A DCM THREE-PHASE HIGH FREQUENCY SEMI-CONTROLLED RECTIFIER FEASIBLE FOR LOW POWER WECS BASED ON A PERMANENT MAGNET GENERATOR

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Abstract **– This paper proposes the use of a three-phase high frequency semi-controlled rectifier operating in the discontinuous conduction mode, feasible for small wind energy conversion systems based on permanent magnet generator. The main advantages of the topology are: simple gate drive circuits, since all active switches of the rectifier are connected to a common point; robustness, as short circuit through a leg is not possible; high efficiency due to reduced number of elements; simplicity since the DCM operation avoid feedback circuits and sensors as well as it allows open loop control. As a disadvantage, higher but acceptable THD of the generator currents results. The complete operation of the converter and theoretical analysis are presented. Additionally, a conventional single-phase PWM inverter is also employed in the grid connection. Experimental results on 1.6 kW prototype are presented and discussed.**

Keywords **- Three-phase PWM rectifier, discontinuous conduction mode, grid-connected system, power factor correction, and wind energy conversion system.**

I. INTRODUCTION

According to the U. S. Department of Energy, through of International Energy Outlook 2006 (IEO) report of Energy Information Administration (EIA), the global consumption of energy will grow at an annual average of 2% between the years of 2003 and 2030. The forecast for the growth of demand for energy specifically in the electric form is even greater i.e. 2.7% by year [1].

Either for ambient, strategic, or geographic questions, the generation of electric energy from wind energy systems has grown quickly, changing from a global installed power of 4.8 GW in 1995 to 58 GW in 2005, at annual average growth of 24% [2]. Considering the current estimations of increase in the demand for electric energy generation in the next few years, one concludes that the growth of the electric energy obtained from wind systems tends to continue [3]-[5].

As the electrical power available in a WECS based on permanent magnet (PM) generators can not delivery energy directly to the grid, power electronics plays a fundamental role [4]. This paper proposes a variable speed wind energy conversion system (WECS) for connection to the grid feasible to small wind energy conversion systems, improving robustness and efficiency but introducing acceptable harmonic content in the generator currents. The considered system is composed by a high frequency semi-controlled rectifier and a full-bridge single-phase PWM inverter.

II. WIND ENERGY CONVERSION SYSTEMS

It is observed that the maximum extraction of the wind energy is achieved when the rotational speed of the turbine varies with the wind speed, keeping a constant λ(tip speed ratio), as a variable speed WECS results. The possibility to control the frequency and the amplitude of the generated voltage through the excitement, independent of the speed rotation, made the doubly-fed induction generator (DFIG) the main choice in variable speed WECSs of great size directly connected to grid (Fig. 1) [6]-[8].

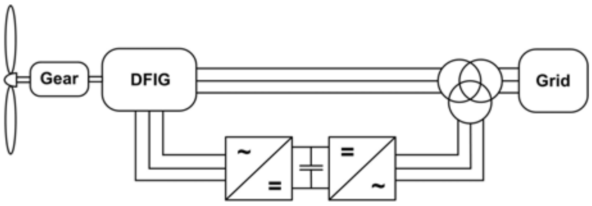

Fig. 1. Variable speed WECS directly connected to the grid based on DFIG.

The WECS in Fig. 1 allows the processing of high power levels, since the power converter processes only about 30% of the rated power [9]. On the other hand, the reduced number of poles of the DFIG demands the use of gearbox between the wind turbine and the generator, implying higher weight, size, and maintenance, reducing its efficiency and reliability [7].

An alternative to the DFIG is the permanent magnet synchronous generator (PMSG), which can be designed with higher number of poles to avoid the use of gearbox. Being a synchronous generator, all the generated power must be conditioned through a power converter before it can be used (Fig. 2), restricting the power of this type of WECS.

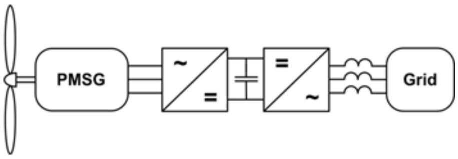

Fig. 2. Variable speed based in PMSG.

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The PMSG presents some advantages when compared with the DFIG [10]-[11]:

- No external excitation current is required;
- Light weight;
- Small size;
- High reliability;
- Low maintenance;
- High efficiency;
- Smaller wind turbine blade;
- Large mechanical speed control.

