A Low Voltage Electronic Ballast Designed For Hybrid Wind-Solar Power Systems

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Abstract—**This paper describes the development of an illumination system for open and/or isolated areas like gardens, sidewalks, outdoor lighting for residences and rural areas, demonstration plants on Universities, et cetera. The proposed system is based on a 70 W electronic ballast (EB) for high-pressure sodium (HPS) lamps designed to operate from a low voltage automotive lead-acid battery charged by a Hybrid Wind-Solar Power System. A new design criteria for a Push-Pull EB based on the rated current RMS of the lamp is presented. The paper also includes technical issues faced in building the prototype such as transformer losses generated by skin effect, transformer winding isolation and the effect of high MOSFET drain source current.**

I. INTRODUCTION

The purpose of this paper is to report the development of a stand-alone single stage electronic ballast (EB) for 70 W HPS lamps whose energy is provided by a low power hybrid wind-solar system. In the proposed system, the alternative energy is stored in a 12 V automotive lead-acid battery. Therefore, high input current levels are expected resulting in the increase of converter losses.

Nowadays, a fundamental topic of concern is the importance of environment preservation. Toward this end, significant efforts have been made in the diverse areas of knowledge. In electrical engineering field, this phenomenon has implied in searching for alternatives energy systems, higher efficiency on available resources utilization, losses reduction in equipments and in power quality increase. The technology on photovoltaic and wind systems comes expanding, thanks to a growing demand of alternative energy systems, mainly to reduce the energy demanded from non-renewable sources, and also the utilization of clean energy sources.

In the last few years, the market was flooded by a great number of electronic ballasts for fluorescent lamps operating in high frequency, especially by compact fluorescent lamps. Its utilization was widely stimulated by Brazilian media for energy economy, due to the fact that luminous efficiency increases with the frequency for this kind of lamp. Brazil faced a serious energy crisis in 2001. Many corrective actions were taken to mitigate this serious problem. One of them was the energy rationing which consisted in overtaxing or even cutting energy supply to consumers which exceeds the prefixed energy quotes. As additional consequence, many electric energy concessionaires had distributed gratuitously compact fluorescent lamps for residential consumers, showing the importance of illumination's segment inside the global energy consumption, estimated to be about thirty percent of total consumption of electrical energy in the country.

As a consequence of this period of crisis, an ample national program of energy efficiency is being performed in industries, hospitals, commercial establishments and in the public sector. The street lighting system of the country is being modified from mercury lamps to high pressure sodium discharge lamps (HID) since this kind of lamp presents a large lifetime (which is estimated in approximately 24.000h), a significant luminous efficiency (120 lumens per watt) and a low Color Rendering Index (CRI) (30). Although it generates a yellow-orange light that may cause discomfort, the human sight has the best acuity in this spectrum range. Thus, the HPS discharge lamps are suitable to outdoor lighting since these environments does not demand a high CRI and present a low maintenance cost. Due to this fact, innumerable research groups around the world, like [1] to [8], have dedicated their efforts to the development of new topologies and new control techniques for different kinds of discharge lamps.

Aiming to contribute in this process, this paper approaches the development of an electronic ballast for 70 W HPS discharge lamp. The main goal of this work is to propose the study and implementation of a HPS EB connected directly into a battery to reduce the energy consumption spent with illumination, by using alternative energy sources.

The choice of a hybrid wind-solar power system was based on two important factors: the first one is that the state of Rio Grande do Sul in Brazil has availability in large quantity of both energy sources, and the second one is that this kind of low power systems play an important role in the environment preservation and in the divulgation of this kind of technology. As an example of this fact is that there is a similar system in the core of the Brazilian political scenario. Fig. 1 shows a

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commercial solar PV electronic ballast in front of the Palácio do Planalto (the Brazilian White House).

One of the most expensive components of a stand-alone PV system is the battery pack, necessary to guarantee the required system reliability. Thus in cases of increased system autonomy the battery contribution to the initial or the total operational cost is found to be dominant. In addition, batteries should be replaced every 3 5 years, thus increasing the operational cost of the system. One possibility of reducing the cost of the stand alone PV system and improving the reliability is to incorporate a small scale wind turbine generator in areas having wind energy resource. The introduction of a wind generator in a stand-alone PV system is expected to smooth out the system energy production, significantly decreasing the energy storage requirements, without modifying the initial installation cost of the system.

