

MAXIMUM POWER POINT TRACKER FOR SMALL WIND TURBINES INCLUDING HARMONIC MITIGATION

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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. With this simple load scheme, the wind turbine does not operate in its maximum electrical power in all operating conditions, and voltage and current harmonics flows in PMSG stator, increasing heating and electrical losses.

In this work, it is proposed a system for a SWTG with two main characteristics: maximum power point tracking (MPPT) and power factor correction (PFC) of PMSG. Proposed system is simulated in PSIM® software, with a dynamic SWTG model. A bench test, which simulates the behavior of a SWTG, is developed for testing the proposed system in laboratory. Results show that proposed system increase power generated by PMSG and at the same time decreases harmonic content of voltage and current on the stator.

KEYWORDS: Harmonics, Renewable Energy, PFCs, Small Wind Generators, MPPT.

1. INTRODUCTION

Wind power is the most rapidly-growing means of electricity generation at the turn of the 21st century. Global installed capacity has raised 20% in 2004 [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 isolated operation. This type of application has an interesting market in developing countries, providing electricity in places where no electric grid is available. In isolated operation, wind turbine is the only source of energy generation to consumers, and intermittent characteristic of wind energy creates a need for energy backup. Battery charging is an interesting alternative because of its simplicity and reliability. NUTEMA is developing new concepts of vertical axis small wind turbines for battery charging applications. Figure (1) shows the Three Helical Blades Turbine (Left), and “H Model” High Solidity Turbine (Right). Parallel to wind turbine development, new electronic control methods are being researched to increase efficiency and reliability of these machines.

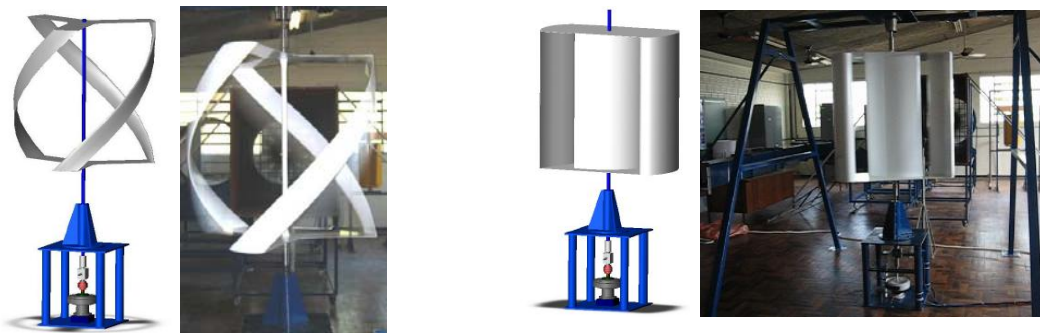


Figure 1 – New concepts of vertical axis small wind turbines for battery charging applications

SWTG in battery charging applications often use permanent magnet synchronous generator (PMSG) and a bridge rectifier, as shown in Figure (2a). 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 electrical power in all operating conditions [2]. The electrical load characteristic of a SWTG must be modified in order to optimize energy generation. Voltage on the generator terminals cannot be constant; it must vary according to rotor angular speed.

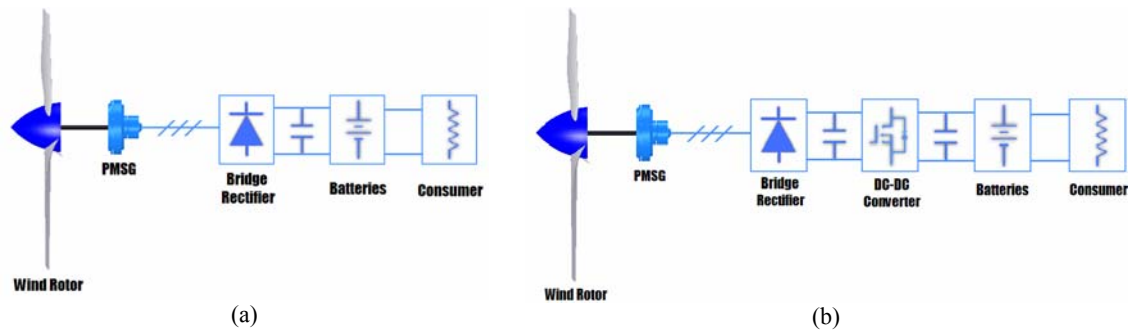


Figure 2 – (a) Conventional scheme of a small wind turbine generator for battery charging and (b) Small wind turbine with DC-DC converter for maximization of power production.