These characteristic makes the PMSG an optimum choice for small WECSs. The main disadvantage of the PMSG is the high cost of permanent magnet material and power converter. The mathematical model of a PMSG and the main power processing topologies are presented as follows.

A. Power Processing Topologies Applied to PMSG

In order to feed the dc link of the inverter stage, a dc-dc stage between the conventional rectifier and the output stage is introduced as shown in Fig. 3.

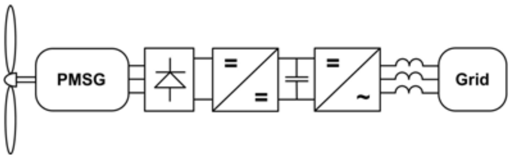

Fig. 3. WECS using intermediate dc-dc stage.

However, the rectifier stage of the power converter used in systems such as that in Fig. 3 must present high power factor, otherwise harmonic distortion in the current and voltage of PMSGs may cause several undesirable effects to the generator, such as [12]:

- Increased heating due to iron and copper losses at the harmonic frequencies;
- Reduction in machine efficiency;
- Torque Loss;
- Increased audible noise emission;
- Eventual occurrence of mechanical oscillations.

In order to avoid these problems, systems capable of emulating resistive loads for the PMSG must be used, resulting in low total harmonic distortion (THD).

A dc-dc converter with current source input characteristic can be used in the WECS of Fig. 3. The simplicity of control, the reduced number of components, and the predominant need to increase the generated voltage, make the boost converter the main choice [13]-[18] in this WECS, as shown in Fig. 4.

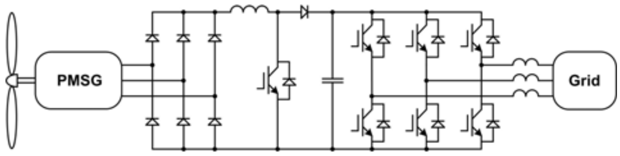

Fig. 4. WECS with intermediate boost converter.

It can be observed in Fig. 4 that there are always three power semiconductors in the input stage conducting the current, reducing the efficiency of this topology. Besides, the power factor correction is achieved only in discontinuous conduction mode.

Another option to achieve high power factor in the generator side is to use a PWM rectifier in the WECS, as shown in Fig. 5.

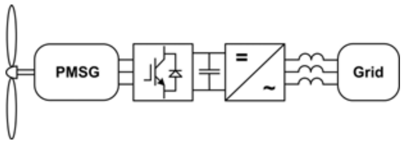

Fig. 5. WECS with power factor correction using PWM rectifier.

The traditional topology applied in high power WECSs is shown in Fig. 6 [8] and uses the back-to-back converter [19]-[20]. In the rectifier stage of this structure there are only two semiconductors in the current path of each phase and the current can be modulated in both half cycles. However, there are switches connected in series, increasing the complexity of the command circuits.

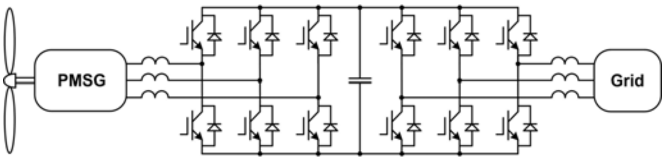

Fig. 6. WECS with back-to-back converter.

Fig. 7 shows a WECS that uses a variation of the back-to-back converter [21], as proposed in [22]. Only four semiconductors are used in the rectifier stage of this topology. Moreover, the voltage balance across the capacitors of dc link is not a trivial task.

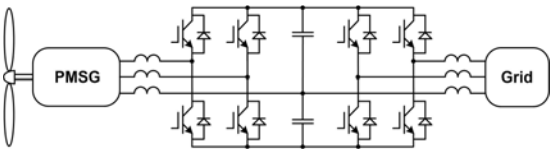

Fig. 7. WECS with back-to-back variation converter.

III. PROPOSED WECS

The wind energy conversion system in Fig. 8 is composed of a PMSG rated at 1.6 kW connected to three-phase semi-controlled rectifier, composed of three IGBT's and three diodes [24]. The dc-ac stage of the wind system is a single-phase full-bridge topology with unipolar modulation.

