Maximum Power Limits in the Field-Weakening Mode of Doubly-Salient Variable Reluctance Machines

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Abstract

This article is aimed at determining operation possibilities in the field-weakening mode of Doubly-Salient Variable Reluctance Motors (DSVRM). A poor literature has evoked this topic. Firstly, the field-weakening mode of operation is presented by the adoption of piecewise model and the results are then used to study the effects of the structural combination of the DSVRM by the experimented defying models and a two-dimensional finite elements computation. The effect of the rotor pole arc on the flux-weakening region is experimentally tested by the realization of two new rotors and by the implementation of a command and control strategy based on a digital signal processing. Experimental results on a four-phase machine show limitations without the coupling model of DSVRM.

Index Terms - *Doubly-Salient Variable Reluctance Machine, Field-Weakening, pole arcs.*

Nomenclature

N_s : number of the stator teeth
N_r : number of the rotor teeth
q : number of phases
L_u : unaligned inductance
L_a : aligned inductance
r : L_a/L_u ratio
I_{RMS} : RMS current
I_{Max} : maximum current
θ_{on} : turn-on angle
θ_{off} : turn-off angle
θp_u : unaligned angular duration
θp_a : aligned angular duration
$D\theta_p$: angular increasing of the inductance
ψ : advance angle of the voltage waveform ($\psi = -\theta_{on}$)
β_s° : stator pole arc
β_r° : rotor pole arc
Ω_b : base rotor speed
Ω_{Max} : maximum rotor speed

1. Introduction

A wide range of speed in flux-weakening mode is very useful in certain applications such as spindle drive in machine tools, electric traction (road or railway), variable frequency generators (car generators, planes, wind wheels), etc. During the last decade, Permanent Magnet Synchronous Motors and Synchronous Reluctance Motors have been made the subject of several studies and realizations concerning flux-weakening mode [1, 2]. The possibilities as well as the strategies, of analysis and control, developed for Synchronous Motors are described in numerous publications [3, 4, 5, 6].

In the flux-weakening region, if we consider the strategy adopted for low speeds (below the base speed), the power decreases rapidly as well as the speed of feeding component are limited (limiting maximum current and voltage). These different studies showed by an adequate control strategy have capability to maximize the power in the flux-weakening region (above the base speed). The evolution of the power as a function of speed depends on the type of motor and its electromagnetic characteristics. By analogy to Direct Current Motors operated with separate excitation, the flux-weakening region is often called maximum constant power mode of operational zone. Less work has been done to address the possibilities of flux-weakening mode operation of Switched Reluctance Motors, that is why this study is motivated with aiming at strategies mentioned below:

- to understand the mechanism of flux-weakening mode of operation of these motors,
- to determine the influence of their magnetic characteristics, and their geometric parameters on the maximum power curve.

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2. Extension of the Speed Range of DSVRM

It has been noticed that, there is an increasing need for high-speed electric actuators, in order to replace the convention used in mechanical transmission systems (e.g. in automotive applications). By this application domain where cost, the performance and the reliability are very important aspects, it has been shown that, by driving DSVRM acted as a possible alternative to other types of motors [7]. Besides its economical, robust and simple construction, this type of machine features a relatively high torque/inertia ratio. These characteristics, among others, make DSVRM an attractive candidate to applications especially in hostile environments (high level of vibration, corrosive atmosphere, high temperatures, etc.).

In the range of speeds that are higher than the base speed, a possible way to meet high power for the machine, is by feeding it, with full wave voltage. The electronic converter is then driven by two control angles (θ_{on} and θ_{off}) defining the beginning and the ending of the magnetization (applied maximal positive voltage). In order to maintain the maximum power at a sufficient level in the flux-weakening region, it is necessary to start increasing the current before the unaligned position, due to the negative electromotive force. The choice of the driving angles is important for the system behavior, and these are optimized with respect to different objectives, such as maximum power, maximum efficiency, reduced torque ripple, and low acoustic noise. For a given maximum value of the current, the maximum developed torque is attained by action on θ_{on} counted from the unaligned position and then by action on θ_{off} in relation with the end of magnetization. The possibility to extend the operating range at maximum power by action on the command and geometric parameters is shown by a study on a test stand including an industrial DSVRM of the type OULTON™ 8/6 of 4 kW at 1500 rpm. The electromagnetic motor model is defined by flux/position/current $\Phi(\theta,i)$ and the torque/position/current $T(\theta,i)$ characteristics were experimentally determined at [8]. The power/speed characteristics (shown in figure 1) are determined with respect to the torque (or power) maximization objective and under the constraints of fixed peak voltage and current 300V and 15A, respectively.

