depending on the application.

The first part of the paper contains a description of a three-phase 12/8 SRM motor and its associated control. It includes the optimized parameters to ensure maximum efficiency for motoring operation at high speed. These parameters were obtained by using a parametric method elaborated with the aim of obtaining smooth control maps, which are required to

achieve a robust digital control. The second part shows the influence of the number of turns on the performances of the machine and describes a new control mode called the continuous mode [1]. This mode has the advantage to allow reducing number of turns without compromising performances at high speed.

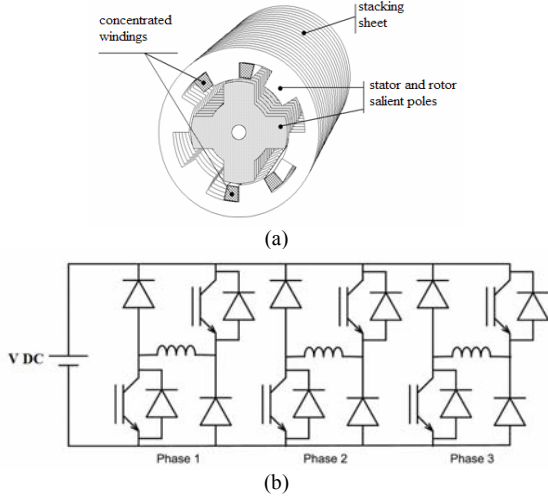


Figure 1.: Structure of 6/4 SRM (a) and its inverter (b)

2. Actuator Control

The main characteristics of the 12/8 SRM and its power converter used in this application are given in Table 1:

Table 1: case study specification

Outer diameter	180 mm
Active length	180 mm
Air-gap width	0.5 mm
Phase resistance (25°C)	0.066 Ω
DC bus Voltage	222V
Peak phase current	150A
Turns per pole	48
Rotor pole arc	16.5°
Stator pole arc	15°
Magnetic sheet	Fe V400-50 HA

A. Computation of performances

The phase voltage equation for a switched reluctance machine is:

$$V = Ri + \frac{d\phi}{dt} \quad (1)$$

Where R is the phase resistance, ϕ the flux linkage of phase and i the phase current ϕ is a function of phase current and rotor position:

$$V = Ri + \frac{\partial\phi}{\partial i} \frac{di}{dt} + \frac{\partial\phi}{\partial\theta} \frac{d\theta}{dt} \quad (2)$$

The co-energy is calculated from the flux linking the coil:

$$W'_m = \int_0^i \phi \cdot di \quad (3)$$

The single phase torque $T_1(i, \theta)$, which give the instantaneous torque value for any given instantaneous current and rotor position, is calculated by deriving the co-energy :

$$T_1 = \frac{\partial W'_m(i_1, \theta_m)}{\partial \theta_m} = N_r \cdot \frac{\partial W'_m(i_1, \theta_m)}{\partial \theta} \quad (4)$$

Where θ_m is the mechanical rotor position and θ is the electrical rotor position.

Neglecting magnetic coupling between phases, global polyphase torque is obtained by:

$$T = \sum_{j=1}^q T_j$$

Where q is the number of phases

The network of flux versus current and rotor position curves are computed by finite element analysis. The network of torque versus current and rotor position are calculated by deriving the co-energy. Fig. 2 shows the curves of flux and torque versus current and rotor position curves for the studied SRM.

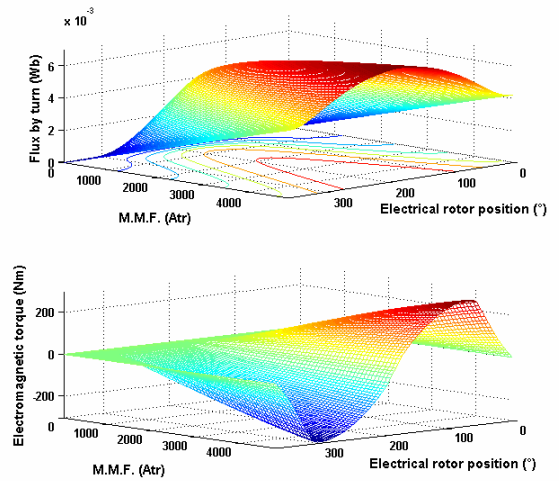


Fig. 2. Flux and torque characteristics versus magnetomotive force and rotor position

