A MAXIMUM POWER POINT TRACKER WITH HIGH POWER FACTOR FOR SMALL WIND TURBINES IN BATTERY CHARGING APPLICATIONS

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***ABSTRACT* - Small wind turbines generators (SWTG) often use a permanent magnet synchronous generator (PMSG) and a bridge rectifier for battery charging applications. With this simple load scheme, the wind turbine does not operate in its maximum power for all wind speeds. Add to this, harmonic content on PMSG voltages and currents increases heating and electrical losses.**

This paper proposes a SWTG power conversion system with two main characteristics: maximum power point tracking (MPPT) and power factor correction (PFC). Proposed system is simulated computationally with a dynamic SWTG model. Results are experimentally confirmed in a bench test that simulates SWTG behavior. Results show that proposed system increase power generated by PMSG and at the same time obtains high quality voltage and current waveforms on the stator.

***KEYWORDS* – Wind turbines, power electronics, PFC, MPPT.**

I. INTRODUCTION

Wind power is the most rapidly growing means of electricity generation at the turn of the 21st century. Global installed capacity has raised 25% in 2006 [1]. Most of this growth is attributed to large wind turbines connected to the grid. In some applications, small wind turbines generators (SWTG) are used in stand-alone systems. This type of application has an interesting market in developing countries, providing electricity in places where no utility grid is available. In stand-alone operation, wind turbine is the only source of energy generation to consumers, and intermittent characteristic of wind creates a need for energy backup. Battery charging is an interesting alternative because of its simplicity and reliability.

SWTG often use a permanent magnet synchronous generator (PMSG) and a bridge rectifier for battery charging applications, as shown in Figure 1a. This conventional load scheme imposes a condition of fixed voltage on generator terminals due to the battery bank. As a consequence, the wind turbine does not operate in its maximum power in all operating conditions [2]. SWTG load must be actively modified in order to optimize energy generation. Voltage on generator terminals cannot be constant; it must vary according to rotor angular speed.

Power electronics have an important role for controlling wind turbine load characteristics. In battery charging applications, DC-DC converters have been used for modifying load in order to maximize energy generation, on its various topologies: Buck [3], Boost [4], and Buck-Boost [5], [6]. Input side of the DC-DC converter is connected to the bridge rectifier with a bulky capacitor (DC link), and the output side is connected to the batteries, as illustrated in Figure 1b. This power electronics topology, with a proper control algorithm to modify duty-cycle of DC-DC converter, is known as Maximum Power Point Tracking (MPPT). The converter changes the apparent DC bus voltage seen by the generator. Thus by controlling the duty-cycle, the terminal voltage of PMSG is adjusted in order to maximize power production. For maximum power transfer in all wind speeds, the converter must be able to reduce PMSG terminal voltage in low wind speeds, and increase in high wind speeds [6]. Therefore, the recommended converter for this type of application must have buck-boost voltage characteristics.

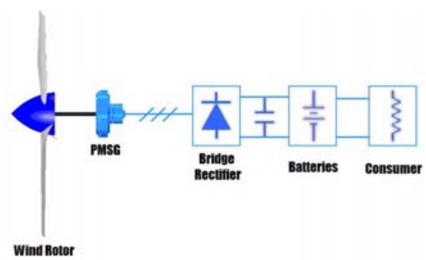


Fig. 1a. Conventional scheme of a small wind turbine generator for battery charging

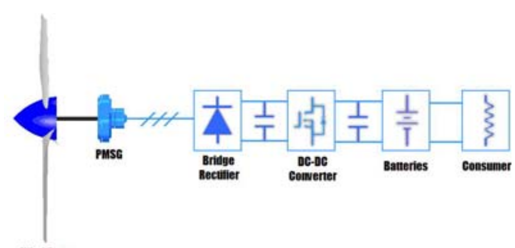


Fig. 1b. Small wind turbine with DC-DC converter for power maximization

A bridge rectifier, which has a non-linear behavior, composes both systems illustrated before. This structure introduces harmonic content on PMSG stator voltages and currents, increasing total losses and decreasing system power capability. Figure 2 shows phase voltage and current experimental waveforms of a 400W PMSG, (a) with resistive load and (b) with bridge rectifier with bulky capacitor, to illustrate the waveform distortion.

