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Low Distortion Boost Rectifier Discontinuous Conduction Mode with Peak Current Mode Control for Wind Power Systems

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Abstract. This work presents a Three-Phase Boost Rectifier with peak current mode control operated in Discontinuous Conduction Mode working as the input stage of wind power systems based on Permanent Magnet Synchronous Generators with variable speed operation. It is shown that the DCM operation significantly reduces the Total Harmonics Distortion of the currents in the Permanent Magnet Synchronous Generator, so that the vibrations and mechanical stress of the generator is minimized. The characteristics of the DCM Boost rectifier are studied considering: 1) The resistance in series of the inductors; 2) The modeling and adjustment of the current injected control yielding a stable loop; 3) The design of an input filter that reduces the switching noise in the currents of the generator.

Key words

Boost Rectifier, Discontinuous Conduction Mode, peak current mode control, Wind Power Systems.

1. Introduction

Renewable energies for obtaining electric power are currently raising a great interest, mainly due to the high price of fossil fuels and to the need of alternative and clean energy sources. Wind energy is one of these sources, although not all places are capable of taking advantage of it.

Due to the fact that both the output voltage and the frequency of a wind power generator depend on the wind speed, an electronic converter is required for connecting the generator to the grid. The simplest electronic converter is constituted by a non-controlled three phase rectifier with capacitive filter followed by a grid connected inverter [1]. The drawback of this option is that the DC-link voltage may be too low for injecting to the grid, so that a high turns-ratio step-up grid connection transformer is necessary. Therefore, the inverter currents are high and, consequently, the inverter losses. Both the grid connection transformer and the grid (usually LCL) filter become bulky because of the high inverter side current. If a higher efficiency and a lower size are desired, a Boost DC-DC converter is usually connected between the rectifier and the inverter, achieving a higher inverter DC-link voltage, so that the grid connection transformer has a smaller turns-ratio, and thus lower inverter currents.

If the Boost Rectifier operates in Continuous Conduction Mode (CCM), the wind power generator current has a high Total Harmonic Distortion (THD_i), resulting in a low power Factor (PF). Besides, a high THD_i produces overheating and torque vibrations in the generator, which increase the mechanical stress and maintenance. Fig. 1 shows the THD_i and the PF of a sample 2kW permanent magnet synchronous generator (PMSG) driven by a three-phase diode rectifier and a Boost DC-DC converter (Boost rectifier) in CCM. The permanent magnet synchronous generator (PMSG) characteristics are described in section 2.

If an input filter between the generator and the rectifier is properly designed, Discontinuous Conduction Mode (DCM) operation of the Boost Rectifier can be achieved. It is shown that DCM operation is useful to reduce the THD_i and to increase the PF of the wind power generator. This operation mode has been proposed in [1]-[2] to reduce the THD_i in switch-mode power supplies.

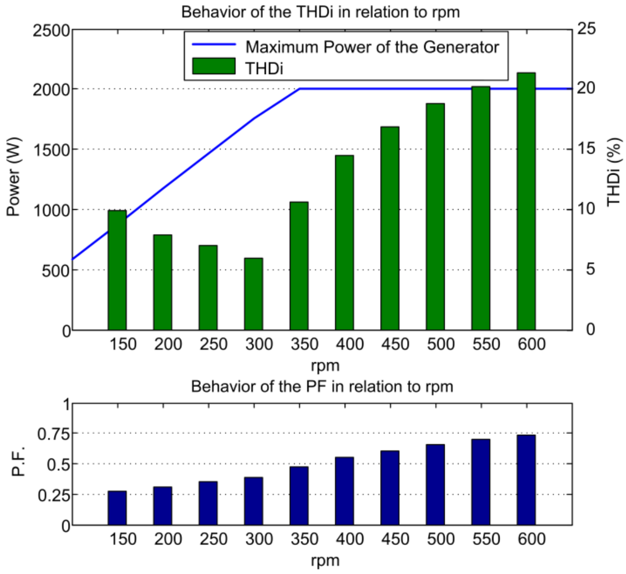

Fig. 1. Behavior of the THDi and the PF of a PMSG driven by a Boost Rectifier in CCM.

