The Switched Reluctance Generator for Wind Power Conversion

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Abstract. The use of wind energy has become increasingly important as a renewable energy source, and therefore there is an increasing interest in exploiting it using a Switched Reluctance Machine (SRM) as a generator and optimise its characteristics in this domain. It is in this context that this paper analyzes the generator mode of the SRM 1) in a direct coupling to the turbine shaft and 2) coupled to the shaft through a gearbox. This paper is aimed at analyzing and proposing an alternative technical solution for wind power conversion, regarding the electrical generator system.

Keywords

Switched Reluctance Generator, Direct-drive Wind Turbine, Current Control Strategy, Torque Ripple, Power Electronic Converter

1. Introduction

In the last decades the SRM has become an important alternative in various applications both within the industrial and domestic markets, namely as a motor showing good mechanical reliability, high torque-volume ratio and high efficiency, plus low cost.

Although less evangelized as a generator, there are a few studies of its application in the aeronautical industry and in integrated applications in wind based energy generators.

Although easy to build, the SRM in the past was a source of complaints concerning to its dynamic performance and the peculiar characteristics of its command and control. At the time, these arguments were sufficiently convincing to stop a sustained development and research of this kind of machine [1]. The development of power electronics, and specially the advancements in the field of semiconductors brought improvements in the command and control technology of this kind of machine, thus spearheading a diversified application of SRMs.

The principles of operation of this machine are simple, well known and based on reluctance torque. The machine has a stator of wound-up salient poles that after energising synchronized with the position of the rotor develops a torque that tends to align the poles in a way that diminishes the reluctance in the magnetic circuit.

Currently the synchronous and induction machines dominate the market of wind energy applications, although, the SRM has been the subject of current investigation and it shows to be a valid alternative for this field [2].

Comparing with the classical solutions of machines integrated in wind applications, a Switched Reluctance Generator (SRG) shows a simplified construction associated with the inexistence of permanent magnets or conductors in the rotor, which results in lower manufacturing costs; in addition both the machine and the power converter are robust. The low inertia of the rotor allows the machine to respond to rapid variations in the load.

Associated with these characteristics, these machines have a control system that allows rapid changes in the control strategy such that the performance of the machine is optimized.

The structure of the SRM is not as stiff as the synchronous machines, and due to its flexible control system, it is capable of absorbing transient conditions, thus supplying more resilience to the mechanical system [3]. The machine has an inherent fault tolerance, especially when under an open-coil fault (in the windings) and in the power converter (external faults) [4]. Under normal operation, each phase of SRG is electrically and magnetically independent from others [5].

The SRM is generally felt to be louder than conventional machines. However an adequate mechanical design can do a lot to improve these figures and new control techniques – current control strategy with a torque reference – permits further improvements.

2. SRG operation

In electrical drives with variable reluctance, as shown in Fig. 1, the torque is function of the angular position of the rotor due to the double salient poles. The operation of this machine as a generator is obtained by energising the windings of the stator when the salient poles of the rotor are away from their aligned position due to the rotating motion of the prime mover. A commercially available switched reluctance machine used in this study was a 2,4-kW 4-phase 8/6 machine.