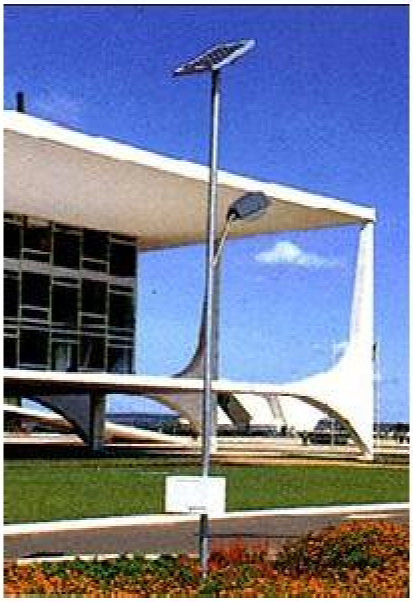


Fig. 1. A commercial solar PV electronic ballast.

The available power in systems based on renewable energy sources changes continuously, and depends basically on weather conditions such as: wind speed, solar irradiation and temperature [9]. For that reason, it is relevant to track the maximum available energy incessantly in the installation site. Several techniques have been used to ensure the maximum power point which is called maximum power point trackers (MPPT).

Photovoltaic power generation is reliable, modular and involves no moving parts. There are many applications where photovoltaics provide a viable means for power generation.

Photovoltaic cells are nonlinear devices, where the current/voltage characteristic depends mainly on the solar irradiation. These devices are expensive and have low efficiency. Studies show that on energy systems based on photovoltaic cells, 57% of the total costs of the implantation refers to the cost of the solar panels and 30% refers to the cost of the battery systems. In order to ensure the economic viability for the implementation of this energy source, it is essential the construction of a system that always obtain the maximum power of these solar panels. Several systems that allow the maximum power transfer between the photovoltaic panels and the power net were proposed, in way to increase the efficiency and to decrease the costs. The objective of these systems is to obtain, through electronic circuits and control algorithms, adjustment in the output voltage of the photovoltaic cells, in order to obtain always the maximum power possible.

For low power wind turbine application, permanent magnet synchronous generators (PMSG) applied to wind energy conversion system (WECS) is being used more frequently [10]. In order to achieve optimum wind energy extraction at low power fixed pitch WECS, the wind turbine generator (WTG) is operating in variable-speed variable-frequency mode. The rotor speed is allowed to vary with the wind speed, by maintaining the tip speed ratio to the value that maximizes aerodynamic efficiency. The PMSG load line should be matched very closely to the maximum power line of the WTG. The amount of energy captured from a WECS depends not only on the wind, but also on the control strategy used in the WECS and on the conversion efficiency. MPPT control is very important for the practical WECS systems to maintain efficient power generating conditions irrespective of the deviation in the wind speed conditions. Instead of all this complex control theory to get MPPT on PMSG WECS, the standard way to implement a PMSG WECS with variable speed is using two conversion stages: the first one as an AC-DC stage and the second one as a DC-DC stage (battery charger). In order to build the first one, a classical three-phase bridge rectifier (BR) associated to a bulky capacitor is used and the second one may be implemented by most of DC-DC converters.

There are many kind of high-pressure lamps and, however, this work will focus only the high-pressure sodium lamps (HPS), widely used in outdoor lighting and known by its high luminous efficiency. The HPS lamps, like any other HID lamps, need ballast to operate correctly. The ballast is an additional equipment connected between the power line and the discharge lamp. The ballast has two main functions: to guarantee lamps ignition through the application of a high voltage pulse between the lamp electrodes and to limit the current that will circulate through it. Without current limitation, the lamp would be quickly destroyed, due to the negative resistance characteristic of the HPS lamp, as it may be observed in Fig. 2.

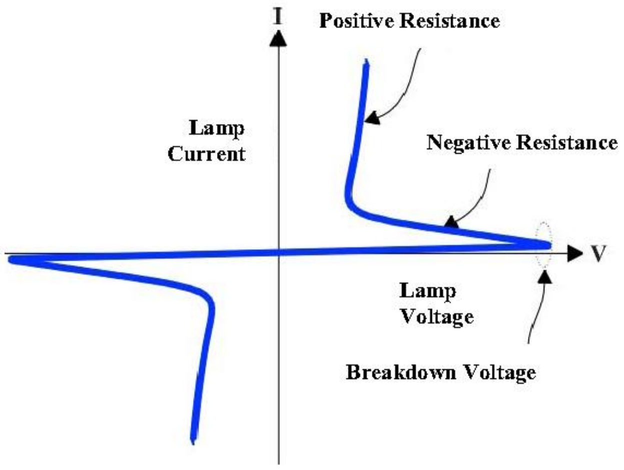


Fig. 2. Typical voltage x current curve for HID lamps.

