THREE-PHASE POWER FACTOR CORRECTION RECTIFIER APPLIED TO WIND ENERGY CONVERSION SYSTEMS

Carlos E. A. Silva, René T. Bascopé, Demercil S. Oliveira Jr
Federal University of Ceará – UFC
Department of Electrical Engineering – DEE
Group of Energy Processing and Control – GPEC
Fortaleza – CE – Brasil
elmano@dee.ufc.br, demercil@dee.ufc.br, rene@dee.ufc.br

Abstract – This paper proposes a topology of three-phase controlled rectifier feasible for small wind energy conversion systems. This rectifier uses six wires of the generator and allows for the operation with high power factor, increasing the generator efficiency. One Cycle Control (OCC) was used in the rectifier control. This study is concerned with the operating principle, a design example, and some simulation and experimental results for a 5kW prototype.

Keywords – three-phase PWM rectifiers, one cycle control, power factor correction and wind energy systems.

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% to the year [1].

Either for ambient, strategic, or geographic questions, the generation of electric energy from wind systems has grown quickly, changing from a global installed power of 4.8 GW in 1995 to 58 GW in 2005, at an 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.

This worldwide context is challenging for all professionals involved in generation, distribution, and processing of electric energy. In energy processing the power electronic specialists and researchers are fundamental, constantly seeking the increase of the processed power with greater efficiency and reduced weight and volume.

This paper intends to contribute with this research considering a three-phase controlled rectifier with active power factor correction employing One Cycle Control (OCC), what allows obtaining high power factor with increased simplicity of the circuit control when compared to conventional techniques. This rectifier is applicable to wind energy conversion systems (WECS).

II. WIND ENERGY CONVERSION SYSTEMS

Any wind energy conversion system (WECS) is composed basically of three parts: wind turbine, electrical power generator, and electronic power system. The wind turbine and the electrical power generator compose the wind generator.

The most used electric power generators in wind energy systems are the doubly-fed induction generators (DFIG) and the permanent magnet synchronous generator (PMSG). Since PMSG’s do not require external excitation current and it presents high efficiency and small size when compared with DFIG’s, they have been widely used in smack WECS rated at some kilowatts [3]-[4].

The focus of this work is small WECS based in PMSG’s. To follow the mathematical model of PMSG and the main topologies of power processing they are presented already proposed for systems based on that generator.

A. Wind Turbine Model

The wind turbine basic principle is to convert the linear motion of the wind into rotational energy. This rotational energy is used to drive an electrical generator, allowing the kinetic energy of the wind to be turned into electric power. The captured power of the wind ($P_v$) for a wind turbine is given by Eq. (1).

$$ P_v = \frac{1}{2} \rho_v \cdot A_v \cdot u^3 $$

Where ‘$\rho_v$’ is the wind density, ‘$u$’ is the wind speed, and $A_v$ is the area swept by the turbine. The mechanical power ($P_m$) generated by the wind turbine from captured power of the wind depends of the power coefficient ($C_p$) of the wind turbine, as it shows the Eq. (2).

$$ P_m = P_v \cdot C_p (\lambda) $$

In Eq. (2) the $C_p$ is a function of tip-speed ratio $\lambda$, given by Eq. (3).

$$ \lambda = \frac{r \cdot \omega_m}{u} $$

Where ‘r’ is the length of the wind turbine spade and ‘$\omega_m$’ is the angular rotor speed. The variation of the $C_p$ with $\lambda$ depends on the aerodynamic characteristics of the wind turbine. The $C_p$ equation is the equation is provided by the turbine manufacturer. In the quality of illustration, a typical curve of $C_p$ vs. $\lambda$ is shown in Fig. 1.