Taking into account, the RMS current is one of the most important criteria for sizing the motor and its electronic converter. However, as long as the RMS current is minimized or kept constant at which its value is lower than what is attained at the base speed, we can improve the power/speed characteristic and extend the maximum power operating range [9]. The required power/speed characteristic for a RMS current is limited at 6A is shown in figure 2. The geometrical parameters as well as the strategy of control [10] define the torque/speed characteristics of the DSVRM.

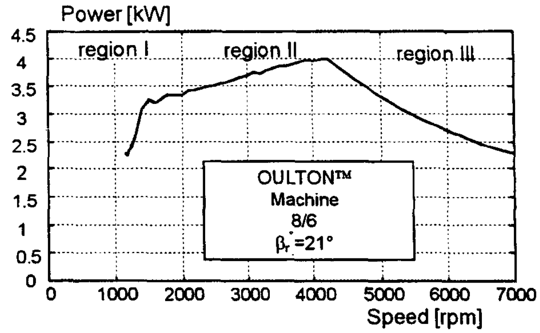

Figure 1: Power/speed characteristics (8/6 OULTON™ Motor, $\beta_r^\circ = 21°$, $\beta_s^\circ = 20°$, $I_{Max} = 15A$)

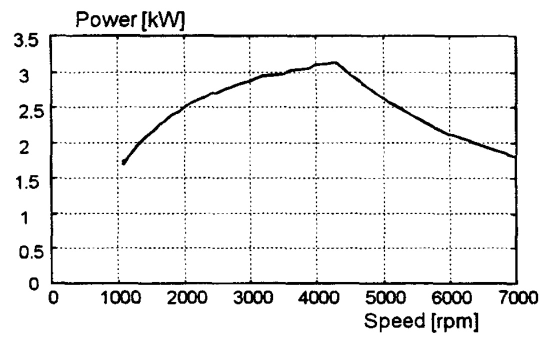

Figure 2: Power/speed characteristics (8/6 OULTON™ Motor, β_r=21°, β_s=20°, RMS current = 6A)

Depending on the speed, the operating mode could be in one of the following possible regions: the first region of the DSVRM characteristic is the rest position up to the base speed, and it is corresponding to operate at constant maximum torque. The current control is obtained by voltage pulse width modulation. The second region is active beyond the base speed where the maximum voltage limit is attained (maximum power operating region). Current and torque are under controlled, by adjusting control angles. In the third region, the driving voltage and the command angles are kept at fixed levels. It is not possible to attain the maximum current and the motor operates according to its intrinsic characteristics.

3. Simplified Analysis Influencing the Possibilities of Operation in Flux-Weakening Mode

Firstly, to realize a general study, we can neglect the magnetic saturation and suppose that the inductance $L(\theta)$ depends linearly on the angle of overlapping of rotor and stator teeth [11]. It takes a minimum value (L_u) in unaligned position and a maximum value (L_a) in aligned position. Between these two extreme values, we assume that the function $L(\theta)$ remains constant at L_u in unaligned position as the stator and rotor pole are not overlapped; i.e. during a mechanical angle equal to :

$$\theta_{pu} = (\frac{2\pi}{N_r} - \overset{\circ}{\beta_r} - \overset{\circ}{\beta_s}) \quad (1)$$

After that, the inductance starts a linear increase from L_u to L_a during an electrical angle:

$$D\theta_p = N_r \min(\overset{\circ}{\beta_s}, \overset{\circ}{\beta_r}) \quad (2)$$

Finally, the inductance again remains constant through the region of complete overlap, therefore during an electrical angle:

$$\theta_{pa} = N_r \left|\overset{\circ}{\beta_s} - \overset{\circ}{\beta_r}\right| \quad (3)$$

The electromagnetic piecewise model is represented in figure 3. On this figure, we define two new angular parameters:

$$\theta_1 = \frac{\theta_{pu}}{2} \quad (4)$$

$$\theta_2 = \theta_1 + D\theta_p \quad (5)$$

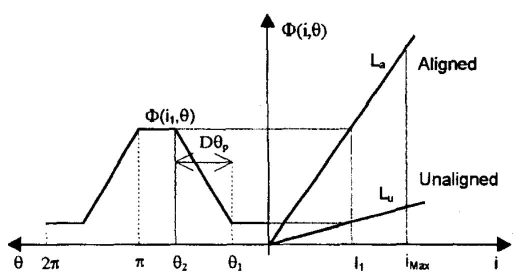

Figure 3: Electromagnetic piecewise model

The main normalized parameters are:
- normalized voltage taken equal to the unit (V_{Max}=1 pu),
- maximum current taken equal to the unit (I_{Max}=1 pu),
- aligned inductance taken equal to the unit (L_a=1 pu).