Most of magnetic ballast manufacturers had to develop electronic ballasts for discharge lamps to guarantee their survival in business because of the rising demand for this type of product in the market. It also simplifies the production line, which has expressive physical reduction and productivity increase in comparison with the line that produces the conventional ballasts. Nowadays, the challenges of the industries are the reduction of production costs, the reduction of converter size, unitary power factor and null harmonic distortion implying in a substantial improvement in the power quality consumed by ballasts, addition of new features for the illumination system (like luminosity and power consumption control), and also make possible the utilization in different power systems.

In this context, the contributions of our research group consist of utilizing a simple EB topology with no tune circuit and proposing a very simple new design criteria for a Push-Pull EB based on the RMS rated current of the lamp and in its harmonic content.

Fig 3. shows the block diagram of the proposed structure where the main focus is in the electronic ballast for the 70 W HPS lamp. The study and implementation of the MPPT wind-solar charge controller circuit is not considered in this paper.

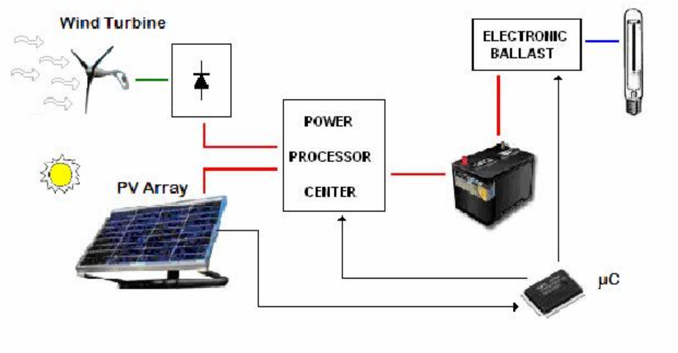


Fig. 3. Block diagram of the proposed system.

II. STUDIED ELECTRONIC BALLAST

The studied Push-Pull topology generates high frequency AC power signal to drive the 70 W HPS lamp. The entire electronic ballast structure consists of: one upper transformer, to elevate the input voltage which comes from the battery; one *LC* series circuit, where the inductor *L* is the high frequency ballast and the main function of the capacitor *C* is to block any DC component of the lamp current, therefore it is designed to offer low impedance to the lamp current, and one igniter to start up the HPS lamp. Fig. 4 shows an electrical diagram of the proposed circuit. This arrangement provides appropriate lamps ignition voltage and current and also rated voltage and current for steady state operation. The igniter is composed by a voltage doubler because the transformer output voltage is matched with lamp rated voltage which is low, an auxiliary upper winding in the inductor *L* and a SIDAC semiconductor to start the HPS lamp when the output voltage doubler capacitors are charged. The Push-Pull high frequency inverter consists of two MOSFETs (M_1 and M_2) and a transformer (T).

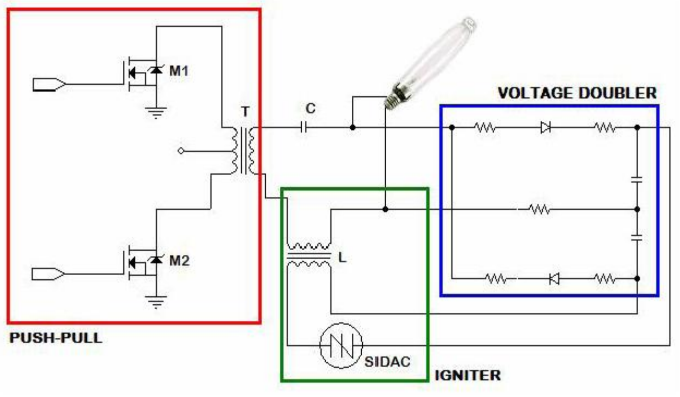


Fig. 4. Studied Electronic Ballast.

III. BALLAST DESIGN CRITERION

In order to verify the performance of the proposed ballast, 70 W HPS lamp electronic ballast was designed. The rated lamp voltage (V_{lamp}) was obtained from the lamp's manufacturer datasheet and its value is 70 V_{RMS} for the 70 W HPS Lamp. The electronic ballast input power voltage comes from the output of a battery. Consequently, this ballast is mains independent. In the present design example, the battery voltage adopted was considered to vary from 10 to 14 V_{DC}. The switching frequency chosen was 21 kHz just to avoid audible noise. Assuming the resistive behavior of the lamp, we can estimate the value of its resistance (R_{lamp}), where R_{lamp} represents the nominal power of the lamp after ignition using (1).

$$R = \frac{V_{lamp}^{\ 2}}{P} \cong 70\Omega \tag{1}$$

Where:
P - Lamp power.

