

Realization, experimentation and simulation of prototypes of synchronous reluctance machines

F. Rebahi¹, A. Bentounsi, S. Yettiche and H. Khelifa

¹Ecole Nationale Polytechnique de Constantine

* E-mail : farebahi@yahoo.fr

Selected paper of JSSE'18, received in final form: March 5, 2019 ; accepted date: March 23, 2019

Abstract

The objective of this work is an approach of design, experimentation and simulation of three prototypes of synchronous reluctance machines, SynRM. After a state of research for this type of machines with interesting performances and applications, we have, for a first approach and following constraints of means of realization, opted for massive rotor topologies. The theoretical study as well as the mathematical model of the SynRM made it possible to identify the parameters of influence of the performances, in particular the inductances of direct axes, L_d , and in quadrature, L_q . After machining three topologies of reluctant rotors associated with the stator of an asynchronous machine, we have experimentally identified these two intrinsic parameters (L_d , L_q) and then carried out various simulations in dynamic mode under MATLAB / Simulink environment.

Keywords: Design; synchronous reluctance machine; parameters identification; modeling; simulation; MATLAB/Simulink.

1. Introduction

The synchronous reluctance machine (SynRM) has received a lot of attention in recent years for its multiple advantages in terms of performance and applications (high-speed electric traction, low-power wind generators, etc...). The SynRM is structurally a synchronous machine with salient poles devoid of excitation. Its stator is identical to that of conventional synchronous or induction machines where the windings are generally powered by AC three-phase currents creating a rotating magnetic field. Its rotor contains neither magnets nor excitation coils. The torque of a SynRM is created through the reluctance effect which depends mainly on the difference between the direct axis and quadrature axis inductances (L_d - L_q), that is to say the saliency of the rotor teeth. It is also shown that its power factor, generally low, is related to the ratio (L_d / L_q). To improve the performance of this type of machine, it is necessary to optimize these two parameters via the geometry of the rotor teeth. [1-5]

In this context, we have designed, with the help of the German company Ain-Smara, three SynRM prototypes with massive rotors : (i) SynRM1 made with a rotor cut to a pair of poles, rotating at 3000 rpm; (ii) SynRM2 made with a perforated cylindrical rotor (improve aerodynamics), also rotating at 3000 rpm; (iii) SynRM3 performed with a rotor with two pairs of poles, rotating at 1500 rpm. These 3 prototypes were experimentally tested and simulated under MATLAB / Simulink environment.

2. The two-axis model of SynRM and performances

2.1. SynRM model in the d-q frame

The two-phase model of the SynRM in the rotor-related d - q referential, based on Park's transformation and generally accepted simplifying assumptions, is represented by the system of equations (1). [4] [6]

$$\frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \Omega \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_d} i_{ds} + \frac{pL_q}{L_d} i_{qs} \Omega \\ \frac{-R_s}{L_q} i_{qs} + \frac{pL_d}{L_q} i_{ds} \Omega \\ \frac{p(L_d - L_q)}{J} i_{ds} i_{qs} - \frac{f}{J} \Omega - C_r \\ p\Omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_d} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \quad (1)$$

Where: (x_{ds}, x_{qs}) represent the current quantities or stator voltages along the axes d and q , R_s the resistance stator phase, p the number of poles pairs, J the moment of inertia, C_r the resistant torque, Ω the angular velocity in rad/s and θ the angular position of the rotor.

2.2. Torque and power factor expressions

The expression of the electromagnetic torque of the SynRM is given by (2) [7] [8]:

$$C_{em} = p \cdot (L_d - L_q) \cdot \frac{i_s^2}{2} \cdot \sin(2\delta) \quad (2)$$

Where δ represents the angle of the stator current vector $\vec{i}$ with respect to the direct axis d. The power factor of the SynRM is written according to (3) [9]:

$$\cos\varphi = \frac{\xi - 1}{\sqrt{2}} \cdot \frac{\sin(2\delta)}{\tan(\delta) + \xi^2 \cdot \frac{1}{\tan(\delta)}} = \frac{\xi - 1}{\sqrt{\frac{1}{\cos^2(\delta)} + \frac{\xi^2}{\sin^2(\delta)}}} \quad (3)$$

Figure 1 represents a family of curves of the power factor F_p of the SynRM as a function of the angle δ and of the ratio $\xi = L_d/L_q$. [1]

It is found that the F_p is even better than the saliency ratio ξ is higher.