In Fig. 1 can be observed that there is an optimum value of $\lambda$ for which the conversion of the captured wind power in mechanical power is maximum.
B. PMSG Mathematical Model

Using the torque definition, the mechanical torque ($T_m$) applied to PMSG is given by Eq. (4).

$$ T_m = \frac{P_m}{\omega_m} $$

(4)

Replacing the Eqs. (1), (2) e (3) in the Eq. (4), the mechanical torque can be expressed according to the Eq. (5).

$$ T_m = \frac{1}{2} \rho_{av} \cdot r \cdot A \cdot \frac{C_p(\lambda)}{\lambda} \cdot u^2 $$

(5)

Using the torque definition again, the electromagnetic torque ($T_e$) of the PMSG is given by Eq. (6).

$$ T_e = \frac{E_a \cdot I_a + E_b \cdot I_b + E_c \cdot I_c}{\omega_m} $$

(6)

Where $E_{a,b,c}$ are the induced instantaneous voltages in the PMSG windings and $I_{a,b,c}$ are the induced instantaneous currents in PMSG windings. Disdaining the friction, the variation of the angular mechanical speed of the rotor with the time is given by Eq. (7).

$$ \dot{\omega_m} = \frac{1}{J} \cdot (T_m - T_e) $$

(7)

C. Power Processing Topologies Applied to PMSG

Fig. 2 show the block diagram of a WECS that can be used so much in the charging battery building as in the input stage of current inverters for grid connected systems [5]-[11]. It consists in a standard rectifier only. The main advantages of this systems are simplicity and low cost.

However, systems like those represented by Fig. 2 develop high harmonic distortion in the current and voltage of PMSG’s, which are troublesome because they can cause several upset to the generator, such as [12]:

- Increased heating due to iron and copper losses at the harmonic frequencies;
- Reduction in machine efficiency;
- Loss to the torque production;
- Increased in audible noise emission;
- Can cause or enhance the refusal to start smoothly in induction generators;
- Can cause mechanical oscillations;

In order to overcome these problems, systems capable of emulating resistive loads for the PMSG must be used by replacing conventional diode rectifiers, allowing the operation with high power factor. These systems can be implemented basically in two ways: introducing a dc-dc stage between the conventional rectifier and the output stages (Fig. 3) [13] or using PWM rectifiers with appropriate modulation (Fig. 4) [14]-[17].

III. PROPOSED RECTIFIER

The proposed topology is a novel three-phase PWM rectifier, based on the single-phase rectifier introduced in [18]-[19], and is recommended for applications where six wires are accessible. The proposed rectifier is composed by three single-phase rectifiers, as shown in Fig. 5, each one connected to one phase of the PMSG. This rectifier is fully controlled, being able to provide unity power factor and low harmonic content of the generator currents.
In Fig. 5 $E_{a,b,c}$ are the induced magneto-driving force in each winding of the PMSG stator, the inductors $L_{a,b,c}$ represent the inductances of each winding of the PMSG stator and are coupled to each other, $L_{1,2,3}$ are boost inductors. The main advantages of the proposed rectifier, when compared to standard three-phase PWM rectifiers are:

- All switches are connected to the same reference, simplifying the command circuit;
- Depending of the operation mode, both switches of each leg receive the same command signal;
- There is not switches in series, discarding the possibility of the short-circuit;
- For each leg there are only two semiconductors in the current path, increasing robustness with reduced losses;

The principal disadvantage of the proposed rectifier is the high number of semiconductors, which is justified in high power applications.

A. Operation Principle of the Rectifier

To each phase of the generator there is a rectifier module associated that operates in an independent way and similar to a boost converter. The stages of operation of each rectifier module are illustrated in the Fig. 6.

Depending on the modulation technique, two operating modes are available:

1) First Operation Mode

Only one switch operates during a given half cycle of the line voltage, as the operation of a single boost converter results. Thus, switch $S_1$ is turned/off while $S_2$ always remains turned on during the positive half cycle, and vice-versa during the negative half cycle. The semiconductor that remains turned on during half line cycle will conduct the current through itself, and not through the antiparallel diode, reducing conduction losses. On the other hand, this operating mode increases the complexity in generating the drive signals [18].

2) Second Operation Mode

Both semiconductors are driven with same gating signal. Thus, in the positive half line, when $S_2$ is turned on, the current will flow in the reverse direction through itself and, when $S_2$ is turned off the current will flow in the reverse direction through the antiparallel diode. In the negative half cycle of the line voltage where $S_1$ is turned on, the current will flow in the reverse direction through the switch itself, and when $S_1$ is turned off, the current will flow in the reverse direction through the antiparallel diode. The second operating mode simplifies the drive signal generation, but will lead to a little bit larger conduction losses those in the first one[18].