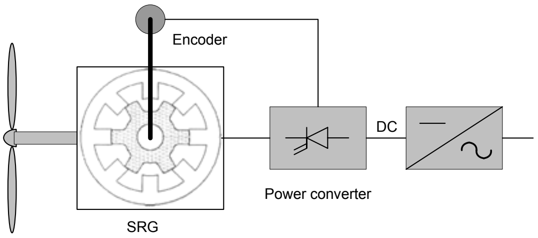


Fig. 1 Switched reluctance generator in a wind turbine

The Switched Reluctance Machine (SRM), although being simple from the construction point of view, it's characterized by a peculiar mode of controlling its phase currents. For that matter a power electronic converter is used, which functions in a way that the phase currents of the machine are imposed for certain positions of the rotor. In this study is used a standard topology of the converter usually applied in SRM drives, given that it provides a greater flexibility regarding its control and better fault tolerance. Another reason of its reliability during fault conditions is the electrical independence among phases [4]. The control system of this converter must regulate the magnitude and even the waveshapes of the phase currents to fulfil the requirements of torque and output power available and to ensure safe operation of the generator. This implies that the electronic switches associated with controller are fully controlled devices. These devices work to invert the voltage applied to the phases in certain angular positions of the rotor and also assist phases' commutations. The topology shown in Fig. 2 uses power transistors (IGBT or MOSFET) that work as electronic switches. The capacitor shown in the aforementioned topology prevents fluctuations in the voltage Vs.

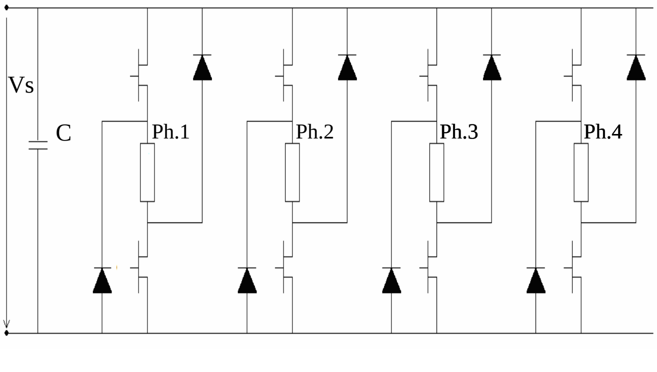


Fig. 2 –Circuit diagram of the 4-phase converter for SRG

If losses are neglected the output energy over each stroke exceeds the excitation by the mechanical energy supplied [6]. It is considered that there is no magnetic saturation and each phase is magnetically independent from others. In these terms, the expression of the instantaneous power (p) available in a SRG is expressed as in (1), where: n- number of phases; j- phase number; θ - rotor position; ω - rotor speed; i_j - Current in phase j ; $L_j(\theta)$- inductance of phase j as a function of θ.

$$p(\theta, i_1, i_2 \ldots i_n) = \left[\frac{1}{2} \sum_{j=1}^{n} \frac{dL_j(\theta)}{d\theta} i_j^{\,2} \right] \omega \qquad (1)$$

$$j = 1, \ldots, n$$

The average power available P, resulting from the operation of the machine as a generator, is (excluding losses) equal to the mechanical power. Thus, its value can be obtained from the expression of the average value of the torque T_m using equations (2) and (3), where N_r is the number of rotor poles.

$$P = T_m \, \omega \qquad (2)$$

$$T_m = \frac{N_r}{2\pi} \int_{o}^{2\pi / N_r} \left[\sum_{j}^{n} \frac{1}{2} \frac{dL_j}{d\theta} i_j^{\,2} \right] d\theta \qquad (3)$$

$$j = 1, \ldots, n$$

The above equations enable us to infer that the obtained power is approximately constant and it reaches a maximum when the dwell angle is located, entirely, in the descending section of the phase inductance profile, which corresponds to the highest average torque [7]. For this kind of machines the torque ripple appears mainly in the commutation zones related with the sequential process of establishing and removing the phase currents. The imposition of phase current waveform using a current control with an adjusted hysteresis band and a sufficient input voltage, allow a torque ripple reduction.

In this way the ripple can be minimized, thus controlling the phases currents commutation precisely phased relative to the rotor position. For that effect the current control is done using a trapezoidal phase reference torque model [8]; two adjacent phases can be supplied at the same time to ensure continuity in the generated torque.