B. Control

Fig. 3 defines the electrical control angles in conventional control of SRM:

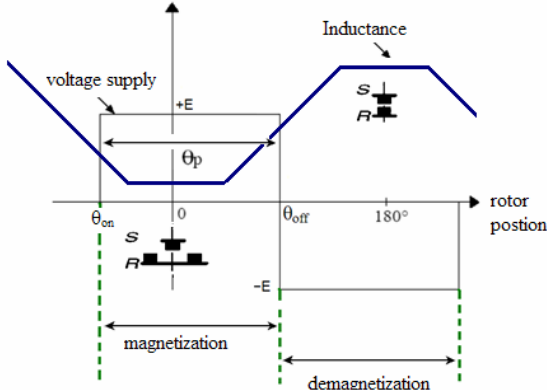


Fig. 3. Definition of control angles in full wave voltage supply

- θ_{on} , called the turn-on angle, corresponds to the beginning of the magnetization of the phase. It is referenced to the unaligned position.
- θ_p , called conduction (or magnetization) angle, corresponds to the duration of the magnetization of the phase. $\theta_p = \theta_{off} - \theta_{on}$ where θ_{off} is the turn-off angle.

Classically, two control modes are used:

- Below the base speed, the back-emf is lower than DC bus voltage. From equation (2), it can be seen that when the converter switches are turned on or off to energize or de-energize the phase, the phase current will rise or drop accordingly. The phase current amplitude can be regulated from 0 to the rated value by turning on or off the switches. Maximal torque is available in this case when the phase is turned on at unaligned position and turned off at the aligned position and the phase current is regulated at the rated value by hysteresis or PWM control. The typical waveforms of the phase current and voltage of the SRM below base speed are shown in Fig. 4. Note that positive voltage is applied to the coil during the rise of inductance in motoring mode and during the decrease of inductance in generating mode. The phase current amplitude and the switching angles adjust the operating point.

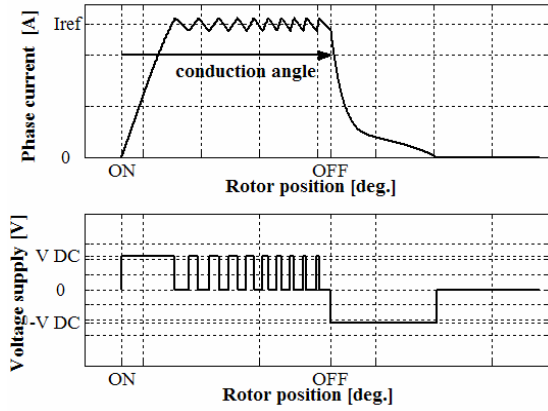


Figure 4. Phase current and voltage phase versus rotor position at low speed

- Above the base speed, the back-emf is higher than the DC-Bus voltage. At the rotor position at which the phase has a positive inductance slope with respect to the rotor position, the phase current may drop even if the switches of the power inverter are turned on. The phase current is limited by the back EMF. In order to impose high current, hence, produce high motoring torque in SRM, the phase is usually excited ahead of the unaligned position and the turn-on position is gradually advanced as the rotor speed increases. Since the back-emf increases as the rotor speed, the phase current, hence the torque, drops as the rotor speed increases. If the turn-on position is advanced to obtain as high as possible current in the SRM phase, the maximum SRM torque almost drops as a linear function of the reciprocal of the rotor speed. The typical waveforms of the current phase and voltage at high speed operation are depicted in Fig. 5.