The main advantages of the proposed WECS, when compared to standard WECSs are:

- All switches are connected to the same reference in the rectifier stage, simplifying the drive circuit;
- There are not switches in series in the rectifier stage, discarding the possibility of the short-circuit through legs;
- There are only two semiconductors in the current path, increasing efficiency;
- The DCM operation required the use of smaller magnetics than those used in CCM operation.

Besides the DCM operation avoids the use of current sensors and feedback circuits as well as it allows open loop control with the same duty cycle for all switches.

A. Rectifier Operation

The rectifier operates as a boost converter in discontinuous conduction mode. When switches S1, S2, and S3 are turned on, the current flows through them and the current through the respective inductor will increase, while diodes D1, D2, and D3 are reverse biased and capacitor C supplies power to the inverter.

When switches S1, S2, and S3 are turned off, diode D1, D2, or D3 can be forward biased depending on the current direction, and energy is transferred to the load.

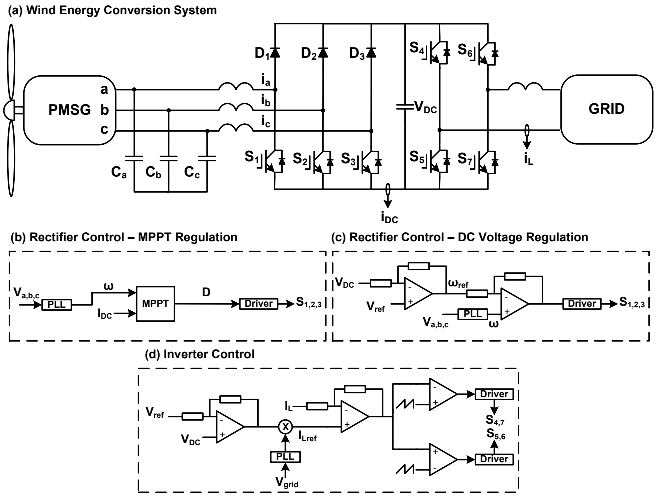

Fig. 8 Schematic diagram of the proposed WECS.

The input voltages Va, Vb, Vc can assume two states: positive (+) or negative (-), resulting in eight combinations. However, only six combinations are physically pertinent, as shown in Table I.

TABLE I

Possible Combinations of the Input Currents

Sector	I_a	I_b	I_c
1	+	-	+
2	+	-	-
3	+	+	-
4	-	+	-
5	-	+	+
6	-	-	+

In Fig. 9 it can be observed that a complete period of voltages Va, Vb, and Vc can be divided in six sectors with similar behavior.

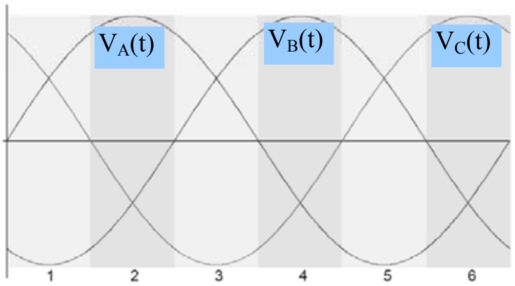

Fig. 9 Theoretical waveforms of the voltages Va, Vb, and Vc.

1) Sector 1 - In this sector voltages Va and Vc are positive, and voltage Vb is negative. When switches S1, S2 and S3 are turned on the line currents Ia and Ic increase linearly flowing through switches S1 and S3 and the line current Ib decreases linearly flowing through the anti-parallel diode of switch S2, as shown in Fig. 10a, Fig. 11a and Fig. 12. When switches S1, S2 and S3 are turned off the line currents Ia and Ic decrease linearly flowing through diodes D1 and D3, and the current Ib increases linearly flowing through the anti-parallel diode of switch S2, as shown in Fig. 10b and 11b. When current Ia or Ic becomes null the other one becomes equal to Ib and the currents vary linearly until they become null. The resulting currents envelopes are sinusoidal as show in Fig. 13 and Fig. 14. The generator current filtered by its internal impedance and the external capacitors C_a, C_b and C_c are nearly sinusoidal without high frequency components, as shown in Fig. 15.