In the proposed wind power system the grid connected inverter regulates both the DC-link voltage (i.e. the output of the Boost rectifier) and the grid currents. Therefore, the inverter may be 'seen' by the boost rectifier as a DC voltage as a first approximation.

An outstanding contribution of this work with respect to [1]-[2] is that both the amplitude and the frequency of the generator output voltage are variable with the wind speed, so that it is necessary to carefully design both the power stage and the control loop.

2. Boost Rectifier in DCM

Fig. 2 shows the scheme of the Three-Phase Boost Rectifier with input filter under study, with the following values:

- Output Power of the generator: P = 2 kW
- Output Voltage of the rectifier: V_o = 800 V.
- Output voltage range of the generator: V_{ab}= 104 - 416 V_{rms}
- Inductance of one phase of the generator: $L_{ga}=L_{gb}=L_{gc}$=25 mH
- Resistance of one phase of the generator: R_{ga}= R_{gb}= R_{gb}= 5 Ω
- Number of poles: n_p = 12
- Nominal Current: I_{nom} = 4.87 A_{rms}
- Speed Range of the generator: n_m = 150 – 600 rpm

The circuit used for the analysis considers two phases, in the moment that the diodes of each one allow rectification; the circuit is reduced to that shown in Fig. 3.

Considering that L_g = $2L_{ga}$, R_{Lg} = 2 R_{Lga}, L = $2L_a$, R_L = $2R_{La}$ and C_i = $3C_1/2$. V_i is the rectifier output voltage averaged in a complete rectification period, where the voltage drops in the rectifier diodes and inductors resistances have been neglected. The equivalent circuit is shown in Fig. 4.

A. Input filter desing.

In order to reduce the switching frequency components of the rectifier input current, an LCL input filter is applied. The input filter is designed to attenuate the switching frequency without affecting the frequencies corresponding to the speed range of the generator, Fig. 5 shows the equivalent circuit considering that the switching frequency component of V_i is null.

The transfer function from the rectifier current to the generator current is determined by (1).

$$\frac{I_i(s)}{I_r(s)} = \frac{1}{s^2 C_i L_g + s C_i R_{Lg} + 1} \tag{1}$$

With C_i = 3.3 μF an attenuation of -44.3 dB at the switching frequency (f_s = 5 kHz) is obtained, without affecting the generator frequency range (F_{gen} ≤ 65 Hz). The Bode diagram of the filter is shown in Fig. 6.

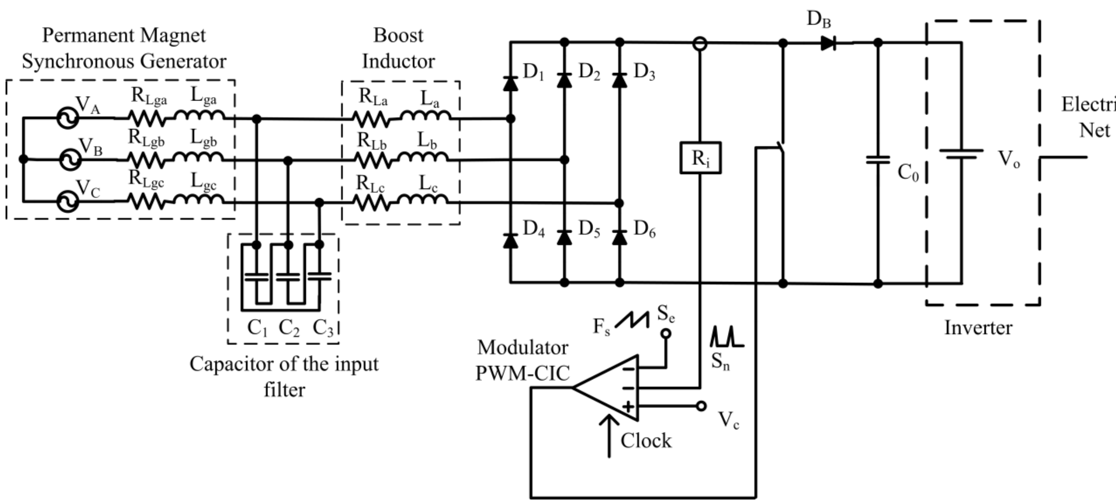

Fig. 2. Three-Phase Boost Rectifier with input filter.

