



**HAL**  
open science

## Extension of the Maximum Power Region of Doubly Salient Variable Reluctance Motors

Hedi Yahia, Rachid Dhifaoui, Bernard Multon

► **To cite this version:**

Hedi Yahia, Rachid Dhifaoui, Bernard Multon. Extension of the Maximum Power Region of Doubly Salient Variable Reluctance Motors. IMACS Conference, Aug 2000, LAUSANNE, Switzerland. 6p. hal-00674085

**HAL Id: hal-00674085**

**<https://hal.science/hal-00674085v1>**

Submitted on 24 Feb 2012

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# EXTENSION OF THE MAXIMUM POWER REGION OF DOUBLY-SALIENT VARIABLE RELUCTANCE MOTORS

H. YAHIA\*

R. DHIFAOU†

B. MULTON‡

## Abstract

This paper develops a new command strategy, ensuring the extension of the maximum power region of Doubly-Salient Variable Reluctance Machines when the phase switching control angles reach their limits. This new mode is often called Incomplete Demagnetization Operating Mode. The interest of this methodology is that the current in phase of demagnetization does not come back to zero. A new control parameter corresponding to minimum current is introduced when the optimization of the maximum possible power operation of the doubly-salient SRM. This concept is applicable to the full wave mode feeding.

**Key words:** Doubly-Salient Variable Reluctance Motors, Incomplete Demagnetization Operating Mode, Maximum Power Region.

**AMS subject classifications:** Motion Control.

## 1 Introduction

The Doubly-Salient Variable Reluctance Motors (DSVRM) has been investigated and developed for variable-speed drives during the last decade. The Motor itself is robust and reliable, practically independent on the operating environment and qualified to run both at very high speed and at low speed. It is promoting solution for a high number of domestic and automotive applications [1,2,3].

The DSVRM presents intrinsically undeniable advantages in terms of fabrication cost and robustness thanks to its simple and perfectly balanced rotor structure. In addition, they have good performances in torque and specific power. All these advantages reinforce the interest presented by the DSVRM, in high speed industrial applications (electric vehicles, variable-frequency generators, wind wheels, machine tools, etc.). In these applications, it is generally necessary to operate in a regime of a high speed flux-weakening (zone of maximum constant power), for a better use of the electronic converter [4].

The choice of the switching angles ( $\theta_{on}$  and  $\theta_{off}$ ) of switched reluctance motor drives is of great importance for the system behavior. These angles are chosen according to different objectives such as maximum power, optimum efficiency, little torque ripple or small acoustic noise radiation. The value of the rotor polar arc ( $\beta_r^\circ$ ) has a considerable importance as for the natural waveform of the inductance or the flux [5]. This value  $\beta_r^\circ$  could be determined to maximize the range of constant maximal torque operation (high values of ( $\beta_r^\circ$ )). However, if a large range of the maximal constant power operation is required, a minimal value of ( $\beta_r^\circ$ ) is necessary [6].

In the reach for a subsequent elevated power at higher speed range, feeding the machine with a full wave voltage is recommended. The electronic converter is then controlled by the two control angles ( $\theta_{on}$  and  $\theta_{off}$ ) defining the beginning and the end of the magnetization (application of the maximal voltage). This operating mode spreads from

---

\*ENIM, Tunisia, email hyahia@hotmail.com

†ISET Rades, Tunisia, email Rachid.Dhifaoui@iset.rnu.tn

‡LESIR, Cachan, email multon@ens-cachan.fr

basic speed to the maximal speed. For a given constraint of peak voltage, the maximum speed is reached, when at given  $\theta_{on}$  and  $\theta_{off}$  angles the extinction point of one phase current reaches the starting point of the following current cycle of the same phase; the safety clearance disappears [7]. The aim of this paper is to exhibit the possibility and the mechanism to extend the maximum speed under incomplete demagnetization mode operating. This new approach is illustrated by a test stand composed by an industrial switched reluctance motor, type OULTON 8/6 of 4 kW to 1500 rev/mn. The electromagnetic model of the motor is defined by the two family of characteristics flux/current/position ( $\Phi(i,\theta)$ ) and Torque/current/position ( $T(\theta,i)$ ) experimentally determined [8].