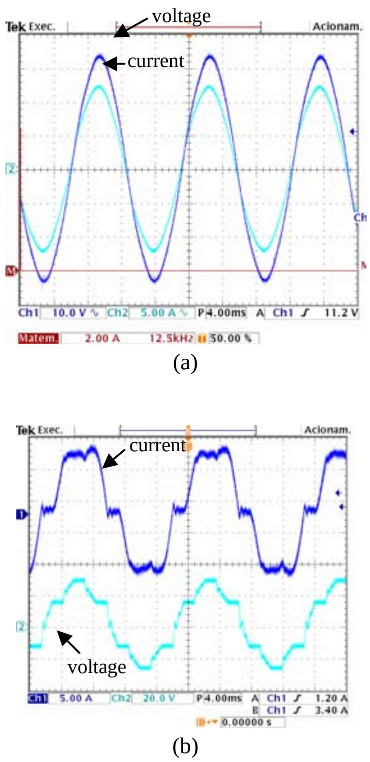


Fig. 2. Phase voltage and current waveforms for (a) resistive load and (b) bridge rectifier with bulky capacitor.

According to IEEE Std. 519-1992 [7], the main effect of harmonic voltages and currents in rotating machines is overheating due to core loss and copper loss, and therefore machine efficiency is reduced. As a reference, IEEE Std. 519-1992 says that overheating due to harmonics typically decrease efficiency from 5 % to 10 % when compared to a resistive load. It would be interesting that the converter responsible for MPPT could also drain high quality voltage and current waveforms from PMSG. In power supplies, a converter called Power Factor Corrector (PFC) guarantees that utility grid "sees" a resistive load. Rectifiers with PFC have been studied in wind turbines connected to the grid, and results show that it is possible to obtain high quality waveforms in PMSG terminals [8].

This paper proposes a SWTG conversion system with two main characteristics: maximum power point tracking (MPPT) and power factor correction (PFC). The paper analysis is based on real SWTG aerodynamic and electrical parameters of a 400W nominal power Brazilian wind turbine. Those parameters were determined experimentally on previous work [9].

II. PROPOSED SYSTEM

On proposed system, a Three-Phase Single-Switch SEPIC Rectifier, operating with input currents in discontinuous mode, replaces the conventional bridge rectifier. This structure can be seen on Figure 3. A control algorithm based on Power Signal Feedback Method (PSF) is used for maximum power point tracking.

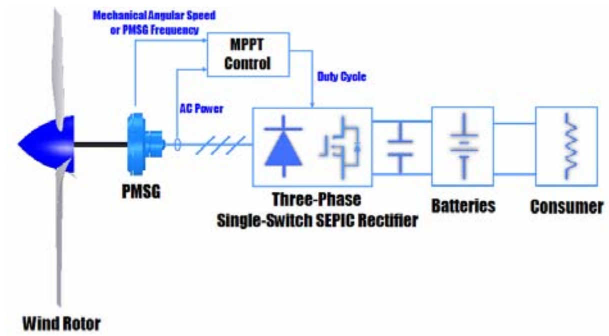


Fig. 3. Proposed System: Small wind turbine with Single-Switch SEPIC Rectifier for maximum power point tracker and power factor correction.

A. Single-Switch Three-Phase SEPIC Rectifier

The Single-Switch Three-Phase Single-Ended Primary Inductor (SEPIC) Rectifier is a cascade combination of a bridge rectifier and a single-phase SEPIC converter. It is placed between generator terminals and battery bank, as illustrated on Figure 4.