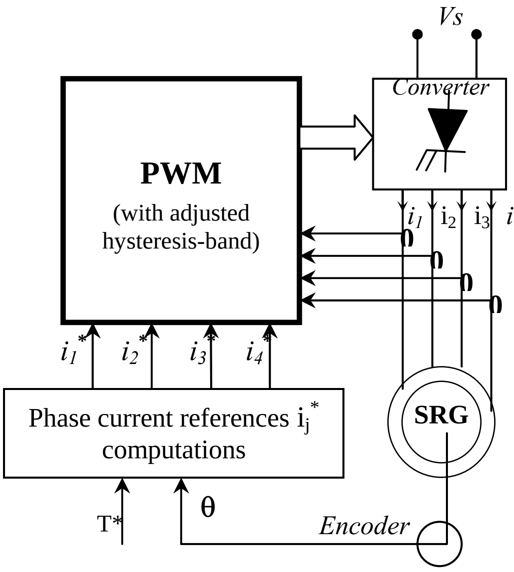
The SRM is capable of operating continuously as a generator by keeping the dwell angle so that the bulk of the winding conduction period comes after the aligned position, when $\frac{dL_j}{d\theta} < 0$.

The waveforms of the of the phases reference current, i_j^*, resulting from the desired torque T^* , are given by equation (4), and are themselves the reference signal to be treated using the feedback pulse with modulation (PWM) technique with adjusted hysteresis-band.

$$i_j^* = \sqrt{\frac{2.T_j^*}{\frac{dL_j(\theta)}{d\theta}}} \qquad (4)$$

$j=1,\ldots,n$

The block diagram shown in Fig.3 exemplifies a current control with torque reference applied to the 8/6 SRG, where the waveforms of the reference currents (i_1^*, i_2^*, i_3^*, i_4^*) are calculated using the trapezoidal model torque associated to each phase (T_1^*,T_2^*,T_3^*,T_4^*).



The following figure – Fig. 4 – shows the phase inductance profile and the corresponding phase torque positioned in the region where the machine works as a generator.

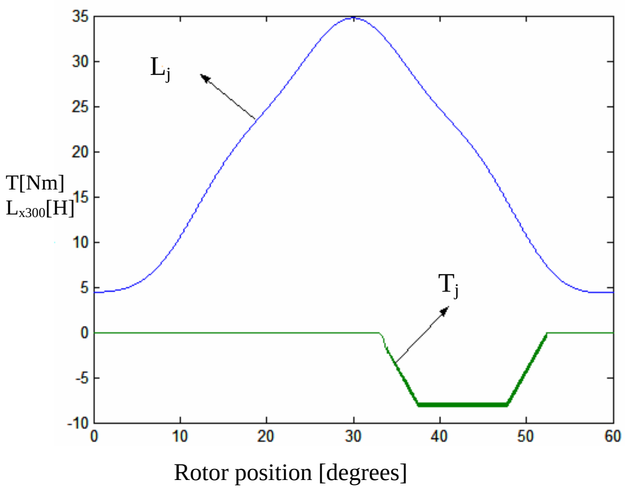


Fig. 4 – Phase torque

Fig. 5 represents the phase current resulting from the trapezoidal phase torque reference shown previously. The total instantaneous torque for the 8/6 SRG is represented in Fig.6.