## 2 Operating under incomplete demagnetisation regime

A new operating mode is achieved such that the current in phase of demagnetization, does not come back to zero. We define a new command parameter of minimal current allowing the optimization of the DSVRM operating mode. Figure 1 shows, an electric period as function of control parameters in the case of idealized representation of an inductance associated to a phase of the 8/6 OULTON machine. The main geometrical parameters associated with the DSVRM structure are :

- $N_r$  : number of the rotor teeth = 6
- $N_s$  : number of the stator teeth = 8
- $e$  : width of air gap = 0.3 mm
- $e_c$  : thikness of the yoke = 10.5 mm
- $h_r$  : height of rotor teeth = 17.6 mm
- $h_s$  : height of stator teeth = 30.4 mm
- $r$  : radius of the rotor = 47.8 mm
- $\beta_r$  : rotor pole arc =  $21^\circ$
- $\beta_s$  : stator pole arc =  $20^\circ$

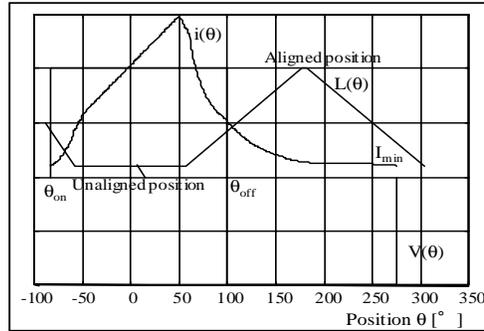
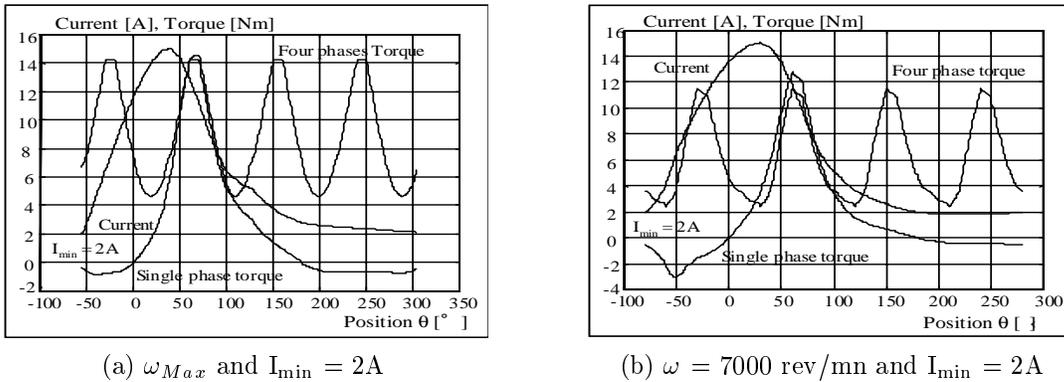


Figure 1: Definition of control parameters within one current cycle



(a)  $\omega_{Max}$  and  $I_{min} = 2A$

(b)  $\omega = 7000$  rev/mn and  $I_{min} = 2A$

Figure 2: current, single phase torque and four phase torque waveforms

Both basic and maximal speed ( $\omega_b$  and  $\omega_{Max}$ ) obtained with the limit characteristic relative to the 8/6 OULTON motor, are  $\omega_b = 1400$  and  $\omega_{Max} = 4200$  rev/mn respectively [5]. The constraints of voltage and maximal peak current are fixed to  $V_{Max} = 300V$  and  $I_{Max} = 15A$  respectively. The way of feeding is used beyond the maximal speed and it spreads from  $\omega_{Max}$  to  $\omega_H = 7000$  rev/mn for the present study. Waveforms of the current, single phase torque and four phase torque corresponding to  $\omega_{Max}$  and  $\omega_H$  and under minimum current of  $I_{min} = 2A$  are given by figures 2(a) and (b) respectively.