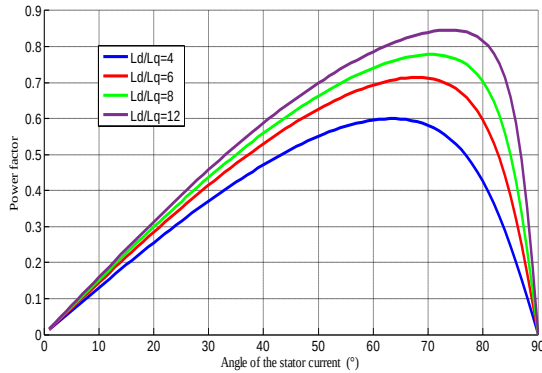


Figure 1. Power factor of the SynRM as a function of $\xi = L_d/L_q$ and δ [1]

3. Realization, testing and simulations of SynRM prototypes

3.1. Realization of SynRM prototypes

The synchronous reluctance machine, SynRM, studied here being structurally a synchronous machine with salient poles devoid of excitation, its stator is identical to that of conventional synchronous or induction machines [10] [11] [12]. Thus we took advantage of this structural remark to design prototypes of SynRM using the stator of an induction machine existing in our laboratory and then realizing only three topologies of rotors with 2 and 4 salient poles represented figures 3 to 5. [13]



Figure 2. Rotor SynRM1



Figure 3. Rotor SynRM2



Figure 4. Rotor SynRM3

3.2. Experimental determination of SynRM parameters (L_d, L_q, R_s, J)

In order to simulate the dynamic operation of the SynRM under MATLAB / Simulink, we started by carrying out various experimental tests to determine the parameters of the SynRM, namely : stator resistance, R_s , inductances, L_d and L_q , moment of inertia, J .

Concerning the measurement of the 2 inductances, we opted for a low slip test according to the experimental setup of figure 6 and the following steps:

- Determine the direction of rotation of the SynRM in motor mode
- Power the DC motor and drive the SynRM in the previous direction at speed $N = N_n$
- Power the stator of the SynRM under reduced voltage ($V_s \leq 0.5 * V_n$) and read the stator current $I_s(t)$ using Cassy-Lab connected to a PC
- Determine the 2 currents I_{smin} and I_{smax} which correspond to the 2 reactances :

$$X_d = V_s / I_{smin} \text{ and } X_q = V_s / I_{smax}$$

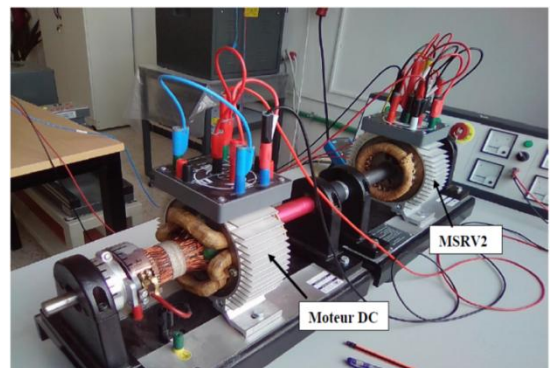


Figure 5. Low slip test setup

Table 1: Experimental values of the parameters of the three SynRM prototypes

	SynRM 1	SynRM 2	SynRM 3
$R_s(\Omega)$	0.485	0.485	0.485
$L_d(H)$	$2.55 \cdot 10^{-2}$	$2.38 \cdot 10^{-2}$	$1.54 \cdot 10^{-2}$
$L_q(H)$	$1.24 \cdot 10^{-2}$	$2.10 \cdot 10^{-2}$	$0.98 \cdot 10^{-2}$
L_d/L_q	2.05	1.13	1.57
$J(Kg.m^2)$	$2.89 \cdot 10^{-3}$	$2.53 \cdot 10^{-3}$	$2.66 \cdot 10^{-3}$

The results in Table 1 show that SynRM 1 has the best ratio (L_d / L_q).