We study the influence on flux-weakening mode of operation of following parameters:
- ratio variation of inductance in aligned and unaligned position (L_a/L_u) or magnetic salient ratio,
- the angular position (θ_1) beginning of the phase of inductance growth,
- the angular length in growth of inductance ($D\theta_p$).

Parameters θ_1, $D\theta_p$ and L_a/L_u defining the linear model of reference used are respectively 30°, been able to 120° and 10.

3.1. Influence of the magnetic salient ratio

The inductance L_u is inversely proportional to the ratio of the magnetic saliency (L_u is maintaining constant in this study). To attain its maximum value at the position θ_1, the current, corresponding to a low magnetic salient ratio structure needs an important advance angle ($-\theta_{on}$) which therefore limits the speed variation range. We chose to vary it in the range 3 to 10, with respect to the same base structure. The operating range at maximum power as a function of this same ratio is presented in figure 4. We notice an increase of the speed range when the magnetic salient ratio increases, similar to what was observed for synchronous reluctance motors [5].

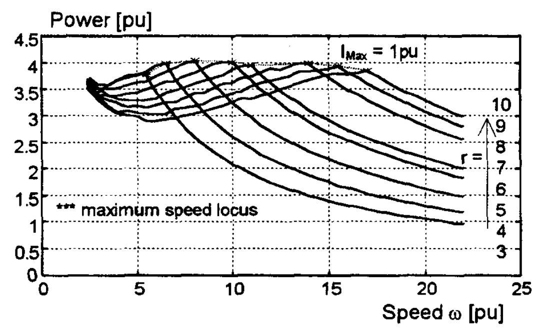

Figure 4: Influence of the L_a/L_u ratio on the power/speed characteristics (θ_1 = 30°, $D\theta_p$ = 120°, q = 4)

3.2. Influence of the angle θ_1

The angle θ_1 depends on the variations of the rotor teeth angle as well as on the variations of the stator teeth angle (equation 1). An optimum value of the rotor teeth angle permits the current regulation to obtain a maximum torque with an acceptable one (without going to a full wave mode) [12]. To study the sensitivity of the flux-weakening mode to the angular parameter θ_1, other structures have been simulated. A model containing the digital characteristics $\Phi(\theta,i)$ and $T(\theta,i)$ from the spatial distribution of the inductance, is established for each structure.

The effect of the variation of θ_1 on the power/speed characteristics is shown in figure 5. We notice that the base speed is not affected by the θ_1 variation. However, the maximum speed become high with the increasing θ_1. It goes from 11.5 to 21pu, when the angular position θ_1 goes from 0 to 60°.

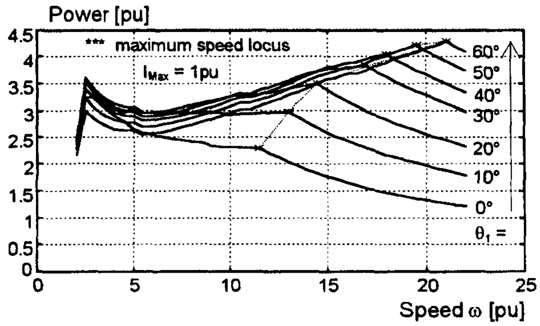

Figure 5: Influence of θ_1 on the power/speed characteristics ($r = 3$, $D\theta_p = 120°$, $q = 4$)

3.3. Influence of the angular duration on the inductance increasing $D\theta_p$

In a switched reluctance machine, the torque production can only be done during the interval $D\theta_p$ (piecewise model). The stator polar arc affects this range of production when the rotor polar arc β_r° has a higher value than the stator polar arc β_s° (equation 2). The results, are related to the effect of $D\theta_p$ variation in the process of operation at a maximum power, are shown in figure 6, under the same constraints of maximum voltage and current for the aim of maximizing the torque.