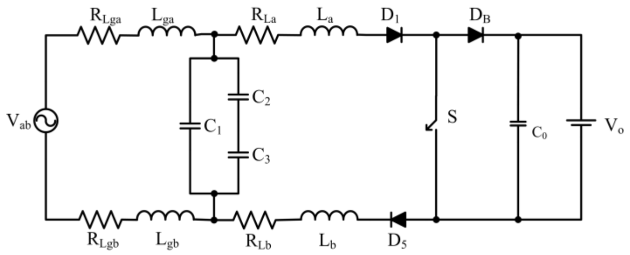

Fig. 3. Circuit of the Boost Rectifier when there are current in the phases A and B.

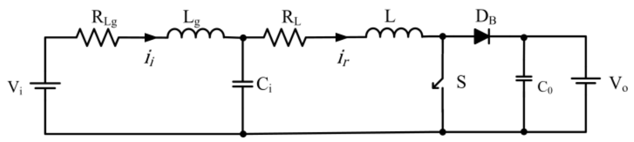

Fig. 4. Equivalent Circuit of the Boost Rectifier with input filter.

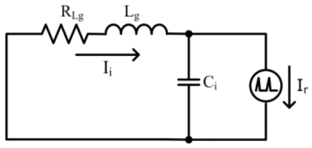

Fig. 5. Equivalent Circuit of the Boost Rectifier with input filter.

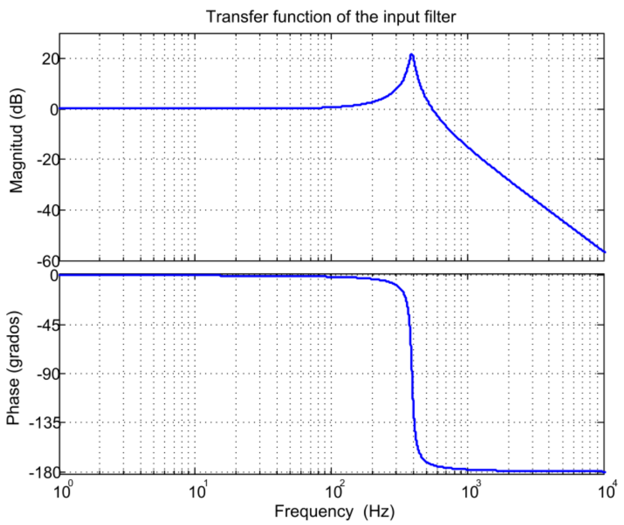

Fig. 6. Bode Diagram of the Input Filter Transfer Function $I_i(s)/I_r(s)$.

B. Operation in Discontinuous Conduction Mode

In order to work in discontinuous conduction mode (DCM) [3], condition (2) should be met. This condition allows calculating the correct value of L. D is the duty cycle; L is the equivalent Boost inductance, K_{crit} allows to determine the conduction mode of the Boost and f_s is the switching frequency.

$$K = \frac{2LPf_s}{V_0^2} \quad \text{and} \quad K_{crit}(D) = D(1-D)^2$$
$$K < K_{crit}(D) \quad \text{for} \quad \text{DCM} \tag{2}$$

The duty cycle in DCM is obtained by means of (3)

$$D = \frac{(2V_0 - V_i) + V_i\sqrt{1 + \frac{8V_0 L f_s}{R_L^2 P}(V_0 - V_i)}}{V_0\left(\frac{2V_i^2}{PR_L} - \frac{R_L}{Lf_s}\right)} \tag{3}$$

The maximum value of the Boost inductance (L_{max}) is obtained from (2) and (3). For a switching frequency (f_s) of 5 kHz, considering the generator speed range, it results: L_{max} = 815.2 µH. L = 750 µH is selected, so that the Boost rectifier operates in DCM.