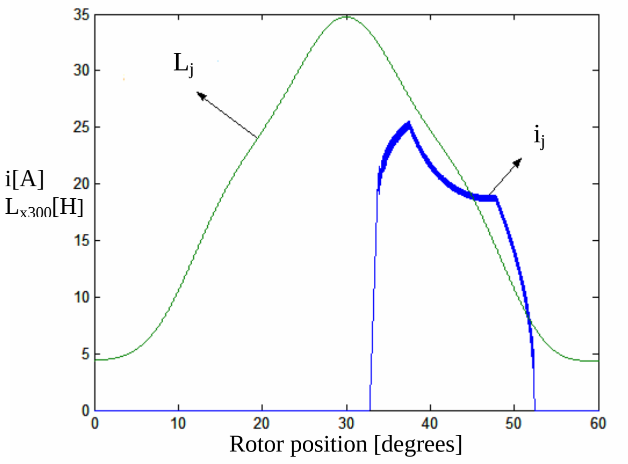


Fig. 5 – Phase current

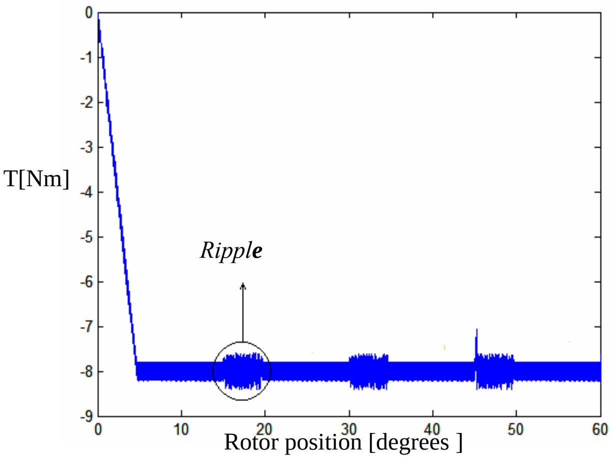


Fig. 6 – Total torque

In these simulation examples of the SRG operation, the converter voltage used was Vs=800V, which allow reduced torque ripple and the rotor speed is 1000 rpm.

In order to achieve higher performance in SRG operation and higher efficiency in the conversion we have to include optimal dwell angle control to further reduce the torque ripple. This methodology is based on equations that model the phase currents of the SRM in the overlap region of two adjacent phases. Besides a low level of ripple, this feature assures a commitment with the voltage by limiting the derivative di_j/dt, and it also allows to estimating the adequate voltage value to apply to the converter [6].

3. Concepts on the conversion of wind energy

The captation of the wind energy, in an efficient way, requires the existence of a constant wind flow sufficiently strong.

Currently wind turbines are designed to achieve a maximum power at wind speeds above 10 m/s. However, they can be adjusted to the local wind profile.

The maximum theoretical efficiency for the wind to energy conversion is 59,3% (Betz´s Limit). The effective efficiency conversion is given by the Power Coefficient (*Cp*), which is expressed by (5), where *Pmec* is the mechanical power of the turbine and P_w is the available wind power.

$$C_p = \frac{Pmec}{P_w} \qquad (5)$$

The power Pw is related with the wind speed V_w by equation (6),

$$P_w = \frac{1}{2}.\rho.A.V_w^3 \qquad (6)$$

where ρ is the air density (ρ = 1,225 kg/m3) and A is the cross-sectional area of the turbine rotor. When considering the generator efficiency (η), the output power is given by (7).

$$P_{out} = \frac{1}{2}.\rho.A.V_w^3.(\eta C_p) \qquad (7)$$

In order to relate the wind speed with rotor radius (r) the expression of the Tip Speed Ratio (λ) , as given in (8), is used, where ω is the rotor speed.

$$\lambda = \frac{r\omega}{V_w} \qquad (8)$$

Cp varies with λ as given by equations (9) and (10) and its behaviour in modern turbines is represented in Fig 7.

$$C_P = 0{,}22\left(\frac{116}{\lambda_1} - 5\right)\exp\left(-\frac{12{,}5}{\lambda_1}\right) \qquad (9)$$

$$\lambda_1 = \frac{1}{\frac{1}{\lambda} - 0{,}035} \qquad (10)$$

The low rotor speeds of the turbine bring about small turbulences in the air flow. On the other hand, with high speeds the turbine behaves as a wall for the wind. Therefore the priority is to adapt the wind speed to the rotor speed with the purpose of obtaining a greater conversion efficiency, which results in a maximum Cp.