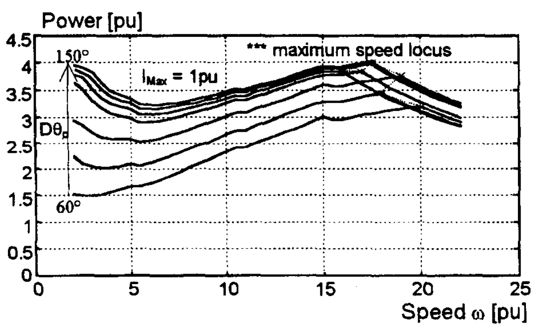

Figure 6: Influence of $D\theta_p$ on the power/speed characteristics ($\theta_1 = 30°$, $D\theta_p = 120°$, $q = 4$)

We notice that from the base structure and for these idealistic conditions:
- the maximum speed increases considerably with increasing θ_1 proving the possibilities of operation at maximum power for a large range of speed,
- the increase of $D\theta_p$ is favorable to an increase of the deliver power,
- the increase of the magnetic salient ratio also permits the extent of the speed range, however with a loss of the output power.

3.4. Consideration of magnetic saturation

In order to determine the domain of validity of the linear model using a trapezoidal partition of the inductance to evaluate the potential of doubly salient switched reluctance machines, we chose to compare the results of this model with those of a continued numerical model corresponding to the OULTON™ machine. Figure 7 reveals this comparison for two levels of maximum current, 6 and 15A.

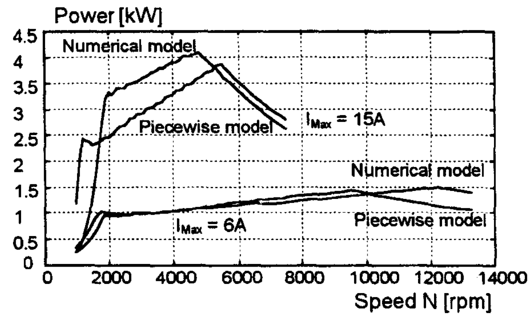

Figure 7: Comparison of computation results with piecewise and numerical models (8/6 OULTON™ machine, $I_{Max} = 6A$ and 15A)

In the non-saturated regime (maximum current limited to 6A), we notice a good agreement between the two characteristics. The simplified conditions, for which we have realized this study, gave satisfactory results, which are very convenient for a preliminary analysis. In the saturated regime (maximum current limited to 15A), the piecewise model shows limitations, in fact, the magnetic saturation allows an increase in power. The extension of these results will be used to examine the rotor pole arc effect using the furnished experimental models and/or finite element computation.

4. Influence of the Rotor Polar Arc

At a given value of β_s° (generally by start and torque ripple conditions), the value of β_r° can be chosen with respect of constraints of the moment of inertia and the required torque/speed characteristic. A high value gives a large aligned angular duration, which renders the demagnetization easier and allows a better regulation of the optimized current forms in order to minimize the torque ripple. On the other hand a low value increases the unaligned angular duration and permits an extension of the maximum power curve in the flux-weakening regime, but renders one more difficult by obtaining a low instantaneous torque ripple [13].

With the geometric parameters of the OULTON™ machine are conserved, we have varied the rotor polar angle in the range 10 to 35°. The corresponding electromagnetic characteristics were determined by a two-dimensional finite element modeling. The simulation results are shown in figure 8.

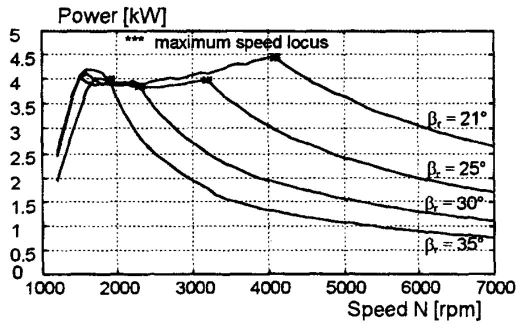

Figure 8: Influence of the rotor pole arc on the power/speed characteristics ($\beta_s = 20°$, $I_{Max} = 15A$)

From the power/speed characteristics (figure 8), we notice that the operation at a power of 4 kW (rated power of the machine at 1500 rpm) is insured on the whole range of speed (Ω_b - Ω_{Max}) for an increase of β_r° ($\beta_r^\circ > \beta_s^\circ$).

5. Experimental Validation

To experimentally validate the simulation results relate to the rotor polar arc effect on the possibilities of operation in the flux-weakening regime, we chose to realize two new rotors having rotor angles of β_r° of 21° and 30°, respectively (photo 1). A test bench was also setup, experimentally consisted of an industrial switched reluctance machine coupled to a direct current machine, of a converter, and an electronic control constructed around a digital signal processing: the TMS320C26. The experimental results of the power/speed characteristics with the two new rotors are shown in figure 9.