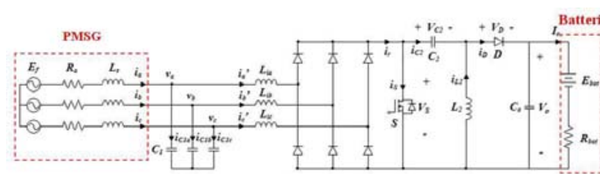


Fig. 4. Single-Switch Three-Phase SEPIC Rectifier placed between generator terminals and batteries.

Buck-boost voltage characteristic can easily be obtained by pulse width modulation (PWM) command of switch "S". Inductors placed before rectifier (L_{ia}, L_{ib} and L_{ic}) are the converter input inductances. Operation as a power factor corrector occurs with constant frequency and duty-cycle, and with input currents on three inductances (i_a', i_b' and i_c') in discontinuous current conduction mode (DICM). Figure 5 illustrates DICM, observing that current peaks are proportional to voltage. Prasad et al [10] first proposed this PFC technique. The i_a' waveform presents high harmonic content on switching frequency. Capacitors C_1 are placed between input inductors and PMSG terminals, creating a low-impedance path for high frequency currents, thus only the fundamental component (i_a), in phase with voltage, flows on PMSG stator.

A master thesis which origin this paper [11] brings detailed converter qualitative and quantitative analysis and design criteria. Most important components to be dimensioned are the input inductors, because its values determine DICM, so basic equations are shown here. Limit duty-cycle for DICM is dependant on output voltage V_o and rectified voltage v_r:

$$\delta < \frac{V_o}{V_o + v_r} \tag{1}$$

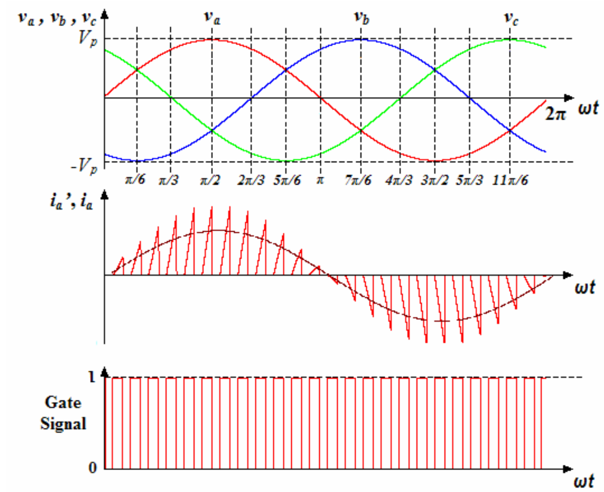


Fig. 5. Operation in discontinuous input current conduction mode (DICM).

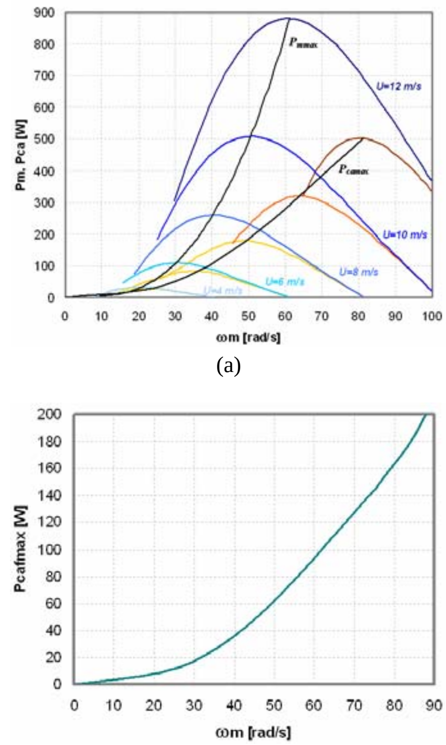
Duty-cycle δ is used on equation below to determine the maximum value of input inductors L_i:

$$L_i \leq \frac{3V_p^{\ 2} \cdot T \cdot \delta}{4 \cdot P_o} \tag{2}$$

Where V_p is the peak phase voltage of PMSG, T is the switching period, and P_o is the output power of three-phase SEPIC rectifier. V_p and P_o must be determined with maximum power of SWTG, V_o is the minimum allowable terminal battery voltage, and $v_r=\sqrt{3}V_p$.