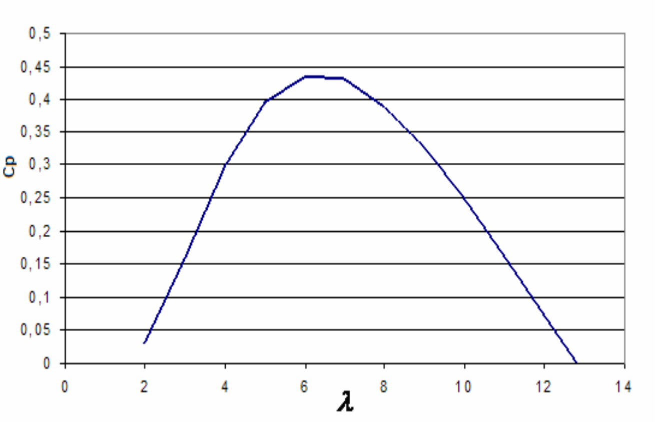


Fig. 7 – Power Coefficient versus Tip Speed Ratio

Given the lack of trustworthy values regarding low power wind turbines, the SRG studied has a rated power inferior to 3 kW, all calculations and simulations that were performed are based in the values of λ, which maximizes the power coefficient: $\lambda=6{,}325$ and $C_p=0{,}438$.

Considering as priority the conversion optimization, it is important to know the rated values of the power, the torque and the rotor speed of the 4-phase 8/6 SRG machine , which is the machine analyzed in this paper:

Rated power- 2,4 kW
Rated torque- 8 Nm;
Rated speed rotor: 300 rad/s; (2850 rpm);
Input converter voltageVs=800 V;

It is noteworthy that to reduce the ripple associated with the torque and output power, a feeding voltage of 800V was used, because it allowed a satisfactory performance of the SRG, for a large range of rotor speeds.

4. Wind System Simulation

This work analyses two kinds of mechanical coupling of the turbine to the generator: The direct coupling to the turbine shaft (4.1, Fig.8) – direct-drive wind turbine – and the SRG coupling to the turbine shaft through a gearbox (4.2, Fig.11).

4.1 Turbine- generator direct coupling

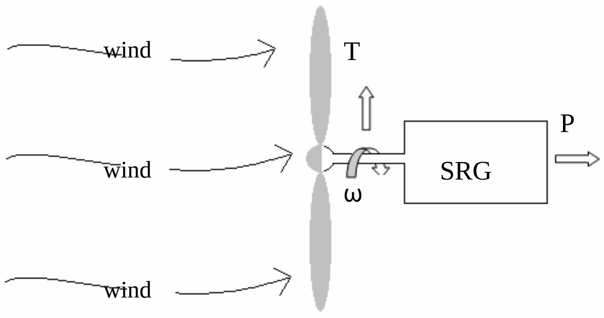


Fig. 8 – Direct-drive wind turbine with SRG

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Based on Fig. 8, in order to assure a torque T of 8 N.m on the turbine shaft for a wind speed of 12 m/s, a possible diameter that can be inferred using (8), is 1.5m.

This means, a rotor speed ω_1 of approximately 100rad/s, which is too high and not compatible for this kind of wind turbines, in normal wind conditions.

Figure 9 shows the behaviour of turbine-generator system in terms of the available power in two cases, without taking into account losses in the generator and including a 90% value for the generator efficiency.

Fig. 10 represents the electric power generated by the machine coupled with the aforementioned turbine, where its average power value corresponds to the power of the system excluding losses in the generator.

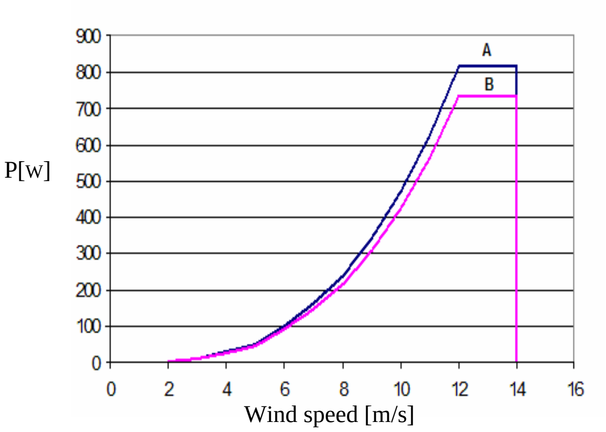

Fig. 9 – Output power system:
Ideal (A) and including losses (B)