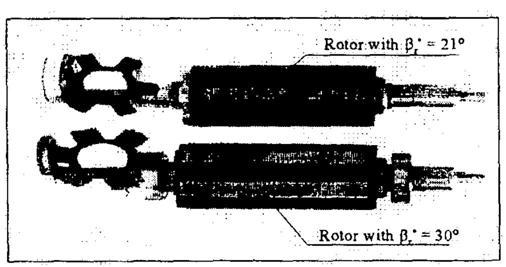

Photo 1: New rotors

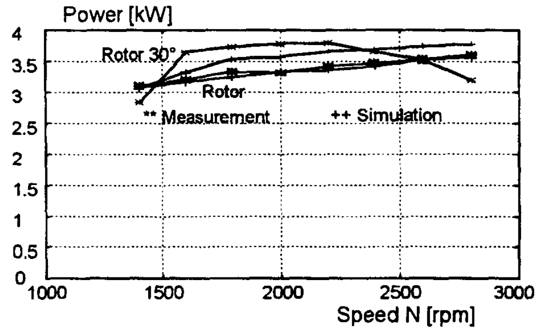

Figure 9: Comparison measurement/simulation of the power/speed characteristics

From the comparison of the measurement/simulation curves with the 21° rotor, we notice a small disagreement between the measurement and the simulation. The standard deviation is 12W. The maximum speed reached by the 30° rotor machine is 2400 rpm from the simulation. For the same measured of power/speed characteristics, we notice that the continuous current machine features a maximum power until the speed of 2800 rpm. This measured power is higher than simulation of speed mentioned above. The registered current waveforms at 2500 rpm are shown in figure 10 and furnish a first element of response. In fact, we notice that the measured current increases more rapidly at this speed and its average value is higher than what is simulated, thus resulting is more important for torque and power. This phenomenon is the result of the hypothesis of neglecting the magnetic coupling of the different phases. This hypothesis is not satisfactory achieved when the machine operates in flux-weakening mode.

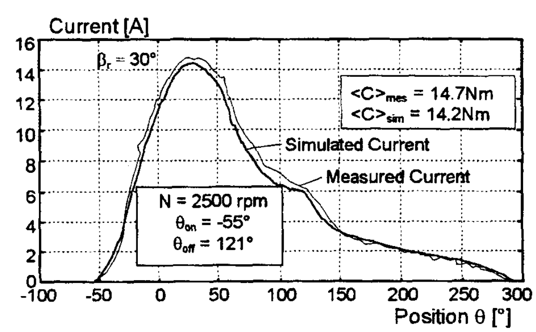

Figure 10: Comparison of current waveforms measurement/simulation (β_r° =30°)

To show the effect of the magnetic coupling between phases, we have registered the current waveforms with a normal operating phase of the DSVRM (four phases feeding), and then with a single phase feeding. The answer is in figure 11: we notice a perfect agreement between the measured and the simulated current waveforms when a single phase is feeding, however when the four phases are used, the measured current features a higher value.

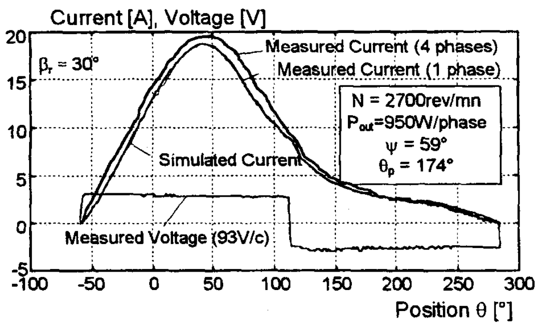

Figure 11: Waveforms for four phases and single phase feeding

6. Conclusion

In this work, we tried to find the optimum parameters for operation with doubly-salient switched reluctance motors. To realize a general study of the influence of the electromagnetic machine parameters, we chose a piecewise model thus allowing a preliminary study. The control angles have a very important effect on the torque quality. High magnetic saliency ratio is favorable to high field weakening speed range. The maximum power curve, in flux-weakening mode, can be extended when a minimum rotor polar arc is used. However, this results are more important for torque ripple.

The experiment-attained performance of high speed is higher than what is predicted by the simulation. The effect of the magnetic coupling proved to be the cause of this difference. The determination of the DSVRM maximum power characteristics in the flux-weakening regime is not satisfy with the single-phase magnetic model, and it proves necessary to consider the magnetic coupling between phases. This is useful for the precise determination of the torque ripple. The most limiting factor that arises, is the heavy numerical code of the non-linear electromagnetic model and the flux characteristic of a phase is the function of the q currents and the position. In addition, to the four phases machine, the power in unidirectional current resulted an asymmetry and the four currents of the phase cannot be identical.

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