The Push-Pull inverter generates an almost perfect square wave. Therefore, this inverter could be represented by a square wave voltage source. A simplified EB topology is shown in Fig. 5 where the inductor *L* represents the inductance of the igniter transformer, the capacitance *C* represents the circuit capacitor and the resistance R_{lamp} represents the HPS lamp equivalent resistance.

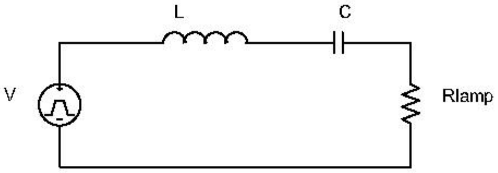


Fig. 5. Equivalent EB topology.

Aiming to design the *L* and *C* components, a Fourier analysis of this simplified circuit is proposed in order to determine the optimum values of these components.

$$V(t) \quad = \quad \frac{4E}{\pi}\sum_{n}\left(\frac{1}{n}\sin\left(n\omega t\right)\right) \tag{2}$$

Where:

E - Transformer output voltage = 280 V.

Consequently, the lamp current can be obtained by simple circuit laws. The results are presented in (3).

$$i_{lamp}(t) - \frac{4E}{\pi}\sum_{n}\left[\frac{1}{n\sqrt{\left(n.\omega.L-\frac{1}{n.\omega.C}\right)^{2}+R^{2}}}\sin\left(n.\omega.t-\tan^{-1}\left(\frac{n.\omega.L+\frac{-1}{n.\omega.C}}{R}\right)\right)\right] \tag{3}$$

Since the HPS lamp has a RMS rated current equal to 1A, it is necessary to express (3) in conformity with the RMS definition. However, the RMS value of the input current could be easily obtained from (3) and taking into consideration the RMS definition. This procedure results in one only equation and two variables: *L* and *C*. In order to overcome this difficulty, a simplified solution is approached in this paper, which consists in initially to neglect the capacitor influence since its main function is to block the DC component of the HPS lamp current. In this case, (3) could be rewritten as shown in (4).

$$i_{lamp}(t) = \frac{4E}{\pi}\sum_{n}\left[\frac{1}{n\sqrt{\left(n\omega L\right)^{2}+R^{2}}}\sin\left(n\omega t-\tan^{-1}\left(\frac{n\omega L}{R}\right)\right)\right] \tag{4}$$

Applying the RMS definition in (4) for the HPS lamp rated current, it is easy to obtain the *L* value (L=1.94 mH). Given that the capacitor *C* is essential to this EB, the real inductor is selected in way to be 10 percent bigger than the simplified one. Thus, L= 2.13 mH.

In order to determine the *C* value, it is enough to use the last value of *L* (L= 2.13 mH) in (3), resulting in capacitance of C=322.7 nF.

These calculations were performed using a Mathcad® spread sheet considering the first two odd harmonics components only. A simulation was performed in the mentioned software and Fig. 6 shows the voltage source inverter output and the lamp current.

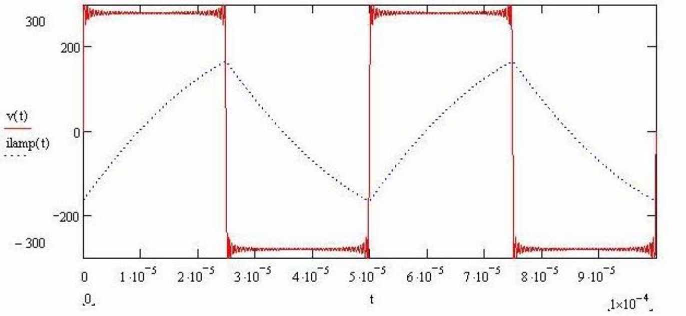
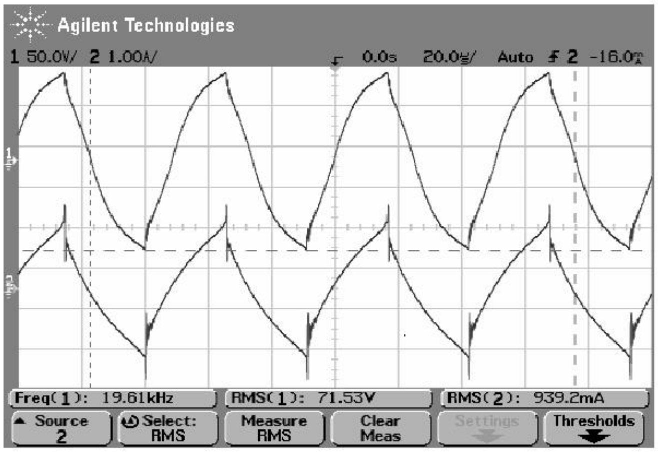


Fig. 6. Voltage source inverter and lamp current.