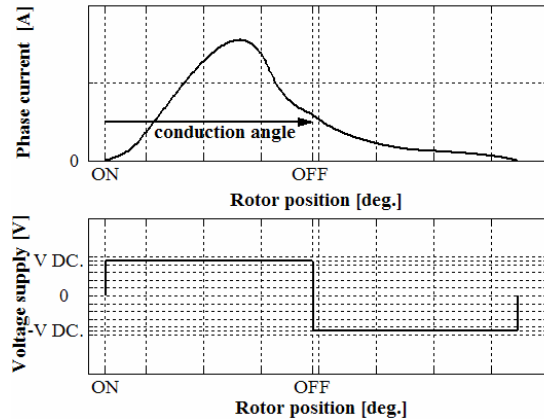


Figure 5. Phase current and voltage phase versus rotor position at high speed

In this mode of operation, called single-pulse mode, the operating point is adjusted by the

switching angles. In classic discontinuous mode, the magnetizing angle θ_p is lower than 180° to ensure complete de-magnetization.

The energy resulting from electromagnetic conversion is proportional to the area delimited by the current-flux trajectory during one electrical period. Fig. 6 shows conversion energy strokes at low and high speed.

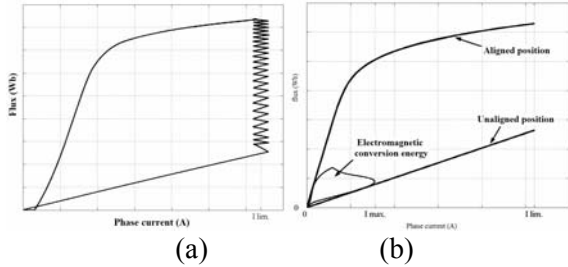


Figure 6. Conversion energy strokes at low speed (a) and high-speed (b)

The average electromagnetic torque (T) is:

$$T = q \cdot W \cdot \frac{Nr}{2\pi} \quad (5)$$

Where q is the number of phases, W the converted energy per stroke and Nr the number of rotor poles.

The network of flux versus current and rotor position is computed by finite element method [6]. Then, the maximum power and torque-speed curves at a 222 V DC bus voltage, 150 A maximum phase-current and 48 turns per pole are plotted in Fig. 7.

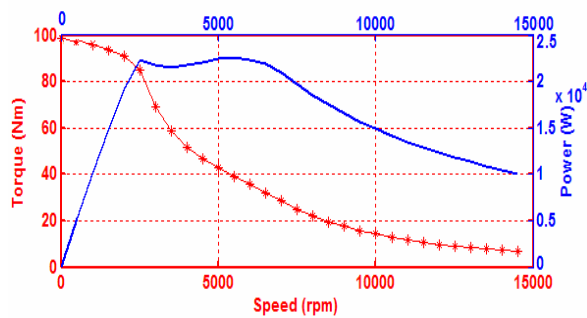


Figure 7. : Maximum power and torque versus speed in discontinuous mode

These curves are obtained by magnetizing a phase as long as possible, while ensuring its complete demagnetization, and by optimizing the turn-on angle θ_{on} using the simplex method. In other words, the conduction angle is fixed at 180° electrical and we seek the optimal turn-on angle to obtain the maximum torque.

B. Control laws at high speed

At high speed, the machine is supplied by a full wave voltage (Fig. 5). The only control parameters of the machine are the switching angles (θ_{on} and θ_p). These angles can be optimized according to various criteria [7,8]: reducing torque ripple, maximizing global efficiency, etc...

Here, the criterion retained in the high speed range is the highest global efficiency of the machine-inverter system.

The optimization method is based on a parametric study, which consists in covering, for a given speed, the entire (θ_{on} , θ_p) plane by varying θ_p from 40° to 180° and θ_{on} from -120° to 20° . Thus, for each operating point characterized by a pair of values (θ_{on} , θ_p), several characteristic values are saved: torque, efficiency, torque ripple, peak current etc

The curve of desired torque is extracted from the equipotential torque curves on Fig.8. It shows the pairs (θ_{on} , θ_p) that allow achieving it. The pair that gives maximum efficiency is extracted from the curve of desired torque (that can be another constraint).