3.3. Simulations of dynamic mode under MATLAB-SIMULINK

The functional model of the SynRM in a reference (d-q) linked to the rotor is carried out under the MATLAB-SIMULINK environment according to figure 6. [14] [15]

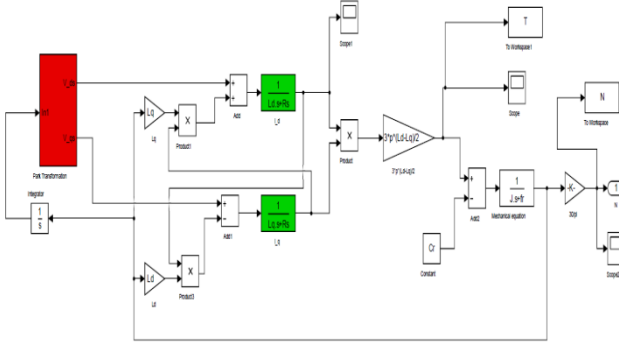


Figure 6. Simulink block of the SynRM

3.3.1. Simulation results of SynRM1 prototype

The characteristics of speed and torque at no load of the SynRM1 are shown in figures 7 and 8 respectively.

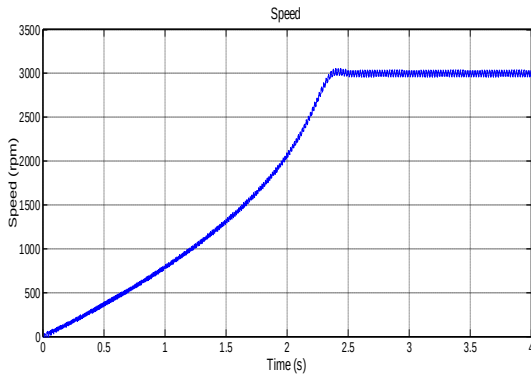


Figure 7 a. Dynamic characteristic of the speed of SynRM1 at no load

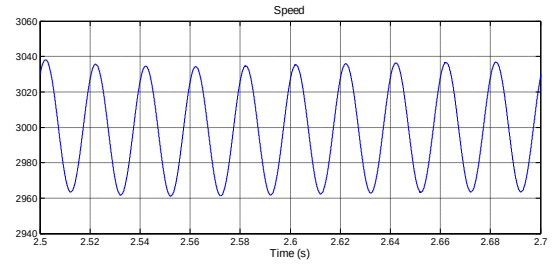


Figure 7 b. Zoom of the speed of SynRM1 at no load

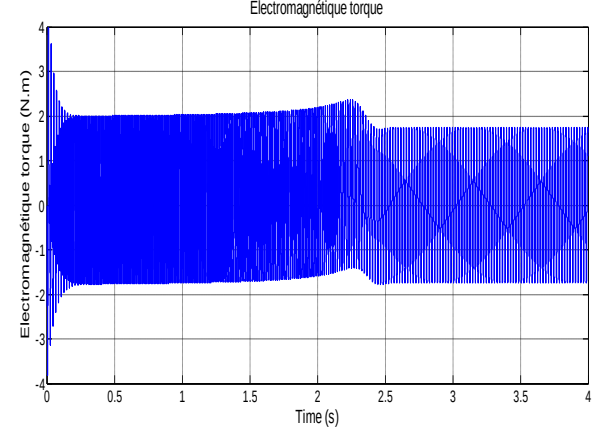


Figure 8 a. Dynamic torque of SynRM1 at no load

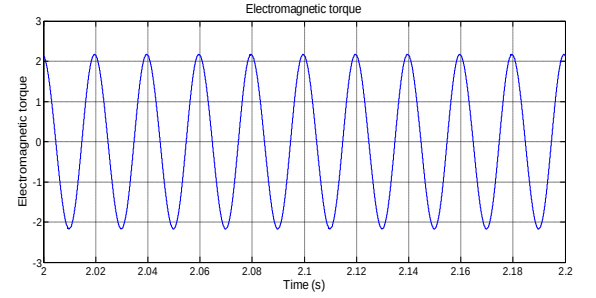


Figure 8 b. Zoom of the torque of SynRM1 at no load

3.3.2. Simulation results of SynRM3 prototype

The characteristics of speed and torque at no load of the SynRM3 are shown in figures 9 and 10 respectively.