Power electronics have an important role for controlling electrical characteristics of wind turbines. For SWTG in battery charging applications, DC-DC converters have been used for modifying the electrical load in order to maximize energy generation, on its various topologies: Buck [3], Boost [4], and Buck-Boost [5], [6]. Input of the DC-DC converter is connected to bridge rectifier and a bulky capacitor (DC bus), and output is connected to the batteries, as illustrated in Figure 2(b). This scheme with a proper control algorithm to modify duty-cycle of DC-DC converter for maximum energy generation is known as Maximum Power Point Tracking (MPPT). The converter is used to change the apparent DC bus voltage seen by the generator. Thus by controlling the DC converter the terminal voltage of the PMSG is adjustable 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]. Thus, the recommended converter for this type of application must have buck-boost voltage characteristics.

Both systems illustrated before are composed by a bridge rectifier that has a non-linear behavior. This structure introduces harmonic content of voltage and current flowing in PMSG stator, increasing total losses and decreasing power capability of the system. Figure 3) shows experimental waveforms of phase voltage and current on generator stator, (a) with resistive load and (b) with bridge rectifier and bulky capacitor, to illustrate the waveform distortion.

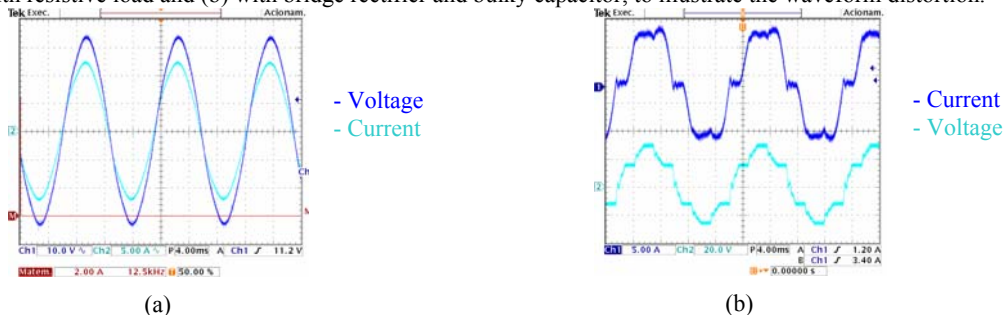


Figure 3 – Waveforms of phase voltage and current for (a) resistive load and (b) bridge rectifier with bulky capacitor.

According to IEEE Std. 519-1992 [7], the main effect of harmonic voltage and current in rotating machines is overheating due to core loss and copper loss. The harmonic content reduces machine efficiency. 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 mitigate harmonic content flowing on PMSG stator. In power supplies, a converter called Power Factor Corrector (PFC) is used to guarantee that electric grid “sees” a resistive load. Rectifiers with PFC have been studied in wind turbines connected to electric grid, and results shows that it is possible to obtain high quality waveforms in PMSG terminals [8].

On this work it is proposed a system for a SWTG with two main characteristics: maximum power point tracking (MPPT) and power factor correction (PFC) of PMSG. The proposed system is simulated in PSIM® software with a dynamic SWTG model. A bench test, which simulates the behavior of a wind turbine, is developed for testing the proposed system in laboratory. SWTG aerodynamic and electric parameters used on computer simulations and bench test are based in a commercial Brazilian wind turbine of 400 W nominal power. Those parameters were determined experimentally on previous work [9].

2. PROPOSED SYSTEM

A new scheme for a small wind turbine is proposed on this work, in order to obtain maximum power point tracking (MPPT) and power factor correction (PFC) of PMSG simultaneously. Bridge Rectifier is replaced by a Three-Phase Single-Switch SEPIC Rectifier, operating with input currents in discontinuous mode. A control algorithm based on Power Signal Feedback Method (PSF) is used for maximum power point tracking. Figure (4) illustrates the proposed system.

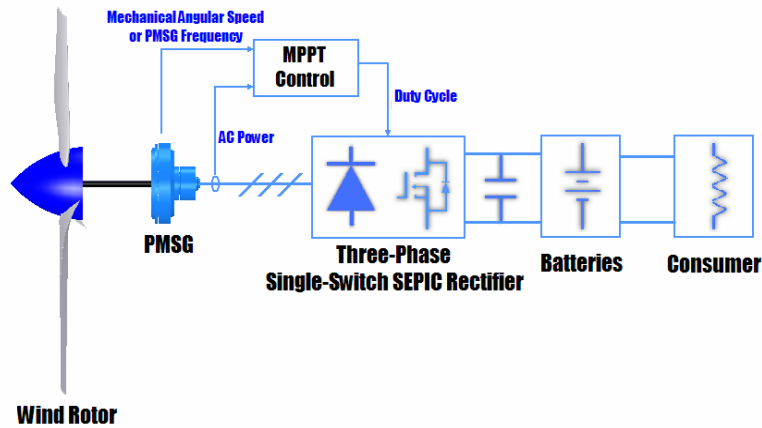


Figure 4 – Proposed System: Small wind turbine with Single-Switch SEPIC Rectifier for maximum power point tracker and power factor correction.