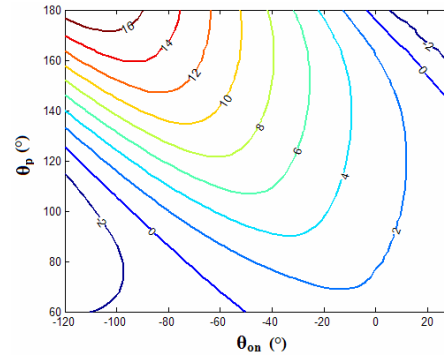


Figure 8.: Equipotential of torque according to θ_p and ψ at 9000 rpm

To illustrate an example, Fig.9 shows the operating point which has the highest efficiency at 9000 rpm and 8 N.m.

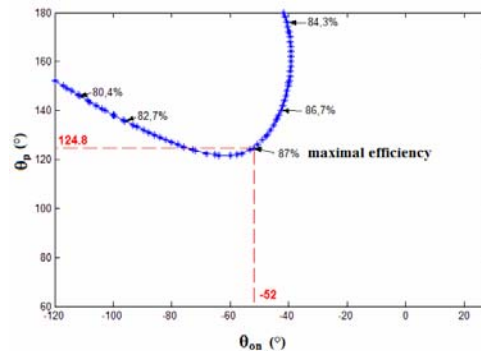


Figure 9.: Extraction of highest efficiency for an operating point (8N.m, 9000 rpm)

Fig. 10 shows the values of θ_{on} and θ_p optimized in the (torque, speed) plane, on which the optimal point calculated above is easily found.

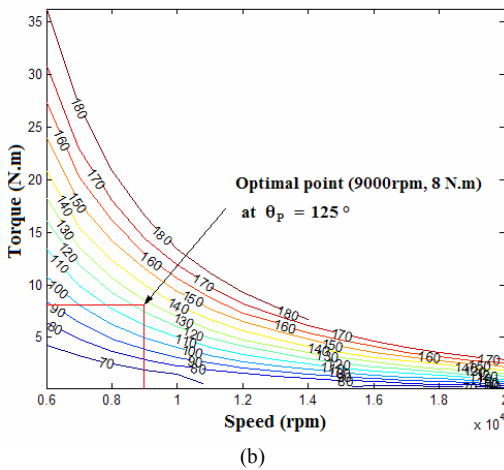
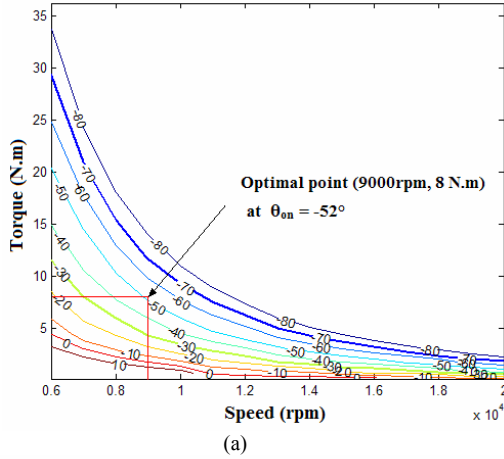


Figure 10. : “Equipotential” curves of θ_{on} (a) and θ_p (b) optimised versus torque and speed.

As shown in Fig. 11 and Fig.12, the optimal control angles vary in a monotonous way with respect to torque and speed. This monotony allows a simple implementation into an embedded numerical control.