B. Strategy for maximum power point tracking

Some control strategies are based on the power coefficient curve (C_p). An example is the TSR control method, which modifies wind rotor angular speed to maintain an optimum TSR value, and consequently a maximum power coefficient (C_p) for all wind speeds [12]. Wind turbines, when operating at maximum C_p, produces maximum mechanical power on shaft. For the small wind turbine used as reference on this work [9], the angular speed (ω_m) for maximum mechanical power points do not coincide with angular speed for maximum electrical power points, so this strategy is not recommended. In order to obtain maximum electrical power points, PMSG characteristics must be considered. To illustrate this fact, wind rotor mechanical power (P_m) and PMSG electrical power (P_{ca}) versus ω_m, for various wind speeds, were determined by simulation on PSIM® software, using a dynamic wind turbine model. On simulations, variable resistors connected in "Y" on PMSG terminals modify wind turbine loading characteristics. Simulation results for steady-state condition are shown in Figure 6. Notice a maximum mechanical power curve (P_{mmax}) and a maximum electrical PMSG power curve (P_{camax}).



(a)

(b)

Fig. 6. (a) Mechanical shaft power (P_m, Blue Lines) and PMSG electrical power (P_{ca}, Yellow Lines) and (b) PMSG maximum electrical power versus angular speed ω_m for single-phase.

MPPT control method of this work is based on the single-phase maximum electrical power curve $P_{camax}(\omega_m)$ seen on Figure 6a. The aim is to control power generated by PMSG to follow $P_{camax}(\omega_m)$. Figure 7 shows MPPT algorithm block diagram. Single-phase voltage and current are measured and multiplied to determine the instantaneous power. A first-order low-pass filter is used to obtain the DC part of power signal, which represents the active single-phase power P_{caf}. Rotor angular speed (or generator frequency) is measured and used as the input parameter of a lookup table containing the maximum power curve for one phase $P_{cafmax}(\omega_m)$ illustrated on Figure 6b. Lookup table output parameter is single-phase active power reference signal $P_{caf}^{\ *}$. Both power signals are subtracted, generating a power error signal to a PI controller. PI control signal modifies the duty-cycle of SEPIC rectifier, actively modifying PMSG power.

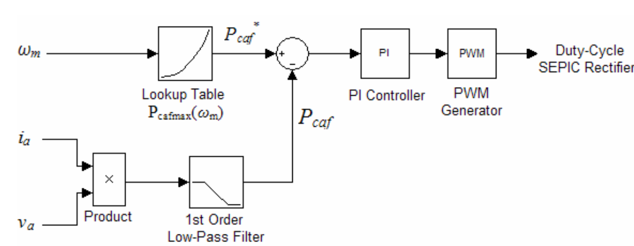


Fig. 7. Block diagram of maximum power point tracking control.

III. COMPUTER SIMULATIONS

Proposed system is simulated in PSIM® software with a dynamic SWTG model to evaluate the effectiveness of MPPT and PFC. A sub circuit containing the dynamic model of a wind rotor is build with electrical components, and in conjunction with other blocks available in PSIM® libraries, constitutes SWTG model. Figure 8 shows the simulation schematic on PSIM® software.

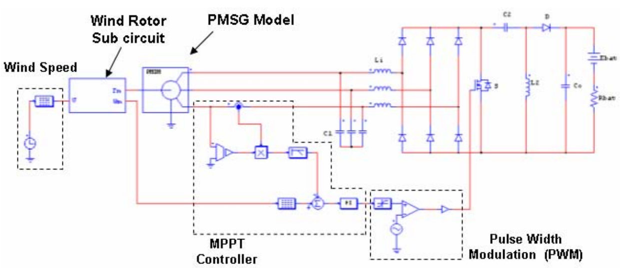


Fig. 8. Simulation diagram on PSIM® software.