2.1 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 in Figure (5).

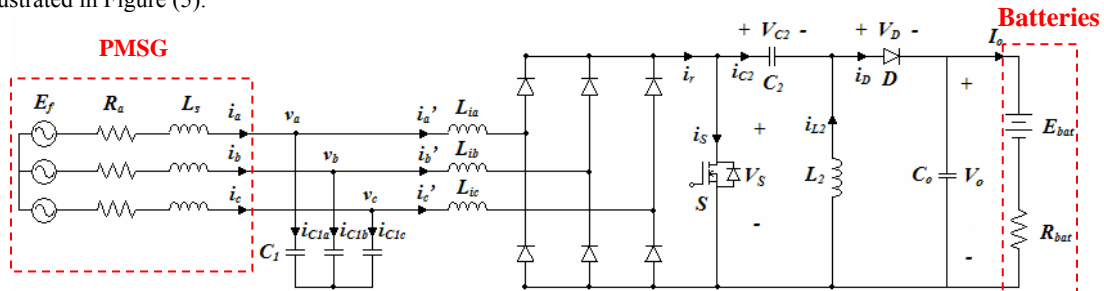


Figure 5 – Single-Switch Three-Phase SEPIC Rectifier placed between generator terminals and batteries.

The buck-boost voltage characteristic can be easily obtained by commanding switch “S” by pulse width modulation (PWM). Inductors placed before rectifier (L_{ia} , L_{ib} and L_{ic}) are the converter input inductance. Operation as a power factor corrector occurs with constant frequency and duty-cycle, and input currents on three inductances (i_a' , i_b' and i_c') in discontinuous current conduction mode (DICM). Figure (6) illustrates this kind of situation, observing that current peaks are proportional to voltage. This PFC technique was first proposed by Prasad et al [10]. Waveform i_a' 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, and only the fundamental component (i_a), in same frequency and phase of voltage, flows on PMSG stator.

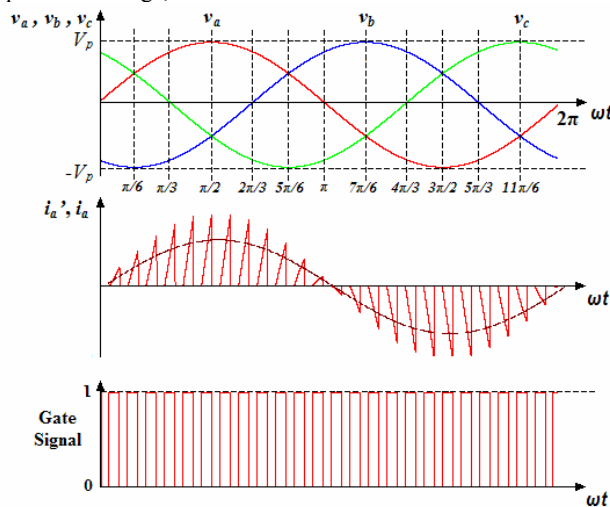


Figure 6 – Operation in discontinuous input current conduction mode (DICM).

A master thesis which origin this paper [11] brings a detailed qualitative and quantitative analysis of the converter, and shows a design procedure for utilization on SWTG in battery charging applications. The most important component of the circuit to be dimensioned is the input inductors, because its values determine DICM, so basic equations are shown here. Duty-cycle for L_i project is dependant on output voltage V_o and rectified voltage v_r :

$$\delta < \frac{V_o}{V_o + v_r} \quad (1)$$

The duty-cycle δ is used on equation below, determining the maximum value of input inductors L_i :

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

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 $v_r = \sqrt{3}V_p$.

2.2 Strategy for Maximum Power Point Tracking

Some control strategies are based on the power coefficient curve (C_p), eg. TSR control method, which modifies angular speed of wind rotor for maintaining an optimum TSR value and consequently a maximum power coefficient (C_p) for all wind speeds [12]. The wind turbine, when operating at maximum C_p , produces maximum mechanical power on shaft. To 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, generator characteristics must be considered. To illustrate this fact, mechanical power produced by wind rotor (P_m) and electrical power produced by PMSG (P_{ca}) versus ω_m , for various wind speeds, can be determined by simulation on software PSIM, using a dynamic wind turbine model. Simulation results for steady-state condition are shown in Figure (7). On simulations, loading of PMSG is modified by variable resistive loads connected in ‘‘Y’’ on its terminals. Notice a maximum mechanical power curve (P_{mmax}) and a maximum electrical PMSG power curve (P_{camax}).