3. Peak Current Mode Control

A. Small Signal Model of the Boost Rectifier DCM

The small-signal circuit of the Boost rectifier in DCM uses the equivalent circuit of PWM switch [4], shown in Fig. 7 This model is valid from DC to $f_s/2$. The rectifier output voltage (V_o) is regulated by the grid connected inverter. Therefore, the load of the Boost rectifier is modeled as an ideal voltage source.

The values of the parameters of the PWM switch small-signal model in DCM are shown in (4).

$$g_i = \frac{D^2T_s}{2L} \qquad g_o = \frac{2LP_o^2}{D^2V_i^2V_o^2T_s} \qquad g_f = \frac{2P_o}{V_iV_o}$$
$$K_i = -\frac{DT_sV_i}{L} \qquad K_o = -\frac{2P_o}{DV_o} \tag{4}$$

$G_{id}(s)=i_L(s)/d(s)$ is the transfer function from the duty cycle to the inductor current, expressed by (5). Fig. 8 shows the Bode plot G_{id}.

$$G_{id}(s) = \frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{-(s^2c_iL_g + sc_iR_g + 1)(K_i + K_o)}{s^3B_3 + s^2B_2 + sB_1 + B_0}$$
$$B_3 = c_iL_gL(g_i + g_o + g_f)$$
$$B_2 = c_i\left[L_g + (g_i + g_o + g_f)\left(LR_{L_g} + L_gR_L\right)\right] \tag{5}$$
$$B_1 = \left[c_iR_{L_g} + (g_i + g_o + g_f)\left(L_g + L + c_iR_LR_{L_g}\right)\right]$$
$$B_0 = (g_i + g_o + g_f)\left(R_{L_g} + R_L\right) + 1$$

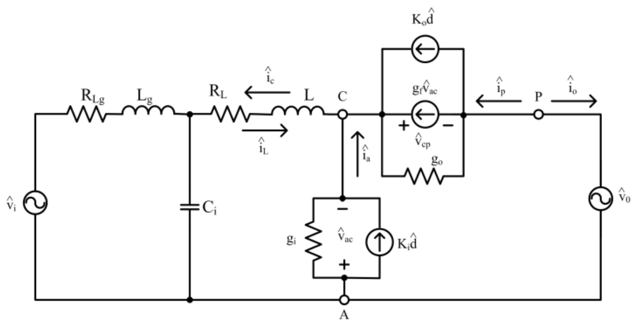

Fig. 7. Small Signal Equivalent Circuit of the Boost Rectifier in DCM with a voltage source at the output.

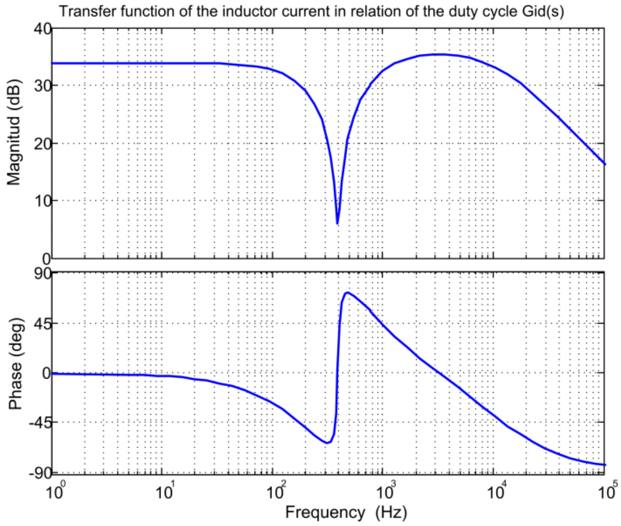

Fig. 8. Transfer Function from the duty cycle to the inductor current, $i_L(s)/d(s)$.

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B. *Peak Current-Mode Control Controller*

The structure of the peak current-mode control (PCC) [5] of this converter is shown in Fig. 9. As it has been previously commented, the output voltage (V_o) of the Boost rectifier is regulated by the grid-connected inverter.