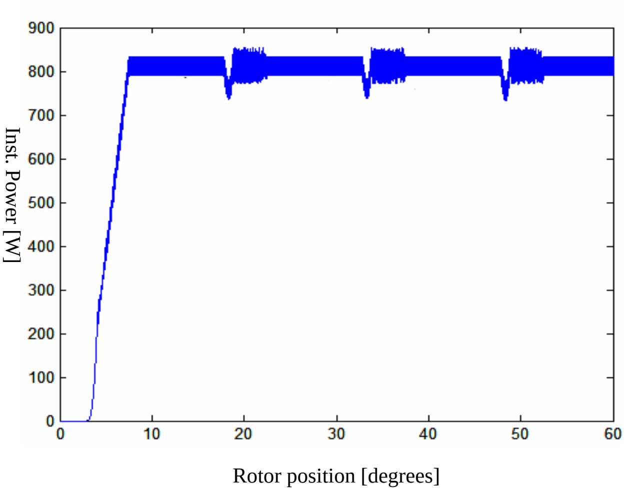

Fig.10 – 4-phase SRG instantaneous power versus rotor position

Associated with the required high rotor speed for a good performance of the SRG, the fact that the rotor diameter is small brings about the problem that the wind speed is not sufficient to overcome the combined turbine-generator inertia, namely at the starting stage.

It is thought that using a gearbox in the mechanical system coupling can attenuate these adversities and improve the SRG operation for wind speeds inferior to 12 m/s, which are in fact the prevalent wind speeds in Portugal.

4.2 Indirect coupling with gearbox

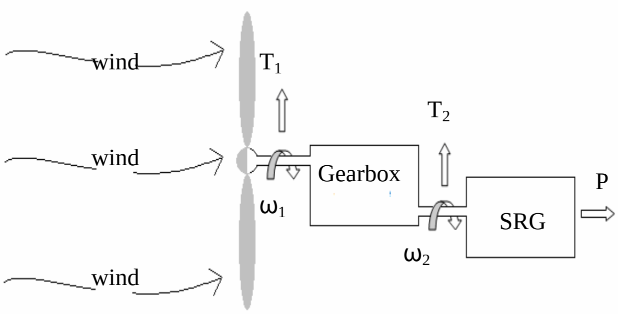

Fig. 11 – Indirect- coupling with gearbox

Assuming that the losses in the gearbox are negligible, and given that the input and output power ($\omega_1 T_1 = \omega_2 T_2$) are equal, the transmission ratio r_t varies in the inverse of the torque's ratios as expressed in (11).

$$r_t = \frac{\omega 1}{\omega 2} = \frac{T_2}{T_1} \qquad (11)$$

Considering a wind speed of 8 m/s and using a rotor diameter of 5 m, which is reasonable for this power range, equation 8 gives the turbine's rotor speed.

The obtained speed ω_1 of 20,2 rad/s and the speed imposed by the SRG under rated operation conditions allow to compute the transmission ratio value.

We conclude using the transmission ratio, that in order to obtain a torque of 8N.m in T_2 it requires a torque T_1=119N.m. In the same way in order to obtain a speed ω_2 =300 rad/s (rated speed of of 8/6 SRG) it requires a speed ω_1=20,2 *rad/s*. Figure 12 shows the progress of two torques, T_1 and T_2, as functions of the wind speed. As the wind speed approaches the 8 m/s value the T_2 value approaches the rated torque of the machine.