MPPT performance can be evaluated by SWTG wind step response. Wind turbine is initially in steady-state condition at 10 m/s wind speed, and at time t=10 seconds, wind speed (U) is suddenly changed to 12 m/s. Figure 9 shows step response results of wind rotor angular speed (ω_m), wind rotor torque (T_m) electromechanical torque from PMSG (T_e), electrical power from PMSG (P_{ca}), reference power (P_{caf}^*) and measured power (P_{caf}). P_{caf}^* and P_{caf} in Figure 9 shows that proposed system is able to control phase power of PMSG. At steady-state condition, the error between P_{caf}^* and P_{caf} is null, and in transient condition the controller gives satisfactory response results.

PFC performance of single-switch three-phase SEPIC rectifier can be evaluated by observing voltage and current waveforms on PMSG stator, in steady-state condition, as seen on Figure 10. On the upper part of Figure 10, there can be seen SEPIC rectifier DICM and PMSG single-phase current after filtering. On the lower part of Figure 10, PMSG single-phase voltage and current waveforms are illustrated. Notice that they are in phase and with near sinusoidal shape.

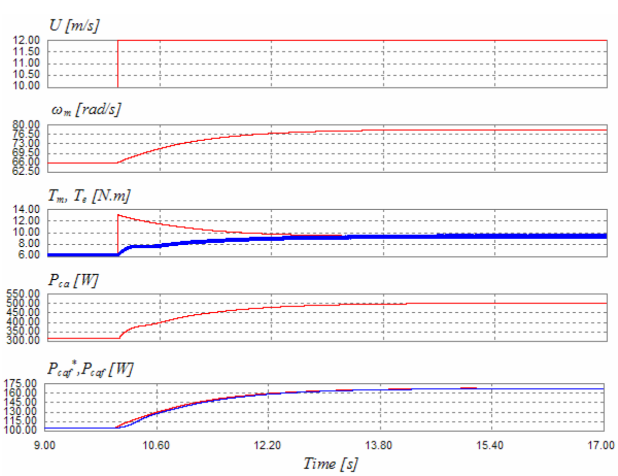


Fig. 9. Step response of proposed system simulated on PSIM software.

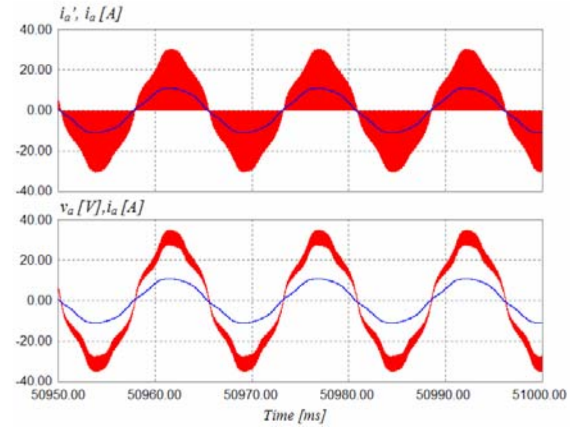


Fig. 10. Simulated PMSG voltage and current waveforms with wind turbine in steady state at 12 m/s wind speed.

IV. BENCH TEST OF PROPOSED SYSTEM

A bench was developed for testing the proposed system in laboratory, and it is composed by an induction motor, which simulates the behavior of a wind rotor, a 400W PMSG, a prototype of SEPIC rectifier, a battery bank, a load controller, and a computer with a data acquisition board for control and supervision of whole system. Figure 11 illustrates bench schematic.