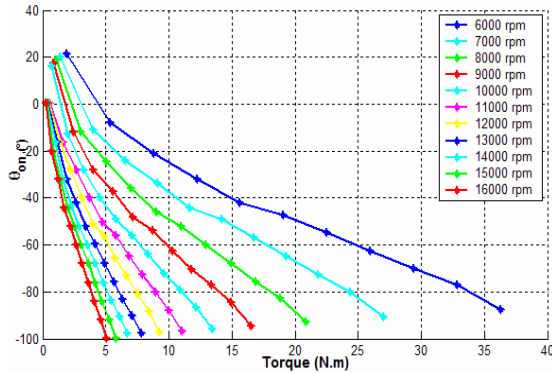


Figure 11. : Optimized values of θ_{on} versus torque for different speeds

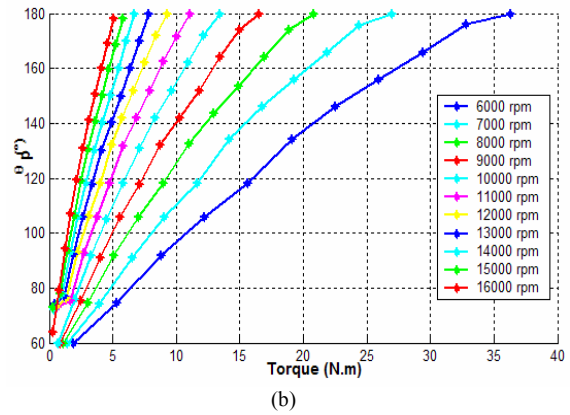


Figure 12. : Optimized values of θ_p versus torque for different speeds

3. Continuous mode

In classical discontinuous mode, the trade-off between torque at low speed and power at high speed is shown in Fig.13 with respect to number of turns.

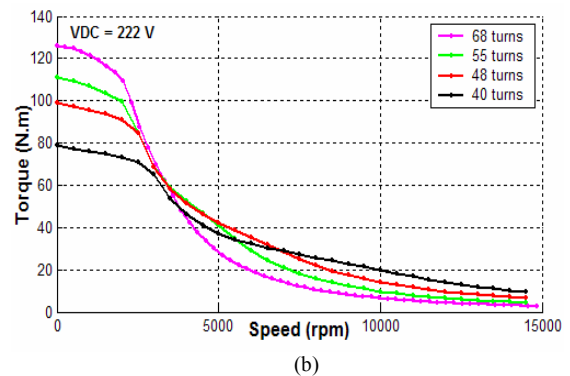
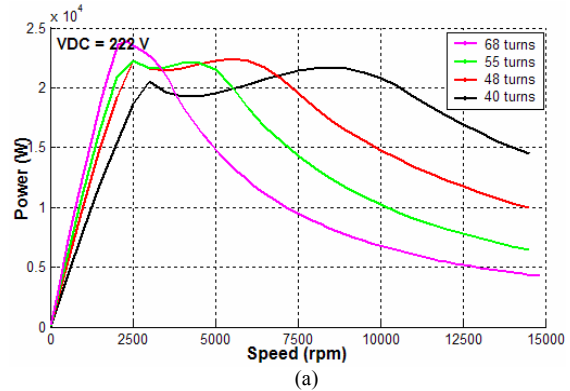


Figure 13.: Maximum power (a) and torque (b) versus speed for different number of turns in conventional discontinues mode

A gain in torque at low speeds is achieved with a high number of turns for a constant current. However, for high speeds, increasing the number of turns decreases the power while respecting the constraints related to the supply voltage. This drawback can be avoided with continuous mode.

The energy resulting from electromagnetic conversion is proportional to the area delimited by the current-flux trajectory during one electrical period. As shown in Fig. 6a the potential energy, which is delimited by aligned and unaligned position trajectories and the maximum phase current I_{lim} is totally used at low speed.

However, as illustrated on Fig.6b, at high speed, the actual coenergy is much lower than the potential value.

To better use the potential coenergy given by a certain quantity of iron and a given maximal inverter current, it is desirable to increase the flux by extending the duration of the magnetisation phase. In that case the risk is a loss of current control: the starting current increases by each period until the inverter limits the current or shuts down. To avoid any instability caused by a divergence of flux and current, it is mandatory to use a regulation loop. An example of torque control loop is illustrated in Fig. 14.

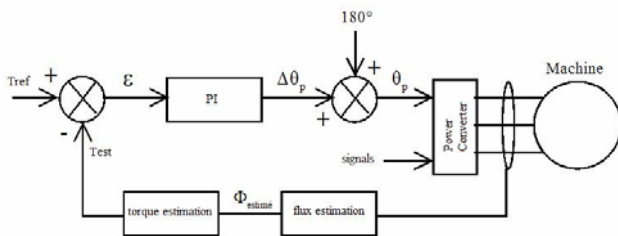


Figure 14. Example of torque control closed loop

This leads to a progressive growth of energy conversion cycle as shown on Fig.15.