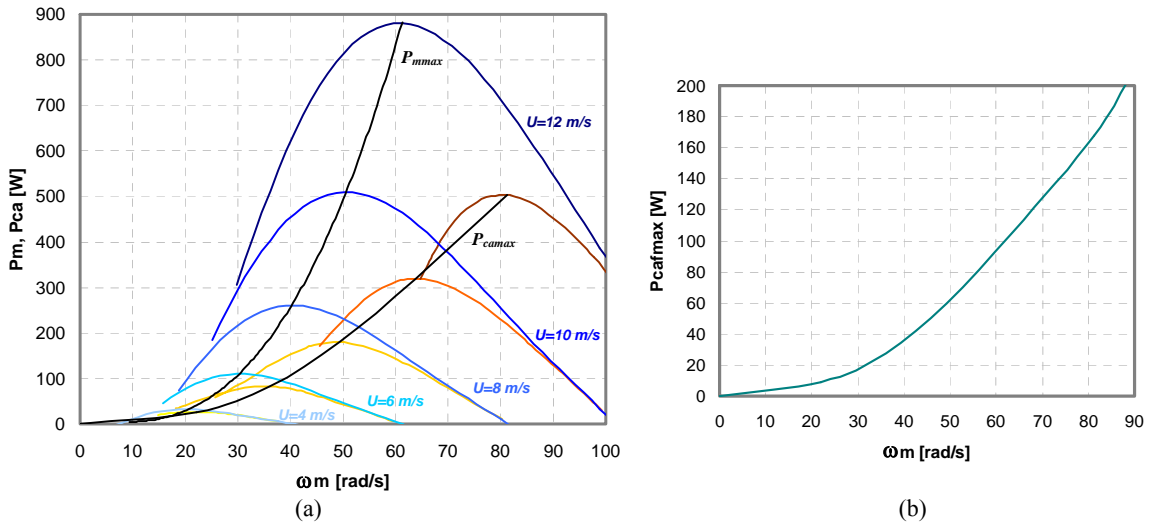


Figure 7 – (a) Mechanical Shaft Power (P_m , Blue Lines) and Electrical PMSG Power (P_{ca} , Yellow Lines) and (b) Maximum electrical power of PMSG versus angular speed ω_m for one phase.

The control method of this work is based on the maximum electrical power curve $P_{camax}(\omega_m)$ seen on Figure (7a). The aim is to control power generated by PMSG to follow $P_{camax}(\omega_m)$. Figure (8) shows the block diagram of MPPT algorithm. Voltage and current of one phase is 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 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 of PMSG for one phase ($P_{cafmax}(\omega_m)$) illustrated on Figure (7b). Output parameter of the lookup table is the reference of active power for one phase (P_{caf}^*). Both power signals are subtracted, generating an error signal to PI controller. Control signal modifies the duty-cycle of SEPIC rectifier, actively modifying power generated by PMSG.

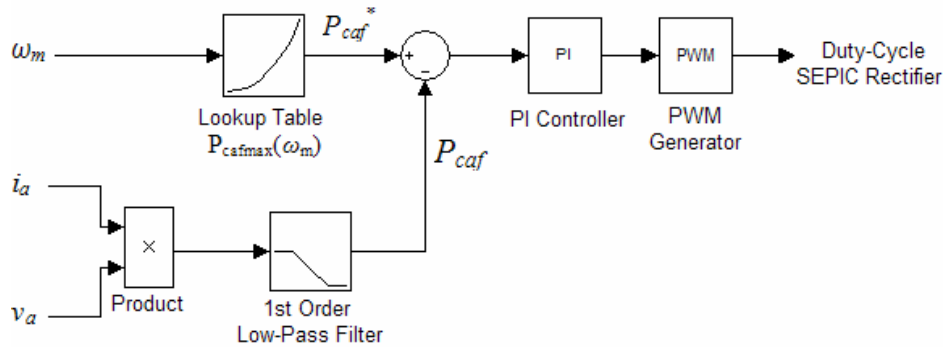


Figure 8 – Block diagram of maximum power point tracking control.

3. COMPUTER SIMULATIONS

Proposed system is simulated in PSIM® software with a dynamic SWTG model, to evaluate the effectiveness of maximum power point tracking and power factor correction. A sub circuit containing a dynamic model of a wind rotor is build with electrical components, and in conjunction with other blocks available in PSIM libraries, constitutes SWTG model. The MPPT algorithm uses zero-order hold (ZOH) and discrete blocks to represent a discrete controller e.g. microcontroller. Figure (9) shows the simulation schematic on PSIM® software.