B. Rectifier Control

The rectifier control schematic diagram is shown in Fig. 7. The control technique used in the rectifier is the One Cycle Control [20]-[26]. This is the only control technique that allows getting high power factor in continuous conduction mode without the necessity of a reference signal for the current. This technique consists of two control loops, a voltage loop and a current loop.
In PFC OCC control technique the duty cycle of switch command pulse depends on the input voltage value, allowing that the current loop keeps the sine wave shape of input current analogous to input voltage in phase and form. The voltage loop controls the boost output voltage through of controller output signal, which changes the average input current by mean of slope ramp integrator.

IV. EXPERIMENTAL RESULTS

The proposed rectifier prototype was built and is being tested. Table I relates specifications and parameters used to implement the prototype.

<table>
<thead>
<tr>
<th>Rectifier specifications and parameters.</th>
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<tbody>
<tr>
<td>Rms input voltage range</td>
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<tr>
<td>Frequency of the input voltage</td>
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<tr>
<td>Output voltage</td>
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<td>Switching frequency</td>
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<td>Input inductors (L₁, 2, 3)</td>
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<tr>
<td>Output capacitance</td>
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<td>Output power</td>
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Fig. 8 shows prototype picture.

Fig. 8 – Prototype picture.

Fig. 9 shows the voltage and current waveforms of phase \( a \) for input voltage of 150Vrms and output power of 3.66kW, as the power factor is 0.997.

Fig. 9 – Voltage (1) and current (2) of phase \( a \) for Vin=150Vrms (100V/Div - 10A/Div - 5ms).

Fig. 10 presents the line current waveforms in phases \( a, b, \) and \( c \) for input voltage of 150V and output power of 3.66kW.

Fig. 10 – Current waveforms in phases \( a \) (1), \( b \) (2), and \( c \) (3) for input voltage of 150Vrms (10A/Div – 5ms).

Fig. 11 shows the harmonic spectrum of the input current in phase ‘a’ for rms input voltage of 150V and output power of 3.66kW. The total harmonic distortion is about 4.5%.

Fig. 11 – Harmonic spectrum of the input current (Vin=150V and Pout=3.66kW).

Fig. 12 shows the voltage and current waveforms of phase \( a \) for input voltage of 220Vrms and output power of 5kW, as the power factor is 0.992.

Fig. 12 - Voltage (1) and current (2) of phase \( a \) for Vin=220Vrms (100V/Div - 10A/Div - 5ms).
Fig. 13 presents the line current waveforms in phases \(a\), \(b\), and \(c\) for input voltage of 220Vrms and output power of 5kW.

Fig. 13 – Current waveforms in phases \(a\) (1), \(b\) (2), and \(c\) (3) for input voltage of 220Vrms (10A/Div – 5ms).

Fig. 14 shows the harmonic spectrum of the input current in phase ‘a’ for rms input voltage of 220V and output power of 5kW. The total harmonic distortion is about 5%.

Fig. 14 – Harmonic spectrum of the input current (Vin=220V and Pout=5kW).

Fig. 15 presents the efficiency curve for rms input voltage of 220V, as the average efficiency is about 97% along the load range.

Fig. 15 – Efficiency versus output power curve.

V. CONCLUSION

A novel three-phase PWM rectifier is presented. The main advantages, when compared to a conventional three-phase controlled rectifier, are the use of switches with the source connected to the same point, robustness due to the absence of controlled switches in the same leg, and reduction of switching losses.

Moreover, the control implementation through OCC allowed a great simplification of the control circuit. With this control technique the current drained follows inherently the input voltage wave form, dispense the synchronism use. This characteristic is very important for the applications with wind energy, therefore the wind generator does not supply a clean wave form voltage.

The experimental results prove the effectiveness of the considered system, which present the referring results to the a power processing of the 5kW, with average efficiency of 97% and power factor bigger that 0.99.

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REFERÊNCIAS


[8] Xiong Xin; Liang Hui, “Research on multiple boost converter based on MW-level wind energy conversion system”, Proceedings of the Eighth International