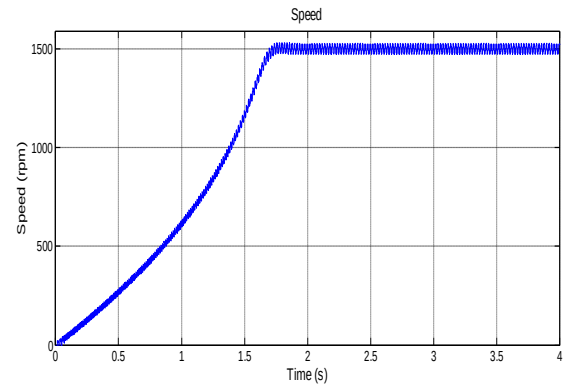


Figure 9 a. Dynamic characteristic of the speed of SynRM3 at no load

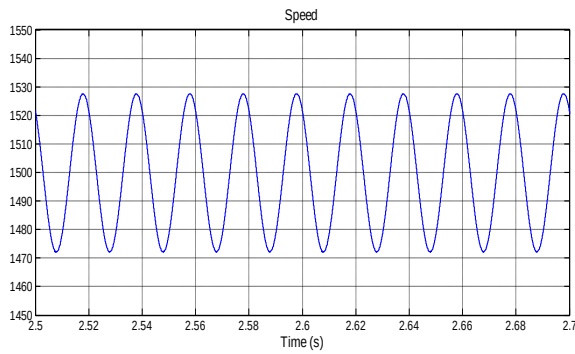


Figure 9 b. Zoom of the speed of SynRM3 at no load

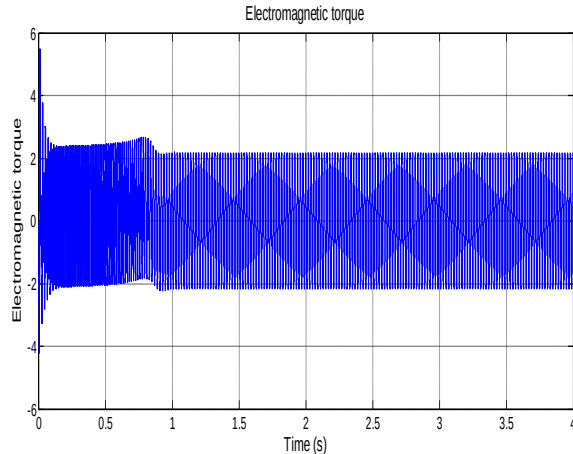


Figure 10 a. Dynamic torque of SynRM3 at no load

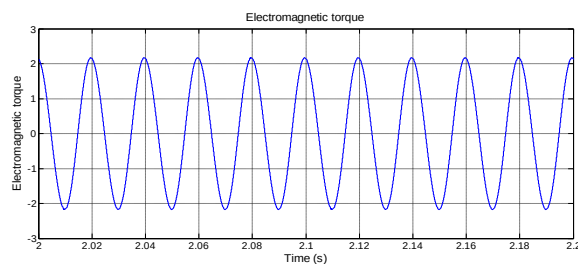


Figure 10 b.

Figure 10. Zoom of the torque of SynRM3 at no load

3.4. Discussion of results

After modeling the system at a mode dynamic using the modified Park transformation in a d-q axis frame linked to the rotor, a simulation of the empty start of the SynRM1 and SynRM3 prototypes was performed. Note that the simulation of the SynRM2 has not given usable results because of the values of the inductances L_d and L_q which are very close. The purpose of these simulations is to validate the model of the SynRM adopted with the parameters identified experimentally and to analyze the behavior of the SynRM prototypes in dynamic mode using MATLAB / Simulink software. It can be seen in figures 7 and 9 that the speed of the SynRM1 and SynRM3 has corrugations because of the pulsating pace of the torque (figures 8 and 10) produced by the interaction of the stator rotating magnetic field with the anisotropic structure of the rotor. This undesirable pulsating aspect is a known feature of variable reluctance machines.