The current loop gain $T_i(s)$ is determined by (6). R_i is the current sense gain, F_M is the modulator gain and $H_e(s)$ is the sampling gain [5].

$$T_i(s) = G_{id}(s)H_e(s)R_iF_M \tag{6}$$

The sampling gain $H_e(s)$ [8] is expressed by (7)

$$H_e(s) = 1 + \frac{s}{\omega_z Q_z} + \frac{s^2}{\omega_z^2} \tag{7}$$

Where

$$\omega_z = \frac{\pi}{T_s} = \frac{\pi}{200\mu s} = 15707.963\frac{rad}{s}$$

$$Q_z = -\frac{2}{\pi} = -0.6366$$

In order to guarantee the stability of the current loop, F_M, expressed by (8), should be adjusted properly.

$$F_M = \frac{f_s}{(S_n+S_e)T_s} = \frac{f_s}{m_c S_n} \qquad m_c = 1 + \frac{S_e}{S_n} \tag{8}$$

In (8) S_n is the on-time slope of the current sense waveform, S_e is the slope of the stabilization ramp and m_c is the modulation index. The value of S_n is obtained from (9).

$$s_n \approx \frac{V_i}{L}R_i \tag{9}$$

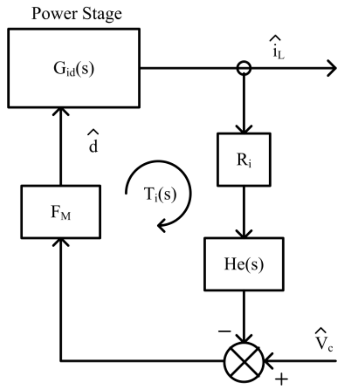

Fig. 9. Peak Current-Mode Control Loop.

With V_i = 562.57 V, L = 750 µH, P = 2 kW and R_i = 0.01 Ω, S_n is equal to 7.501 V/ms. The value of m_c is chosen so that the current loop becomes as stable as possible. Fig. 10 shows the Bode Diagram of the transfer function from the control voltage to the inductor current, $G_{ic}(s)=i_L(s)/v_c(s)$, for values of m_c between 2 and 7, with V_i = 562.57 V, L = 750 µH, P = 2 kW and R_i = 0.01 Ω.

In Fig. 10 it is observed that for m_c = 2 and m_c = 3 the current loop is unstable because the phase of $G_{ic}(s)$ undergoes a positive phase transition corresponding to complex conjugated highfrequency poles. This means that the closed loop poles are located in the complex right half plane, yielding an unstable current loop. With $m_c \geq 4$, it is observed that the control loop is stable because the phase transition of $G_{ic}(s)$ is negative. Selecting m_c= 4, with V_i = 562.57 V, L = 750 µH, P = 2 kW and R_i = 0.01 Ω, it is chosen S_e = 22.503 V/ms, resulting F_m = 0.1666 for this rectifier. V_c is obtained from a maximum power point tracking circuit that is not object of the present study.

After the design of the input filter and PCC control, the behavior of the system has been simulated by means of PSIM software. The complete circuit is shown in Fig. 11.

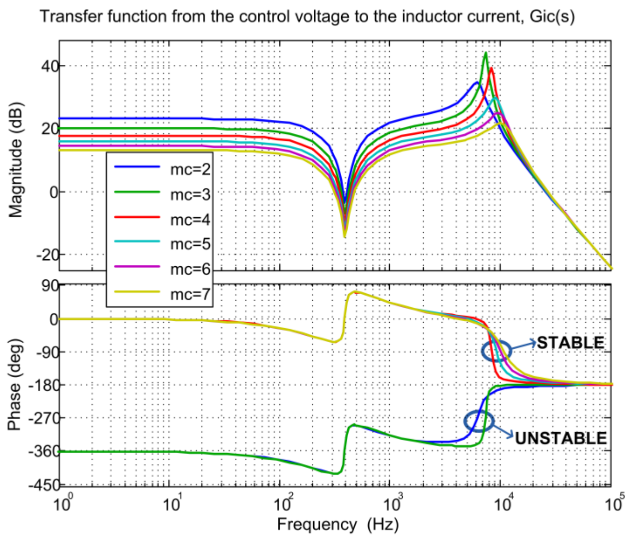

Fig. 10. Transfer Function of the Inductor´s Current in relation of the Control Voltage Gic(s).