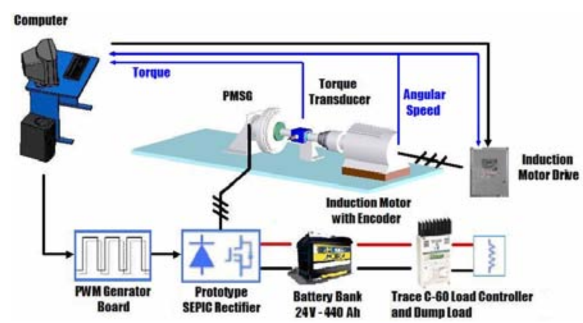
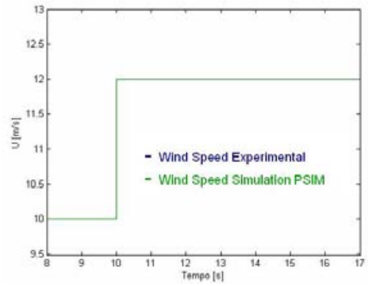


Fig. 11. Schematic of bench test in laboratory for testing of proposed system.

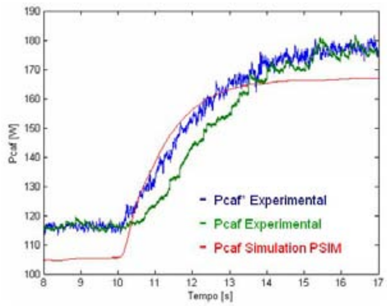
Maximum power point tracker control and bench control are implemented on software SIMULINK® in real time mode. Wind speed can be varied on software, to evaluate system performance for all wind speed range. Proper instruments were used to measure PMSG generated power and power quality. Both conventional SWTG scheme and proposed SWTG system are analyzed and compared. Results are divided by proposed system properties: MPPT and PFC.

A. Results of Maximum Power Point Tracker

MPPT algorithm performance was analyzed experimentally by wind speed step response, and results were compared to simulations. SWTG is in steady-state at 10 m/s wind speed, and on t=10 seconds, wind speed had suddenly changed to 12 m/s. Figure 12a shows wind speed step used to evaluate response of MPPT control, and Figure 12b shows reference phase power (P_{caf}^*) and measured phase power (P_{caf}) time responses.



(a)



(b)

Fig. 12. (a) Wind speed step (b) Reference phase power (P_{caf}^{*}) and measured phase power (P_{caf}).

Figure 12b shows the effectiveness of MPPT algorithm to control power produced by PMSG. In steady-state condition, the error between reference and measured power are null, and on transient condition, a difference between reference and measured power exists because PI controller does not null error for a reference that is dynamically changing. Figure 13 shows a comparison of PMSG power between conventional scheme (fixed bus voltage) and proposed system, showing that MPPT can increase power for low and high wind speeds. At nominal wind speed (12 m/s), power from PMSG with MPPT is 27% higher when compared to conventional scheme.

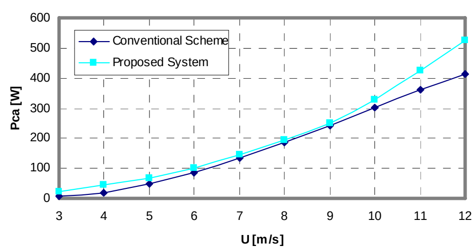
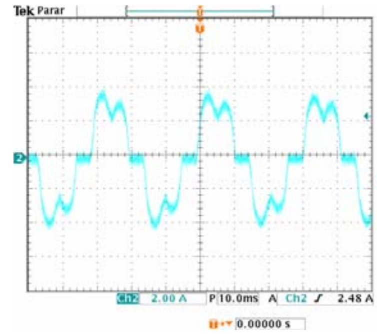


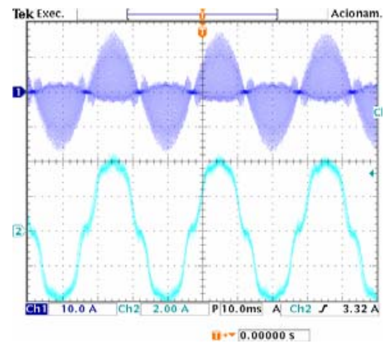
Fig. 13. PMSG active power comparison of conventional SWTG scheme and proposed SWTG system.