### 3 Extention of the maximum power operating zone

The corresponding power/speed characteristic of the flux-weakening operating mode is obtained according to the objective of maximum torque and under the same constraints of maximal current and voltage fixed to  $I_{Max} = 15A$  and  $V_{Max} = 300V$  respectively. Figure 3 illustrates this behavior. In this zone of operation, witch spreads of the basic speed to the maximal speed, the current and the torque are controlled by control angles. Beyond the maximal speed, the applied voltage and control angles are maintained constant. It is not more possible to reach the maximal current and the motor operates according to its intrinsic characteristic. However, we are concerned to improve the flux-weakening when control angles reach their limits.

The interest of the incomplete demagnetization operating mode is shown by figures 4(a) and (b). The power/speed characteristic is compared to the intrinsic one. The lattes corresponds to two levels of the minimal current of 1A and 5A respectively. Conditions of simulation are maintained in the same objective of maximization of the torque and under the same constraints of maximal current and voltage.

From these characteristics, we note that incomplete demagnetization operating mode permits to extend the maximal power operating range effectively and improve the flux-weakening of the MRVDS. The power developed on this zone of operating decreases with the increase of the minimal current limitation. For a given speed, the evolution of operating cycle in the plan "flux/current" for the two values 1A and 5A of the minimal current shows that the energizing cycle decreases with the increase of the minimal current (figure 5).

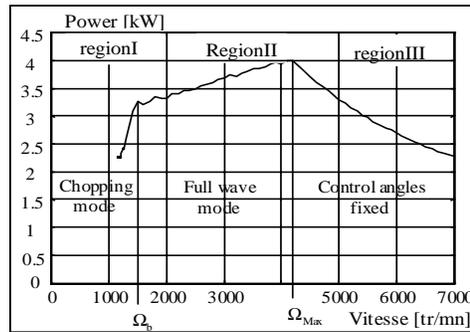
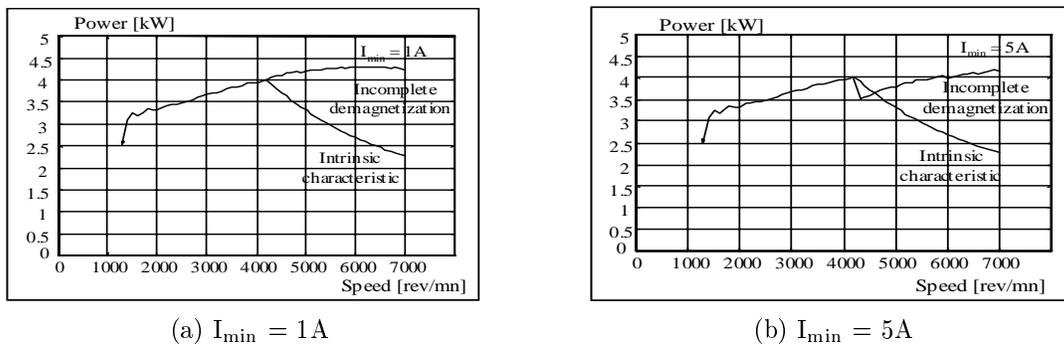


Figure 3: Power/speed Characteristic 8/6 OULTON machine ( $\beta_r = 21^\circ$ ,  $\beta_s = 20^\circ$ ,  $I_{Max} = 15A$ )



(a)  $I_{min} = 1A$

(b)  $I_{min} = 5A$

Figure 4: Available maximal power/speed characteristic

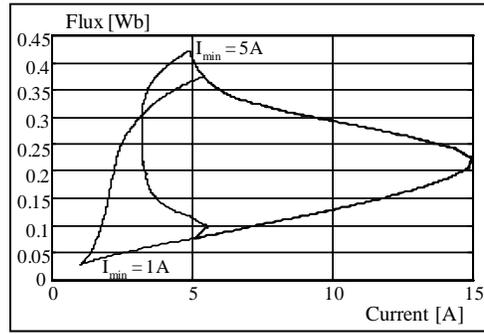


Figure 5: Influence of minimal current limitation on the energizing cycles ( $I_{min} = 1$  and  $5A$ )

### 4 Limits of the maximal power region under incomplete demagnetization regime

The incomplete demagnetization operating mode constitutes a new approach of operating to high speed of doubly-salient variable reluctance motors. In what follows, we try to surround limits of this operating mode in the power/speed characteristics. Figure 6 shows the evolution of the available maximal power according to the rotor speed for different levels of minimal current limitation. The operating at maximal constant power with a large range of speed is accorded in presence of a relatively elevated minimal current ( $I_{min} = 3A$ ). The operating at minimal current above  $2A$ , permits to have an unlimited maximal speed (figure 7).