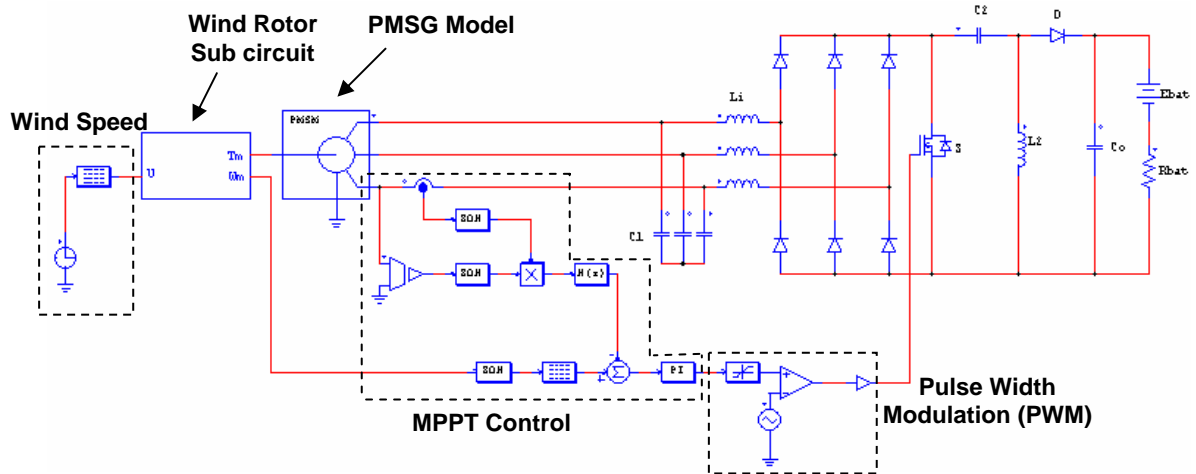


Figure 9 – Simulation diagram on PSIM® software.

The behavior of MPPT can be evaluated by the wind step response of SWTG. Wind turbine is at steady-state condition and wind speed is 10 m/s, and at time 10 seconds, wind speed (U) is suddenly changed to 12 m/s. Figure (10) shows step response of wind turbine with proposed system simulated on software PSIM®, where 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}) against time can be seen. Observation of P_{caf}^* and P_{caf} in Figure (10) shows that proposed system is able to control phase power of PMSG. At steady-state condition, error between P_{caf}^* and P_{caf} is null, and in transitory condition controller give satisfactory response results.

PFC characteristic of single-switch three-phase SEPIC rectifier can be evaluated by observation of voltage and current waveforms on PMSG stator, in steady-state condition. On the upper part of Figure (11), DICM of SEPIC rectifier, and PMSG phase current after filtering can be seen. On the lower part of Figure (11), waveforms of phase voltage and current of PMSG are illustrated, showing they are in phase and with near sinusoidal shape.

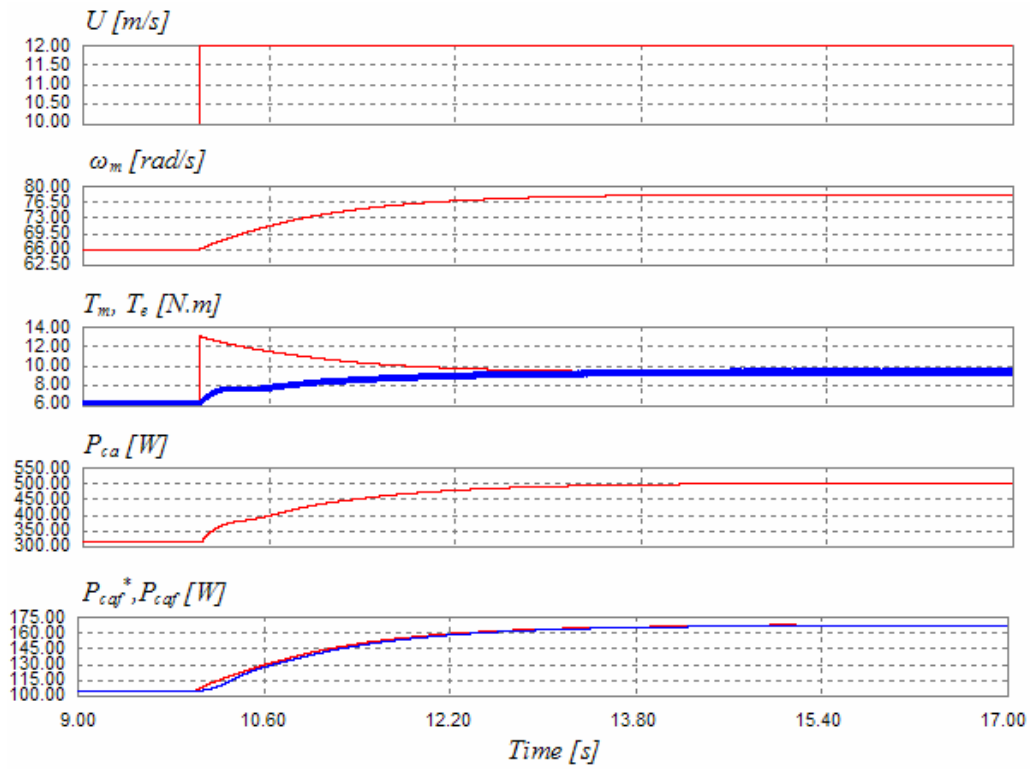


Figure 10 – Step response of proposed system simulated on PSIM software.