4. Conclusion

This work focused on the realization of three prototypes of synchronous reluctance machines (SynRM) and the identification of L_d and L_q parameters of each prototype. Our interest for this type of machine is due to its many advantages (Simplicity, robustness, high performance for a relatively low cost) and applications in sectors usually invested by conventional machines, for example asynchronous type. Concerning the two MSRV1 and MSRV3 prototypes presented here, their operation seems to be satisfactory for certain aspects (synchronism speeds achieved) but not for others (vibrations, bad power factor, ...) certainly related to the nature of the magnetic material used, the bad machining of the rotors and their balancing, the leaks in the open stator (use of a dismountable machine), ...

As prospects for improvement, we are considering the use of flux barrier laminated rotors with geometry optimization using implanted algorithms under FEMM environment coupled with MATLAB / Simulink.

References

- [1] S. Hicham, "Contribution à l'étude de la machine synchrone à réductance variable", Thèse Magister en Electrotechnique, Université Biskra, 01 Juillet 2009.
- [2] I. Lamghari-Jamal, "Modélisation magnéto-thermique et optimisation de machines rapides : application à la machine synchrone à réductance variable", Thèse de Doctorat, Université Nantes, 25 octobre 2006.
- [3] G. Bueno Mariani, "Machine synchrone à réductance -Modèles équivalents à réseau de réductances pour la simulation et l'optimisation", Thèse Doctorat, Université Grenoble, 29 mars 2016.
- [4] T. Lubin, "Modélisation et commande de la machine synchrone à réductance variable avec prise en compte de la saturation magnétique", Thèse Doctorat, Université Henri Poincaré, Nancy-I, 18 Avril 2003.
- [5] T. Raminosa, "Optimisation des performances des machines synchro-reluctantes par réseaux de perméances", Thèse de Doctorat INPL, Octobre 2006.
- [6] M. Gamba, "Design of non-conventional Synchronous Reluctance machine", Thèse d'ingénieria, Politecnico di Torino Department of Energy Denerg, Avril 2017.
- [7] S. Taghavi and P. Pillay, "A Mechanically Robust Rotor with Transverse-Laminations for a Wide Speed Range Synchronous Reluctance Traction Motor," *IEEE Transactions on Industry Applications*, vol. 51, pp. 4404-4414, 2015.

- [8] J. Zekic, "Modeling and analysis of SynRM for hybrid electric vehicle application", Master's thesis in Electric Power Engineering, Chalmers Univ. of Technology, 2016.
- [9] P. Hoa Truong, "Optimisation des Performances de la Machine Synchrone à Réductance Variable : Approches par la Conception et par la Commande", Thèse de doctorat, Université Haute-Alsace, 16 Juin 2016.
- [10] M. Samer Yammime, "Contribution à l'amélioration des performances de la machine à réductance variable synchrone par la conception et l'injection d'harmoniques", Thèse de doctorat, Institut National Polytechnique de Toulouse, 6 Novembre 2015.
- [11] A. Mostafa Fellani, Daw E. Abaid, "Matlab/Simulink-Based Transient Stability Analysis of a Sensorless Synchronous Reluctance Motor", World Academy of Science, Engineering and Technology 44, 2010.
- [12] S. Sathyan, "Synchronous Reluctance Motor for Household Applications", Master of Science in Technology, School of Electrical Engineering, 12 Mars 2013.
- [13] S. Yettiche, "Conception de prototypes de machines synchrones à réductance variable", Mémoire de Master, ENPC, Juin 2018.
- [14] J. Bárta, "Computer Aided Rotor Design and Simulation of Synchronous Reluctance Machine", Doctoral Degree Program (1), FEEC BUT, 2015.
- [15] D. Caroline, V. Lanfranchi, Jean-Paul Vilain, "Conception d'une machine synchro-réductante de faible puissance sous fortes contraintes", Conférence EF, UTC, Compiègne, 24-25 Septembre 2009.