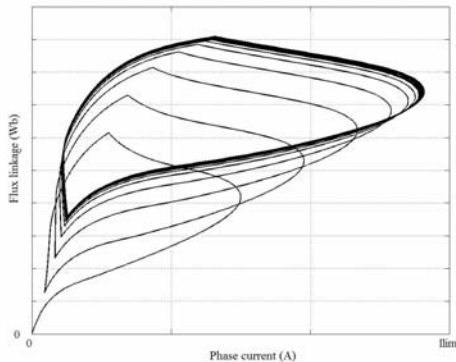


Figure 15.: Evolution of energy conversion at high speed

The magnetization flux during the conduction phase (θ_p) will exceed the de-magnetization flux, between turn-off and phase current actually vanishing. Consequently, the flux-linkage and current will be continuous, meaning they will

not fall to zero. This is called the continuous mode.

Fig. 16 shows the new maximum power-speed curve using a continuous mode at high speed with an rms-current limit.

In this specific case, the continuous mode increases power and torque by a factor of 2 or more at high speed and leads to a very significant improvement in performance. A slight increase in iron losses has been detected but it does not affect significantly the efficiency of the system.

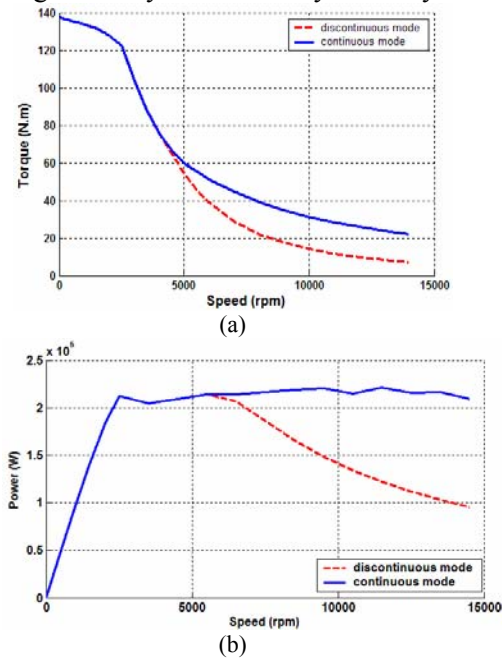


Figure 16. : Torque-speed (a) and Power-speed (b) envelope using discontinuous and continuous modes

It is important to point out that this new control mode can be used with a high number of turns to reduce the inverter current rating and hence silicon requirements without compromising performance at high speed obtained by discontinuous (classical) mode using a lower number of turns. The trade-off between torque at low speed and power at high speed depicted on Fig.13 disappears by using this mode.

4. Competitiveness of the SRM

The new control mode explained above makes SRM competitive compared to other technologies such as induction or synchronous motors for all applications where power is needed over a wide speed range.

In order to demonstrate this competitiveness, a comparison of the performances and efficiency between an SRM and an induction motor (Fig.17) has been conducted. The two compared motors have the same external dimensions and the same

DC bus voltage and maximum RMS current phase.

In automotive applications like electric traction, it is the low speed peak torque requirement which dictates the rating of power semiconductors and therefore the cost of the inverter [9].

The two motors are optimized to achieve the same torque at low speed at about 130N.m

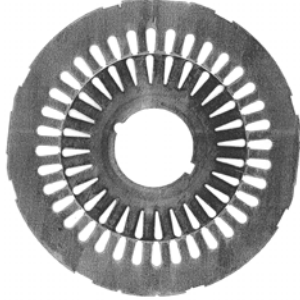


Figure 17.: Cross section of induction motor used for comparison with SRM

The main characteristics of the 12/8 SRM and the induction motor used for comparison are given in Table 2:

Table 2: motors specifications

Specifications	SRM	Induction Motor
Outer diameter	180 mm	180 mm
Active length	180 mm	180 mm
Air-gap width	0.5 mm	0.5 mm
DC bus Voltage	222V	222V
Max RMS current	100A	100A
Turns per pole	68	11

Figure 18 plots the torque-speed envelope of the induction motor and the SRM with and without continuous mode control. The performances of induction motor and SRM with classic mode are nearly the same. The use of the continuous mode in SRM shows the benefits in torque and power at high speed. Moreover, it can be used with a high number of turns to achieve the required torque at low speed. Therefore it allows reducing the inverter current rating and hence silicon requirements without compromising performance at high speed.