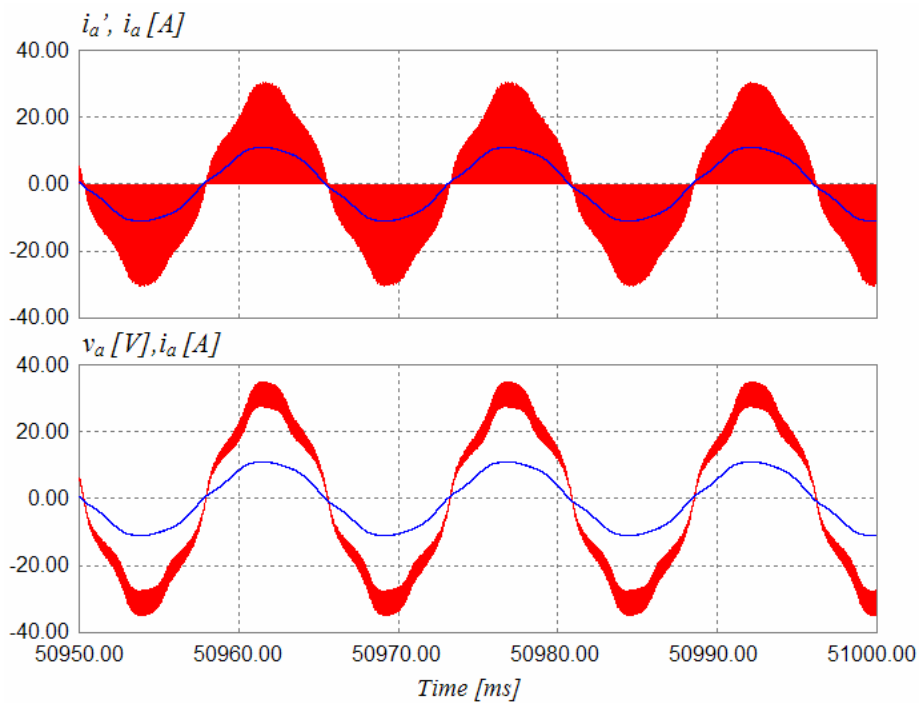


Figure 11 – Voltage and current waveforms in steady-state for wind speed of 12 m/s, simulated on PSIM software.

4. BENCH TEST OF PROPOSED SYSTEM

A bench test 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 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 (12) illustrates the schematic of bench for testing the proposed system.

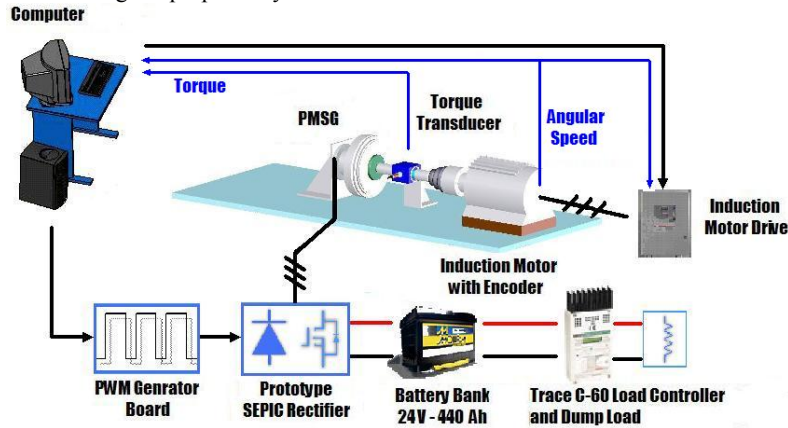


Figure 12 – Schematic of bench test in laboratory for testing of proposed system.

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

4.1 Results of Maximum Power Point Tracker

Behavior of MPPT control was analyzed experimentally by wind step response, and results were compared to simulation on software PSIM. SWTG was at steady-state with 10 m/s wind speed, and at 10 seconds, wind speed had suddenly changed to 12 m/s. Figure (13a) shows wind speed step used to evaluate response of MPPT control, and Figure (13b) shows time response of reference phase power (P_{caf}^*) and measured phase power (P_{caf}).