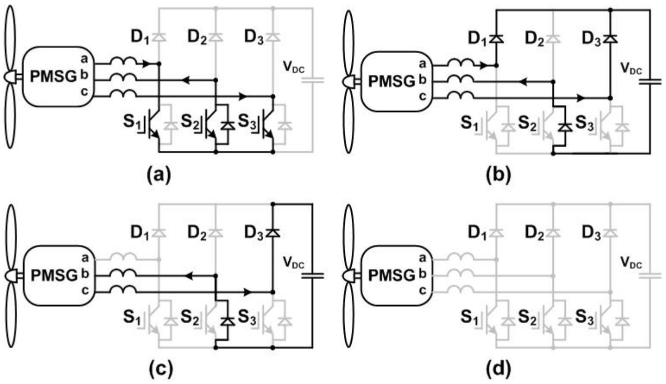

Fig. 10 Topological states associated to the sector 1.

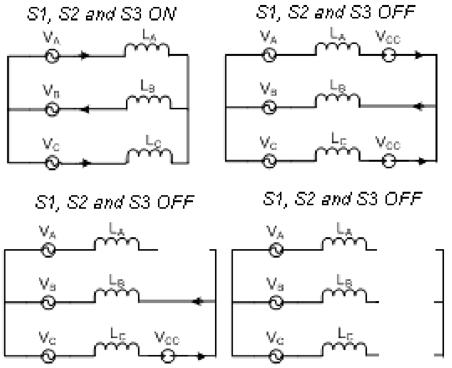

Fig. 11 Equivalent circuits associated to sector 1.

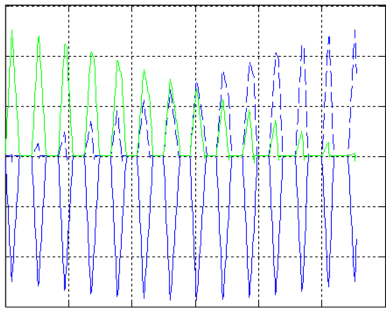

Fig. 12 Line currents Ia, Ib, and Ic.

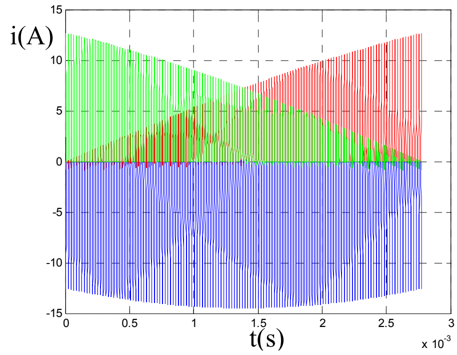

Fig. 13 Line currents Ia, Ib, and Ic.

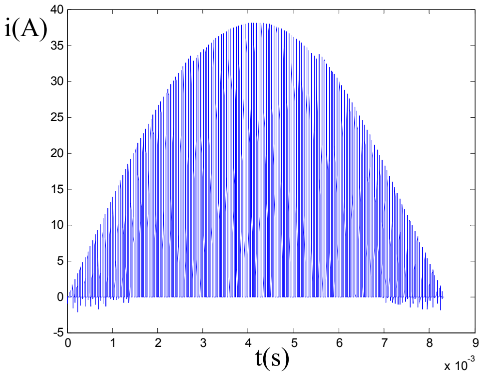

Fig. 14 Line current Ia during T/2.

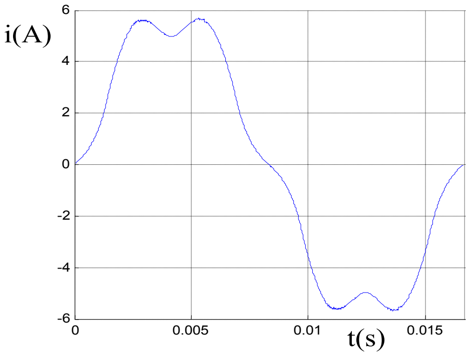

Fig. 15 Filtered input current waveform.

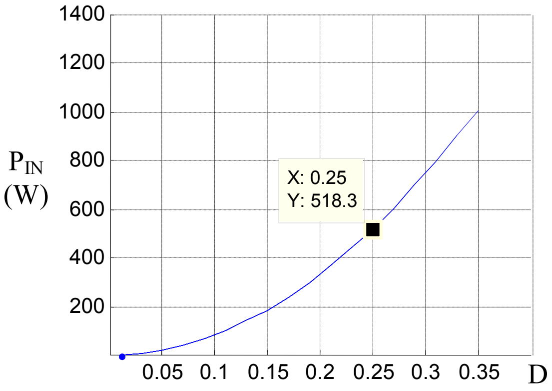

Fig. 16 Output power (per phase) versus duty cycle.