For a low speed peak torque requirement, in the case of induction motor, the increase in power at high speed requires an increase in voltage supply. However, in the case of SRM, the

increase in power at high speed can be achieved with the continuous mode, and hence without any increase in voltage supply.

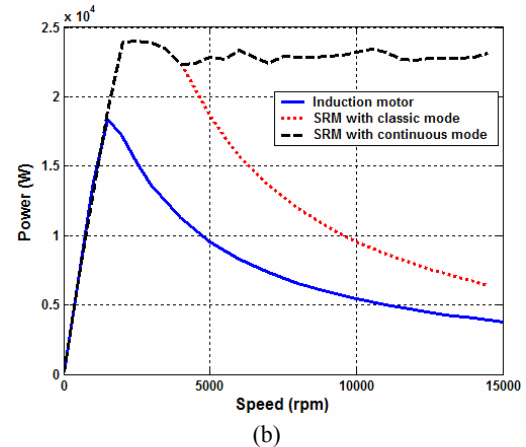
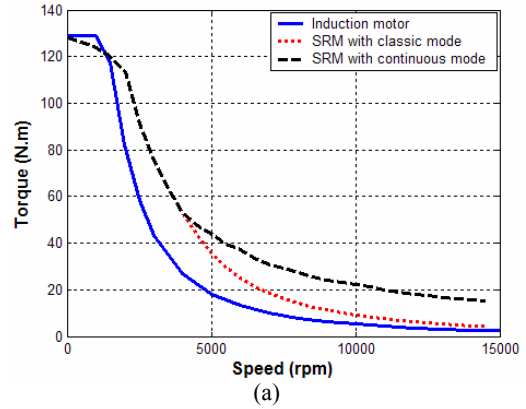


Figure 18.: Comparison of torque (a) and power (b) performance between induction motor and SRM

Figure 19 plots the efficiency of the induction and switched reluctance motors. It shows that the efficiency of the induction motor is lower than that of the SRM at low and medium speeds. This is essentially due to rotor copper losses.

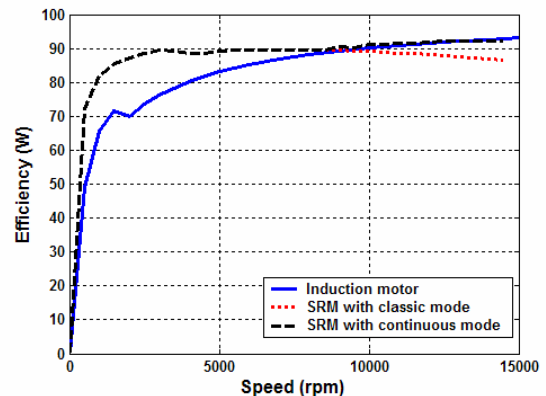


Figure 19.: Comparison of efficiency for induction motor and SRM

Despite the fact that SRM has the advantage of the low cost fabrication and the high

performances in case of use of continuous mode, it is obvious that SRM has the disadvantage of generating a large torque ripple especially at low speed which leads to vibration and acoustic noise compared to induction motors. Moreover, the control of SRM is quite challenging compared to sine-wave motors, and it needs 6 cables instead of 3 to be supplied. Much work is under way to solve problems of torque ripple, noise and vibration [10..16]. The SRM is receiving significant attention from the industry especially in the high speed range.

5. Conclusion

In this paper, an optimal control of parameters at high speed using a parametric method is presented. This method, based on preliminary parametric studies, has the advantage to be exhaustive, to yield monotonous robust maps that can be easily implemented in digital control.

In addition, the application of continuous mode at high speed has shown a very significant increase in torque and power at high speed without compromising the efficiency of the system or the rating of the inverter. This makes SRM more competitive in variable speed application compared to other technologies. A comparison of SRM and an induction motor is proposed to prove the competitiveness of the SRM.

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