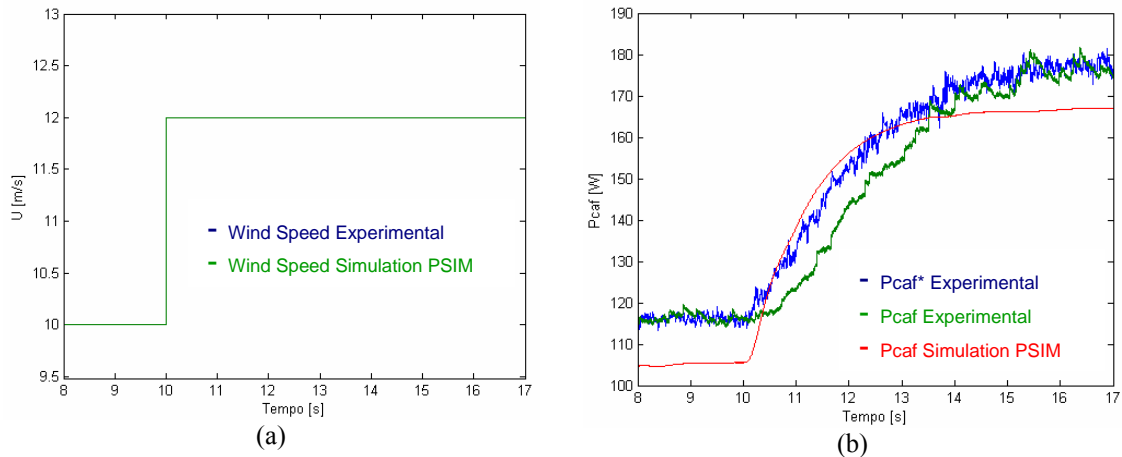


Figure 13 – (a) Wind speed step (b) Reference phase power (P_{caf}^*) and measured phase power (P_{caf}).

Figure (13b) shows the effectiveness of MPPT algorithm to control power produced by PMSG. In steady-state condition, error between reference and measured power are null, and on transitory condition, a difference between reference and measured power exists because PI controller does not null error for a reference that is dynamically changing. Figure (14) 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.

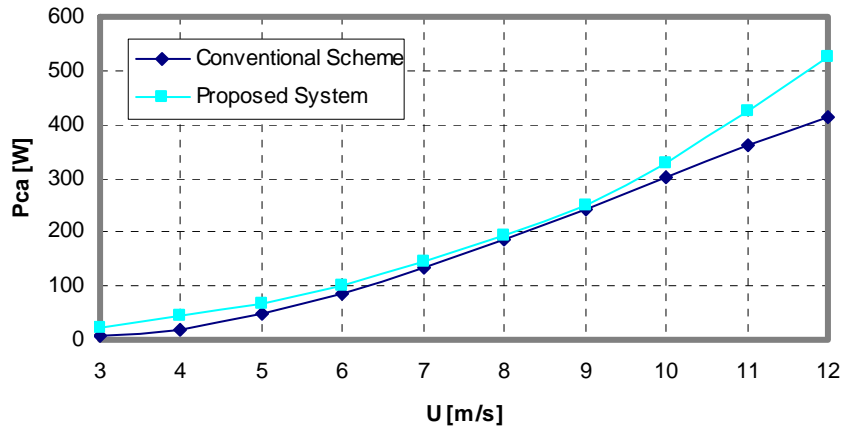


Figure 14 – PMSG power comparison of conventional SWTG scheme and proposed SWTG system.

4.2 Results of Power Factor Correction

Single-Switch Three-Phase SEPIC Rectifier operation as a PFC can be noticed by comparison of phase current and voltage waveforms. Figure (15a) shows phase current of PMSG with conventional SWTG scheme, and Figure (15b) shows DICM of SEPIC rectifier (up) and phase current after filtering (down) of proposed system, for wind speed of 6 m/s.

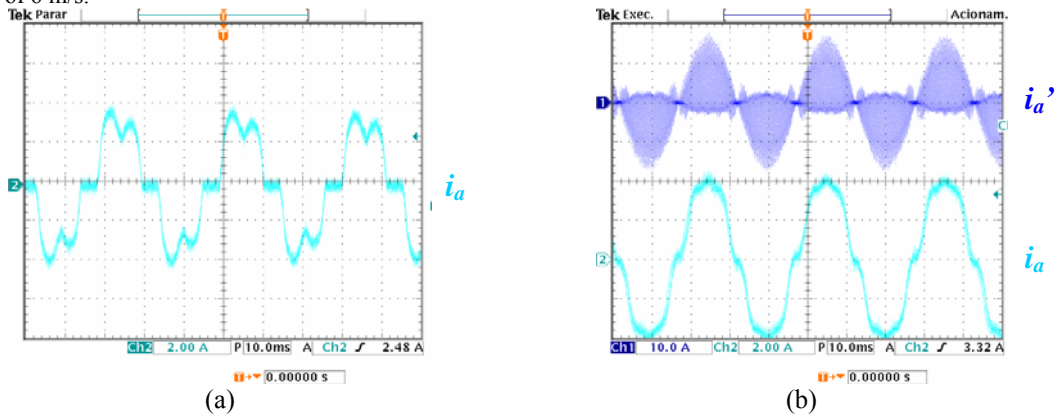


Figure 15 – Waveform of (a) Phase current of PMSG with conventional SWTG scheme and (b) (up) DICM of SEPIC rectifier and (down) phase current of PMSG after filtering, for wind speed of 6 m/s.