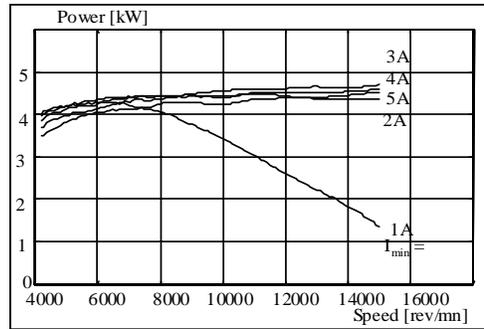


Figure 6: Power/speed characteristics under incomplete demagnetization operating mode

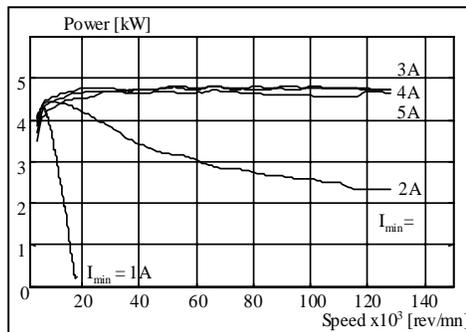


Figure 7: Limits of maximal power region for different levels of the minimal current

## 5 Consequences of the operating at high speeds

Numerous simulation cases on the possibilities of incomplete demagnetization operating mode of the DSVRM are theoretically very interesting and reveal effectively that the field-weakening can be improved. A first conclusion is provided here, at the level of the copper losses and the torque ripple compared to those obtained in flux-weakening regime. By the way of the copper losses, we chose to represent the evolution of the squared RMS current/average power ratio ( figure 8). The evolution of ripple torque is shown in figures 9(a) and (b).

We notice that the  $(I_{RMS}^2/P_{av.})$  remains constant over all speed range covering the flux-weakening zone and the incomplete demagnetization zone. Above 8000 rev/mn, this ratio increase for a minimal current of 1A (corresponding power/speed characteristic shown in figure 6 decreases from 8000 rev/mn). as for torque ripple characteristics, they increases nearly linearly when the level of minimal current limitation is superior to 2A. They become excessive for 1 and 2A and deserve other ways of investigating therefore.

Another phenomenon observed when field-weakening mode of operation of a DSVRM and that deserves to be raised here. Power/speed characteristics measured are superior to characteristics obtained by the simulation [5]. The DSVRM having the particularity to be able to operating on only single phase, it is easy to annul effects of magnetic coupling between phases. In this mode of operation, the simulation by a model without coupling provides results very closed to experimental results. Effects of magnetic coupling were therefore responsible of this increase of torque (figure 10). The hypothesis of model " multi-single phase " finds his limits when the DSVRM operating at maximal constant power and to high speed.

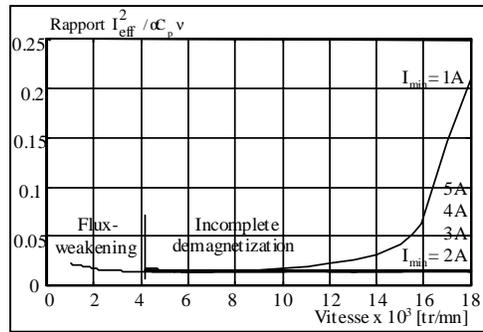
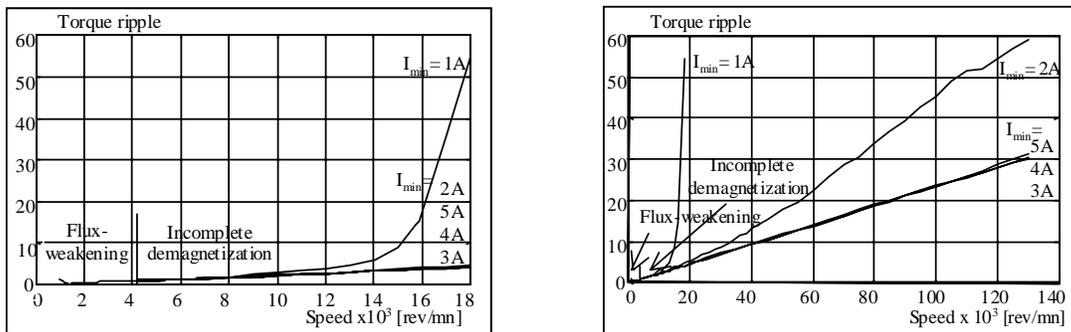