B. Rectifier Control

Considering the magnitude and frequency of the input voltage and the output voltage constant, a fixed duty cycle for all the switches provides sinusoidal envelop of the inductors currents. For wind systems, typical inertia value and a slow loop response guarantee this behavior. Besides, a low-pass filter provides a current whose THD is less than 20%, which is small that obtained in conventional systems (six diodes rectifier associated with a dc dc converter).

In order to achieve the operation of the wind turbine in the maximum power point (Fig. 8b), the mechanical speed of the generator is supposed to be proportional to the wind speed, as the voltage magnitude and frequency varies accordingly. Then, for each mechanical speed value, a previously established current must be obtained. This current can be performed from the characteristic curve of input power versus duty cycle, as shown in Fig. 16.Alternatively, the MPPT can be performed by the conventional perturb and observe method employed in photovoltaic systems [20][22], measuring the I_{DC} or I_L currents. In this mode the rectifier is responsible for the V_{DC} voltage regulation (370V) (Fig. 8d), as performed in [24].

In the moments in which the available wind power could be higher than the nominal and in order to avoid over speed, the control strategy showed in Fig. 8c must be performed. As the inverter stage injects constant power to the grid, the dc bus voltage loop is controlled by the mechanical speed ω_m in order to change de power coefficient in the left side of the power curve. The control of ω_m can be made through the current control, which is a function of D, according Fig. 16.

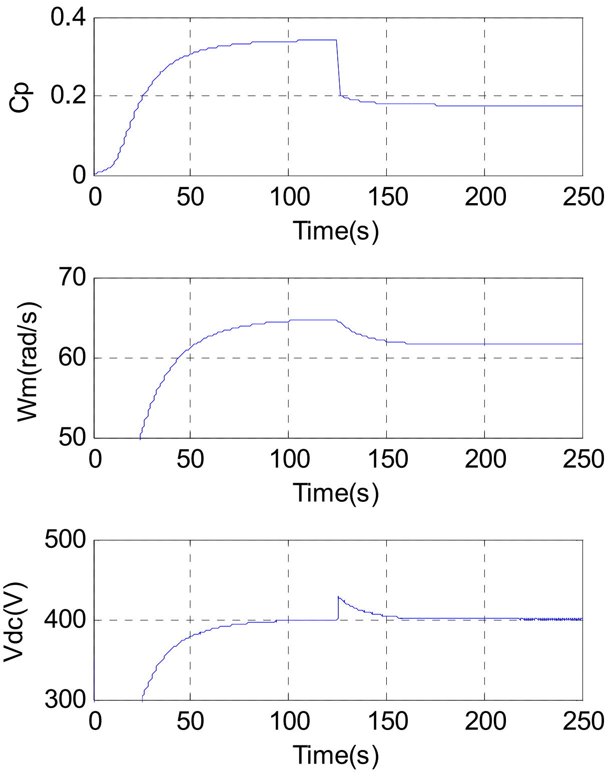

Fig. 17 Power Coefficient (C_p), mechanical speed (rad/s) and dc bus voltage (V_{dc}) during a wind speed step up from 12 m/s to 15 m/s and with dc bus voltage control though the mechanical speed.

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In Fig. 17 and Fig. 18 one can see the step response with this control strategy. The dc bus voltage regulation is performed by the reduction of the mechanical speed and the power coefficient Although the controllers maintain the voltage regulation, the kinetic energy reduction causes a small voltage overshoot across the dc bus. In Fig. 18 the wind speed step down changes the power coefficient instantaneously. So as the mechanical speed increases the power coefficient increases smoothly. The energy necessary to increase de kinetic energy causes a small but acceptable drop in the dc bus voltage.