By observing last figure, it is visible the quality improvement of current waveform when using SEPIC rectifier as a PFC. Harmonic spectrum of phase voltage and current for wind speed of 12 m/s, illustrated on Figure (16), shows harmonic mitigation of proposed system. Notice the reduction of total harmonic distortion for both phase voltage and current.

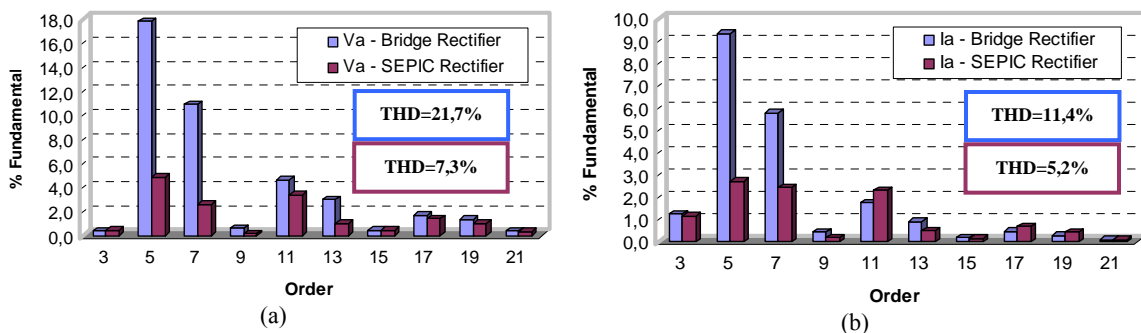


Figure 16 – Comparison of harmonic spectrum of (a) phase voltage and (b) phase current, for wind speed of 12 m/s.

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

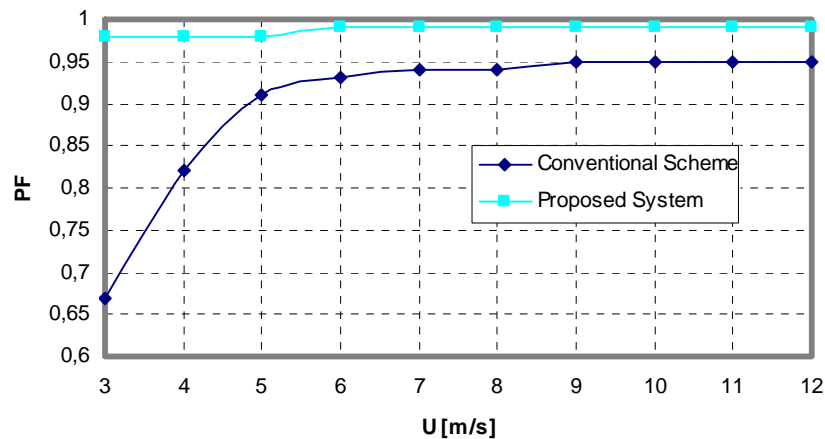


Figure 17 – Power factor comparison of conventional SWTG scheme and proposed SWTG system.

5. CONCLUSIONS

This paper proposed a system for maximum power point tracking including harmonic mitigation of phase voltage and current of PMSG, for small wind turbines in battery charging applications. Bridge rectifier was replaced by a three-phase single-switch SEPIC rectifier, operated in discontinuous input current mode. A maximum power point tracking control was used in order to maximize electrical power from PMSG. Simulation of proposed system was done on software PSIM, and a bench test was especially developed for testing the proposed system in laboratory.

Simulation and experimental results shows that it is possible to maximize power and at the same time increase power factor of PMSG. Regarding MPPT, results shows control algorithm used on proposed system increase power produced by PMSG for all wind speeds, and in nominal wind speed (12 m/s), the increase in power produced was 27% when compared to a conventional SWTG scheme (bridge rectifier connected directly to batteries). Regarding PFC, results shows that with proposed system, high power factor can be obtained for all wind speeds, being in the range of 0,98-0,99 capacitive, while with conventional scheme of small wind turbines, power factor of 0,67-0,95 inductive was found.

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7. ACKNOWLEDGEMENT

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