As an additional part of this work the authors would wish to share a Mathcad® spread sheet that was specially developed to perform this design criterion, available at: http://www.ee.pucrs.br/~fdosreis/ISIE2007.

IV. EXPERIMENTAL RESULTS

Using the proposed design criterion an experimental prototype was implemented. From the implemented EB, it was obtained a set of waveforms acquisitions which are illustrated as follows. Fig. 7 shows the voltage (channel 1) and the current (channel 2) on the lamp. From this figure, the resistive behavior of the HPS lamp when operated at high frequency is easily observable.



Freq(1): 19.61kHz

RMS(1): 71.53V

RMS(2): 939.2mA

Fig. 7. Voltage and current on the lamp.

Fig 8. presents the output voltage of the Push-Pull inverter without any snubber circuit and with an important dead time.

The main purpose here is to show the square wave main characteristic of push-pull hard switch inverter.

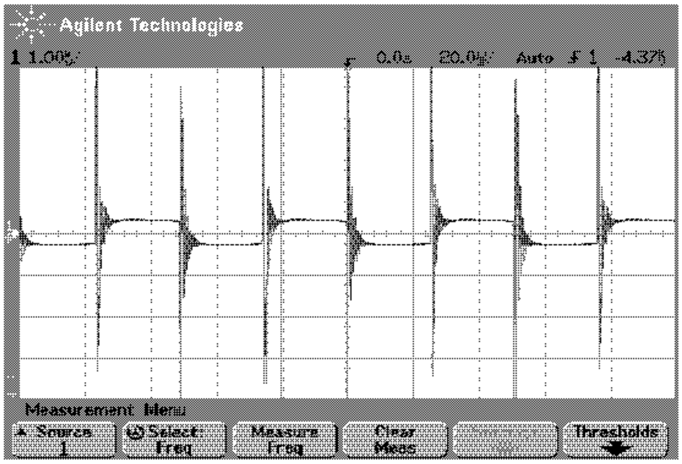


Fig. 8. Output voltage of the Push-Pull inverter.

Fig 9. shows a detail of the Mosfet gate signal which is quite good and provides around 20 V to the Mosfet gate source circuit, minimizing the conducted component losses.

The igniter circuit works properly. During the development of this EB, the main difficulties were experimented in the design and carrying out of the magnetic components due to the high current levels in the primary winding of the Push-Pull inverter. To solve this problem the Skin effect was considered also the maximum magnetic core induction was limited under the rated specification. Special attention was also taken in the transformer winding isolation. In order to increase the efficiency the switches were implemented using two MOSFETs in parallel.

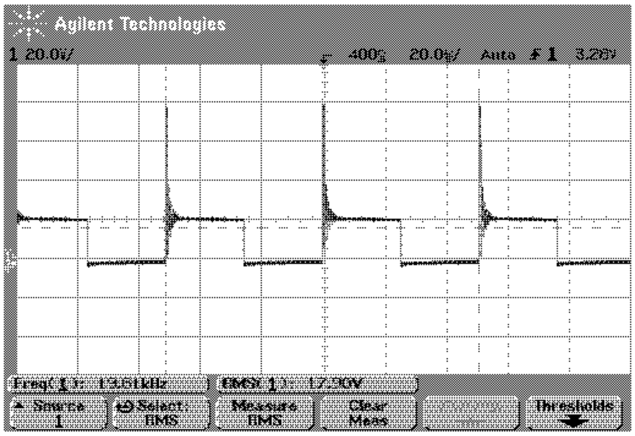


Fig. 9. Detail of the mosfet gate signal.

CONCLUSION

In this paper it was presented the study and design of an EB for HPS lamp. The experimental results demonstrated the functionality of the proposed ballast that may be fed by hybrid renewable energy systems, contributing for environmental preservation.

This ballast presents competitive cost, when compared with similar equipments, with the advantage that it may work not only with PVs but also with other kinds of renewable energy sources like wind energy.

The design procedure proposed is extremely simple and was validated by the experimental results.

The ignition circuit reduced the current stresses in the switches when compared with the LCC conventional EB structure.

This circuit presents a time constant of 10 *s* approximately which is acceptable for a circuit that does not have human intervention and also for HPS lamps that presents a warm-up period higher then 1 min.

The acoustic resonance phenomenon was not observed neither analyzed in this case.

The luminous efficiency of the HPS lamp, working at high frequency, do not increase on the contrary of what occurs with the fluorescent lamps.

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