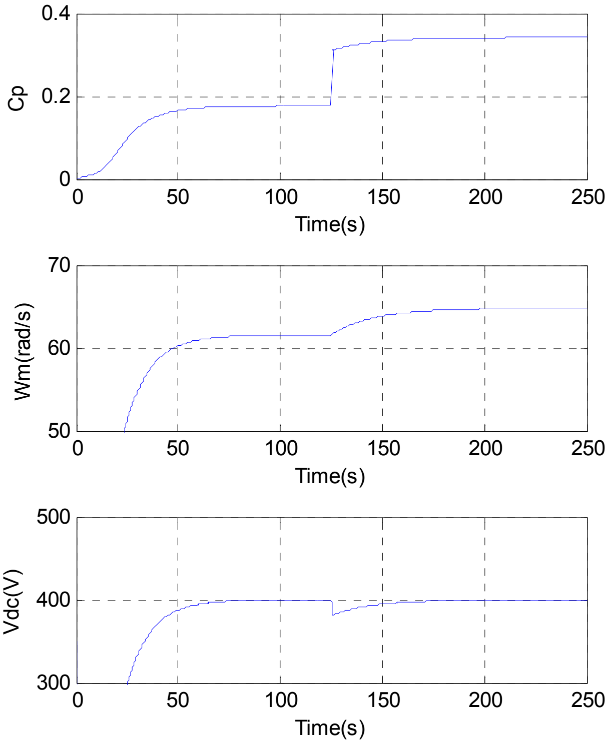

Fig. 18 Power Coefficient (C_p), mechanical speed (rad/s) and dc bus voltage (V_{dc}) during a wind speed step down from 15 m/s to 12 m/s and with dc bus voltage control though the mechanical speed.

IV. EXPERIMENTAL RESULTS

The proposed rectifier prototype was built and tested. The specifications and parameters used to implement the prototype are shown in Table II.

TABLE II
Rectifier Specifications and Parameters

Parameter	Specification
Rms input voltage range	30V – 120V
Frequency of the input voltage	15 – 60Hz
Output voltage	400V
Switching frequency range	50kHz
Input inductors	57uH
Output power	1.6kW

Fig. 17 shows the inductor current I_{La} and the voltage across the respective switch S1. The behavior of the currents is according to the analysis of the operational stages.

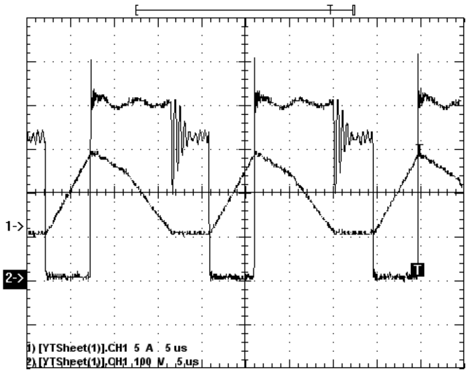

Fig. 17 Voltage across switch S1 and inductor current I_{La} (ch. 1 – 5A/div, ch. 2 – 100V/div).

Fig. 18 shows the nearly sinusoidal envelop of the inductor currents as expected in the discontinuous conduction mode.

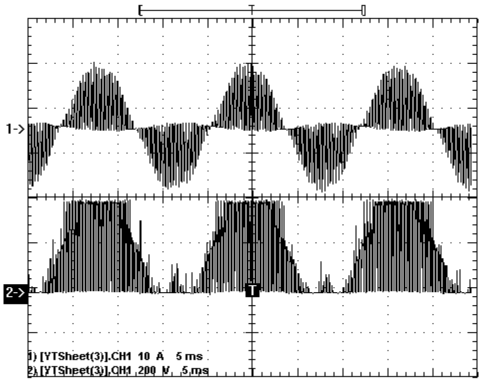

Fig. 18 Voltage across switch S1 and inductor current I_{La} (ch. 1 – 10A/div, ch. 2 – 200V/div).

Fig. 19 shows phase 'a' current as well as its respective voltage including a low pass filter. The power factor is 97% and the voltage distortion tends to increase the current THD.