B. Results of Power Factor Correction

Single-Switch Three-Phase SEPIC Rectifier operation as a PFC can be noticed by comparison single-phase current and voltage waveforms. Figure 14a shows PMSG phase current with conventional SWTG scheme, and Figure 14b shows SEPIC rectifier DICM (up) and phase current after filtering (down) of proposed system, for wind speed of 6 m/s.



(a)



(b)

Fig. 14. Waveforms: (a) PMSG phase current with conventional SWTG scheme and (b) SEPIC rectifier DICM and PMSG single-phase current after filtering, at 6 m/s wind speed.

Figure 15 shows SEPIC rectifier DICM (up) and phase current after filtering (down) of proposed system, at 12 m/s wind speed. DICM waveform shows that SEPIC converter is near conduction boundary condition and validates design criteria.

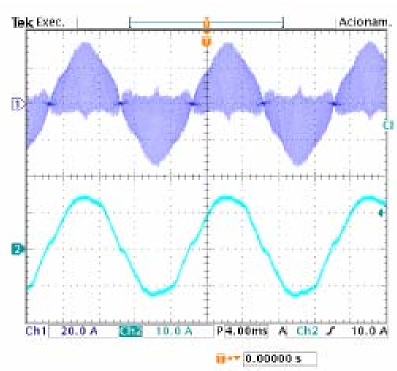
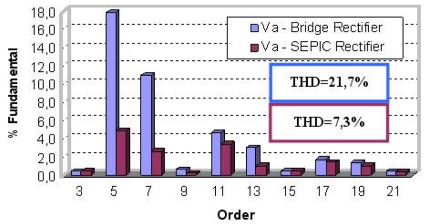
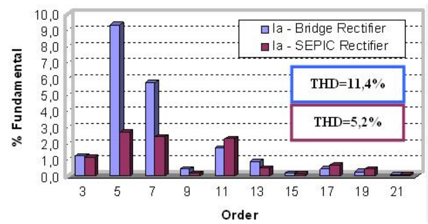


Fig. 15. Waveforms: SEPIC rectifier DICM and PMSG single-phase current after filtering, at 12 m/s wind speed.

Current waveform quality improvement when using SEPIC rectifier as a PFC is visible. Harmonic spectrum of single-phase voltage and current, for wind speed of 12 m/s, illustrated on Figure 16, quantifies harmonic mitigation Notice total harmonic distortion reduction for both single-phase voltages and currents.



(a)



(b)

Fig. 16. Harmonic spectrum comparison of (a) phase voltage and (b) phase current, at 12 m/s wind speed.

Figure 17 shows power factor versus wind speed for both schemes. With proposed system, power factor in PMSG is maintained 0,98-0,99, while with conventional scheme power factor varies from 0,67-0,95. SEPIC rectifier works well as a PFC for all wind speed range.

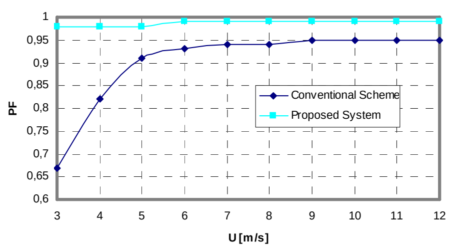


Fig. 17. Power factor comparison of conventional SWTG scheme and proposed SWTG system.

V. CONCLUSIONS

This paper proposed a conversion system with maximum power point tracking and power factor correction for small wind turbines in battery charging applications. A three-phase single-switch SEPIC rectifier, operated in discontinuous input current mode, replaces the conventional bridge rectifier. A maximum power point tracking controller actively modifies duty-cycle of SEPIC rectifier to maximize electrical power from PMSG.

Simulation and experimental results shows that it is possible to maximize power and at the same time increase PMSG power factor. Regarding MPPT, results show that the control algorithm increases PMSG power for all wind speeds. In nominal wind speed (12 m/s), increment in power is 27% when compared to a conventional SWTG scheme (bridge rectifier connected to batteries). Regarding PFC, results shows that high power factor can be obtained for all wind speeds, being in the range of 0,98-0,99, while with conventional scheme, power factor of 0,67-0,95 were found.

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