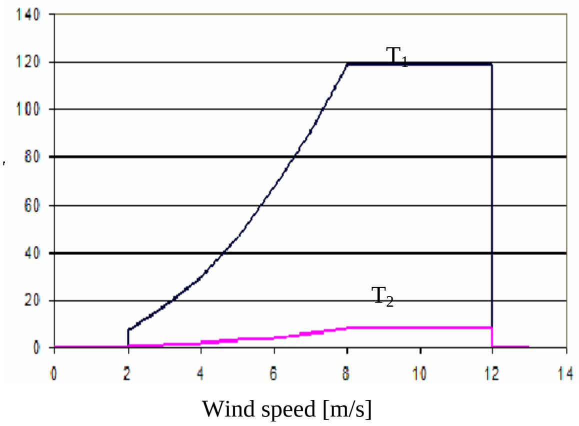

Fig. 12 – Turbine torque (T1) and SRG torque (T2) versus wind speed

Figure 13 shows the behaviour of the turbine-generator system in terms of the available power without taking into account the losses (A) and including the generator efficiency (B).

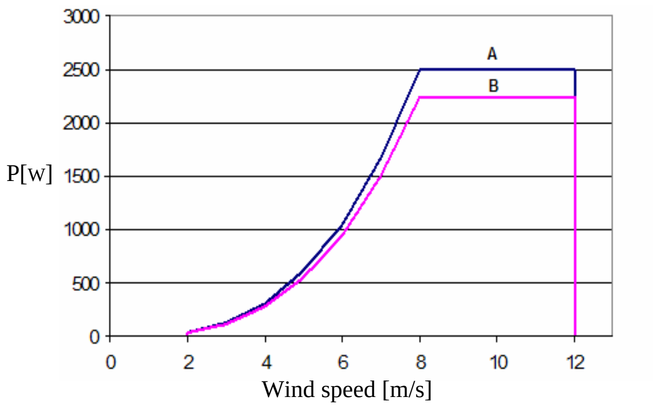

Fig. 13 – Output power system :
Ideal (A) and including losses (B)

Figure 14 shows the behaviour of the electric power generated by the machine, when coupled with a turbine having a rotor diameter of 5m for a constant wind speed of 8m/s.

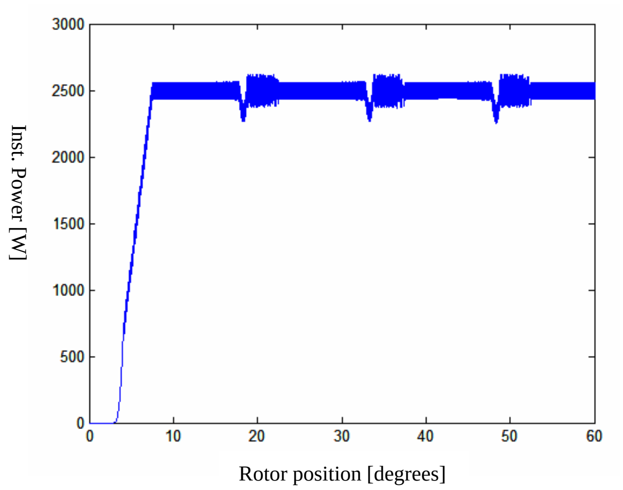

Fig.14 - 8/6 SRG instantaneous power versus rotor position

With a gearbox the rotor speed of the turbine was reduced (although still being high) to less than half of the value obtained in case 4.1 and the power available in the turbine is close to the rated power in the generator.

Considering that the studied SRG is a low power machine and therefore produces low torques, it was expectable that too high rotor speeds would develop, which are hardly compatible with the wind speeds typical of this kind of energy conversions and with the wind turbines available for these applications. Based on these results, it is foreseeable that the SRGs will offer good performance in medium power wind systems.

5. Conclusion

The SRG is a valid alternative in wind energy applications. Therefore it is reasonable to foresee that in the medium power wind systems, the SRGs allow good performance in extracting the energy carried by the wind. On the downside we can point out the fact that the SRG is noisier than the other conventional systems. Nevertheless the current control based on torque reference covered in this paper attenuates this problem; especially via a reduction of the torque ripple.

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