Figure 8: Evolution of  $(I_{RMS}^2/P_{av.})$  ratio under incomplete demagnetization mode



(a) under incomplete demagnetization mode

(b) very high speeds

Figure 9: Evolution of torque ripple

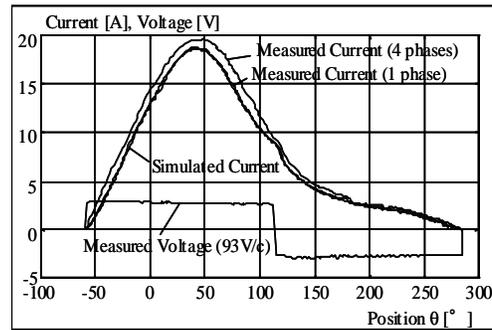


Figure 10: current waveforms of four phases and single phase feeding

## 6 Conclusion

In this paper, we studied an incomplete demagnetization operating mode of doubly-salient variable reluctance motors. This mode of operation permits to extend the range of operating at constant maximum power above the maximal speed attained by action on control angles. Limits mode of operation to high speed as function of minimal current level are also discovered for an industrial machine of type OULTON 8/6. The hypothesis consisting in using a "multi-single phase" models for the DSVRM when operating at maximal constant power and to high speed has been raised. To high speed, we can say a priori, this are not terms of coupling in the inductance matrix who contributes to increase the torque, it is rather bound to the fact that the flux depends on the four currents and no of one alone.

## References

- [1] P.J. Lawrenson, J.M. Stephenson, P.T. Blenkinsop, J. Corda, N.N. Fulton, *Variable-Speed Switched Reluctance Motors*, Proceedings IEE, Vol. 127, Pt. B, No. 4, July 1980, pp.253-265.
- [2] U. Steiert, H. Spath, *Torque control of the doubly-salient reluctance motor*, ETEP Vol. 3, No.4, July/August 1993.
- [3] R. Orthmann, H. P. Schoner, *Turn-off angle control of switched reluctance motors for optimum torque output*, EPE, Brighton'93, pp.20-25.
- [4] J. Y. Le Chenadec, M. Geoffroy, B. Multon, J. C. Mouchoux, *Torque ripple minimisation in switched reluctance motors by optimisation of current wave-forms and tooth shape with copper losses and VA silicon constraints*, ICEM'94, Vol.3, pp. 559-564.
- [5] H. Yahia, *Study of field-weakening possibilities of a doubly-salient switched reluctance motors*(in french), PhD Thesis report, Universite des Sciences, des Techniques et de Medecine de TunisII, Fevrier 1999.
- [6] B. Multon, S. Hassine, J. Y. Le Chenadec, *Poles arcs optimisation of vernier reluctance motor supplied with square wave current*, Electric Machines and Power System, Vol. 21, no. 6, 1993, pp. 695-709.
- [7] R. Orthmann, A. Krautstrunk, H. P. Schoner, *Overload protection and maximum power operating point control of switched reluctance motor drives*, EPE, Trondheim 1997, pp. 3.602-3.607.
- [8] H. Cailleux, J. C. Mouchoux, B. Multon, E. Hoang, J. Y. Le Chenadec, *Comparison of measurement methods to determine the electromagnetic characteristics of switched reluctance motors*, EPE, Symposium on Electric Drive Design and Applications, Lausanne, 19-20 October 1994, pp.639-644.