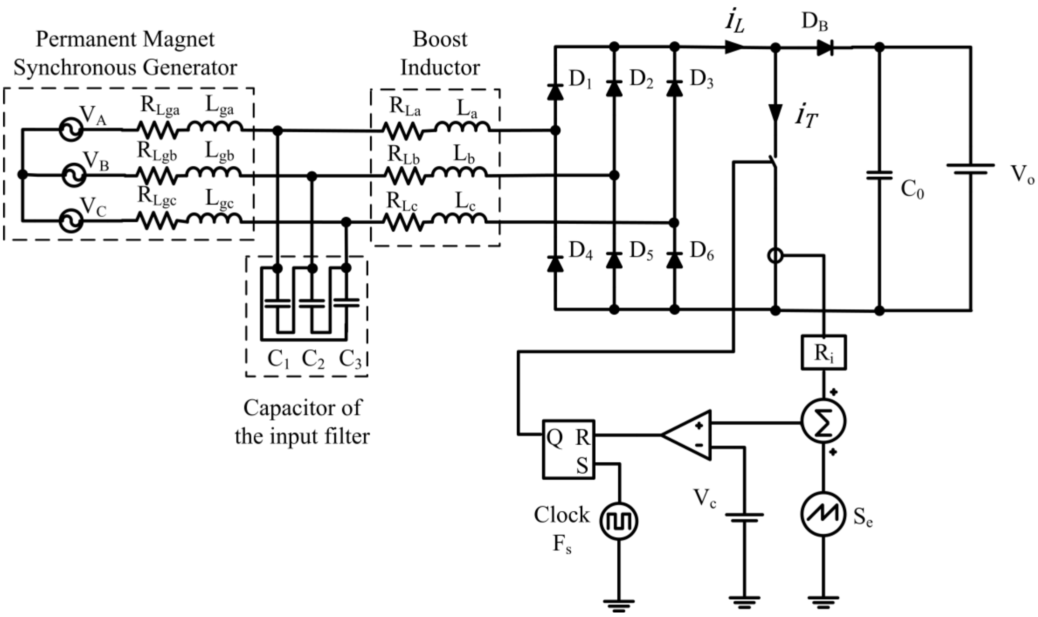

Fig. 11. Three Phase Boost Rectifier in DCM with input filter and PCC Control.

The simulated values are:

- Boost Inductance associated to each phase: L_a, L_b, L_c = 375 µH
- Resistance in series associated to the Boost inductor in each phase: R_{La}, R_{Lb}, R_{Lc} ≈ 100 mΩ.
- Capacitance of the filter: C_1, C_2, C_3 = 2.2 µF.
- Current sense gain: R_i = 0.01 Ω.
- Slope of the stabilization ramp: Se = 22.503 V/ms.

4. Results

The simulation results have been obtained by means of PSIM 7.0.5 [6].

Fig. 12 shows the generator phase current of a Boost Rectifier working in CCM vs. the same current of a DCM Boost rectifier with the designed PCC and input filter, with input filter and peak current-mode control, simulated by PSIM™ with n_m = 450 rpm and P = 2 kW. It is observed that the proposed DCM operation with input filter and PCC reduces both the low frequency and the switching harmonics.

Fig. 13 shows the comparative behavior of the THD_i and the PF seen by the generator with a boost rectifier in CCM and in DCM with the previously designed input filter. The variations of the generator voltage and frequency as a function of the generator speed in rpm have been considered. The maximum power of the generator is also shown in its speed range. Both the THD_i and the PF improve significantly in the whole speed range when the Boost Rectifier operates in DCM with input filter.

Fig. 14 shows the response of the current in one of the generator phases to a control voltage step. This step produces a variation of the generator output current from 2.16 to 4.28 A_{rms}, which is clearly stable.