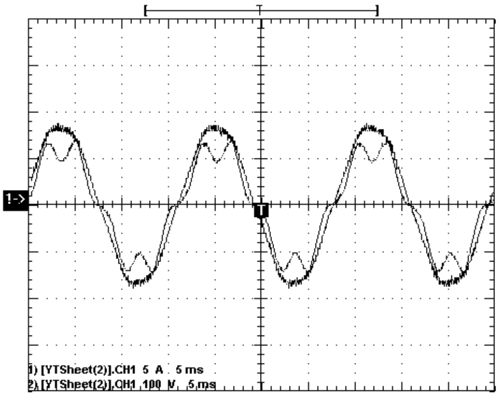

Fig. 19 Input current and voltage in phase 'a' (ch. 1 – 5A/div, ch. 2 – 100V/div)

Fig. 20 shows the harmonic spectrum of the input current. The total harmonic distortion is about 20,776% with predominance of the 5ª harmonic, which also corresponds to the higher harmonic content of the input voltage.

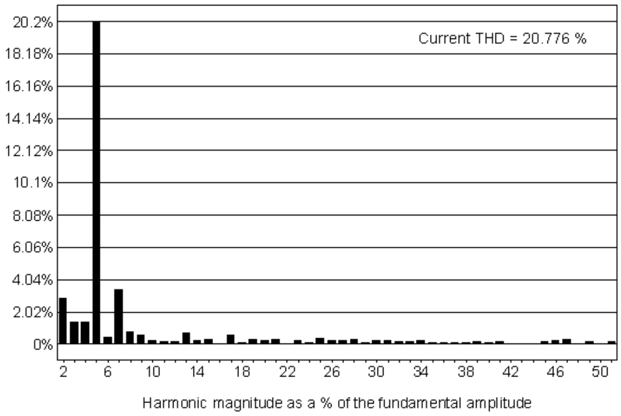

Fig. 20 Harmonic spectrum of the input current.

Fig. 21 shows the harmonic spectrum of the input voltage. The total harmonic distortion is about 2,999%.

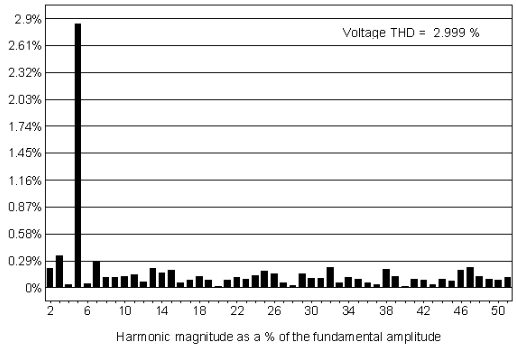

Fig. 21 Harmonic spectrum of the input voltage.

Fig. 22 shows efficiency measured with analog equipments. As it can be seen, efficiency higher than 96% is achieved around the rated power. At low power the measurements accuracy was compromised by the meters. At the final version, new measurements achieved by digital equipments will be presented.

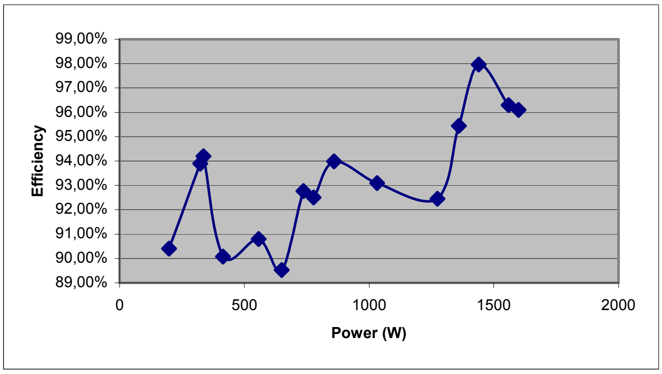

Fig. 22 Efficiency versus output power.

V. CONCLUSION

A low cost high frequency three-phase semi-controlled rectifier operating in the discontinuous conduction mode feasible for small wind energy conversion systems was presented. The topology uses the DCM for the three-phase semi-controlled high frequency rectifier in order to reduce the total harmonic distortion without using current sensors and it allows open loop control with the same duty cycle for all switches. The main advantages, when compared to a conventional WECS, are the use of switches with the source connected to the same point, robustness due to the absence of more than one controlled switch in the same leg, and high efficiency due to reduced number of elements.

The used control technique avoids small transients in the current injected to the grid but introduce small overshoot across the dc link.

ACKNOWLEDGEMENT

The authors acknowledge the Brazilian wind generator manufactory (Enersud) and the governmental support agencies FINEP, ELETROBRÁS and CNPQ.

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