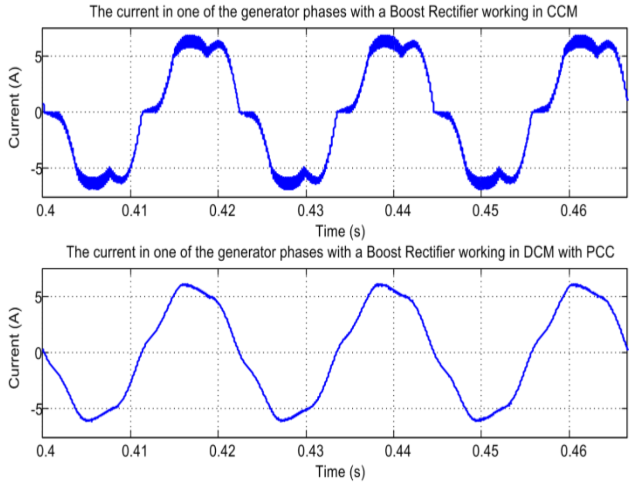

Fig. 12. Generator phase current of a Boost rectifier working in CCM vs. DCM with input filter.

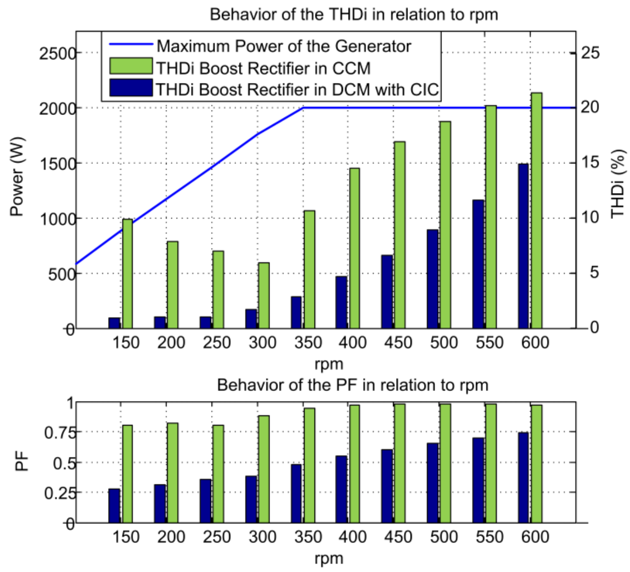

Fig. 13. The comparative behavior of the THD_i and the PF seen by the generator with a boost rectifier.

p

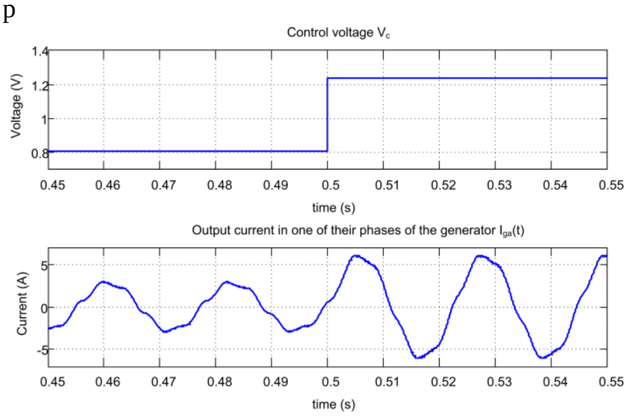

Fig. 14. Output current in one of their phases of the generator with variations of the control voltage.

5. Conclusion

In this paper it has been presented the design and analysis of a Three Phase Boost Rectifier applied to Wind Power with Permanent Magnet Synchronous Generators. The study of peak current mode control of the rectifier output current shows a high power factor of the system, and a low Total Harmonic Distortion of the generator output current. The maximum THD_i is 15%. Another important parameter is the adjustment of the stabilization ramp slope, so that the current loop is stable, because the input filter modifies the transfer function from the duty cycle to the inductor current.

In the next months an experimental circuit will be developed to corroborate the data obtained by PSIM. In a future work, the rectifier using average current control (ACC) will be analyzed, in order to compare the advantages and disadvantages of both controls in this application.

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