Photovoltaic Energy Processing for Utility Connected System

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***Abstract* – In this work the study of a system for exploitation of the energy provided from photovoltaic panels is presented. Through this system the energy is converted, adapted and injected into the electric utility grid. In this way an amount of electrical energy consumed by one given customer is produced, having the advantage that it can be installed easily in the proper place of consumption, dispensing the use of a transmission system.**

The current has sinusoidal shape in the system output, taking as reference the electric grid, obtaining low total harmonic distortion, thus the quality of the electric energy is preserved. Moreover, other requirements are achieved, as the galvanic isolation between the panels and the utility grid, and the protection against energy failure.

The power stages, the control strategy, the system's operation principle, the simulation and experimental results acquired with the prototype constructed in laboratory are presented.

I. Introduction

A photovoltaic panel is a device that, through the photoelectric effect, converts luminous energy into electric energy. Despite the electric energy is available in the terminals of the panels in the same instant that the light reaches it, most of the electric equipment of standard use cannot directly be connected. This because the panel generated current is continuous (DC) and at low voltage (generally between 12 and 68 volts, depending on the technology used in the panel construction) and the majority of the equipment operates at alternating current (AC), at higher voltages.

As this system does not use batteries to store energy, the generation depends exclusively of the solar energy availability. Although it seems a disadvantage, this option is economically advantageous. While the panel useful life is upper 20 years, a battery operates for, in the maximum, 5 years and needs periodic maintenance.

The output voltage of each panel is about 15 V in m.p.p (maximum power point). The power specified to system design was 100 W, proper to convert the energy proceeding from two 50 Wp panels (50 watts at 1000 W/m^2 insolation) each one, connected in series. Currently one observes a certain trend in reducing the photovoltaic systems power in order to standardise them and to get more optimised and cheap designs, in terms of production in wide scale and urban integration. Based in information published in the last years [1, 2, 3], was proposed the system presented.

As the problems related to these types of systems are solved and the panels prices diminish [4, 6], the market options become extend.

II. Circuit Presentation and Operation Principle

The circuit is composed by two distinct processing energy stages like shown in Fig. 1.

A. *Flyback Converter*

The first stage is a flyback converter responsible to increase panels voltage. Moreover, this converter makes possible the galvanic isolation between the panels and the utility grid, propitiating more security to the system in case of atmospheric discharges and people contact with the panels. Even it prevents leakage currents and generation of electromagnetic interference.

The photovoltaic panels directly feed the input of flyback. Its input voltage is approximately 30 V and will be increased to 370 V at the output. The converter operates in continuous conduction mode. This choice allows the lowest RMS S_{11} switch current reducing its conduction losses. Another advantage in the continuous conduction mode is that the voltage output depends only on duty cycle D, imposed for the control system. A regenerative snubber [7] is used for S_{11} switch protection.

B. *Full Bridge Voltage Inverter*

The second stage is the full bridge voltage inverter that performs two basic functions: the continuous voltage inversion and the output current sinusoidal modulation. The input characteristic of this inverter is voltage source and the output is current source.

Thus it can be connected to flyback, which the output is in voltage, and to the commercial utility grid, that has voltage source characteristic. The full bridge voltage inverter can produce a sine form current with low harmonic distortion at the output when modulated in a convenient way.

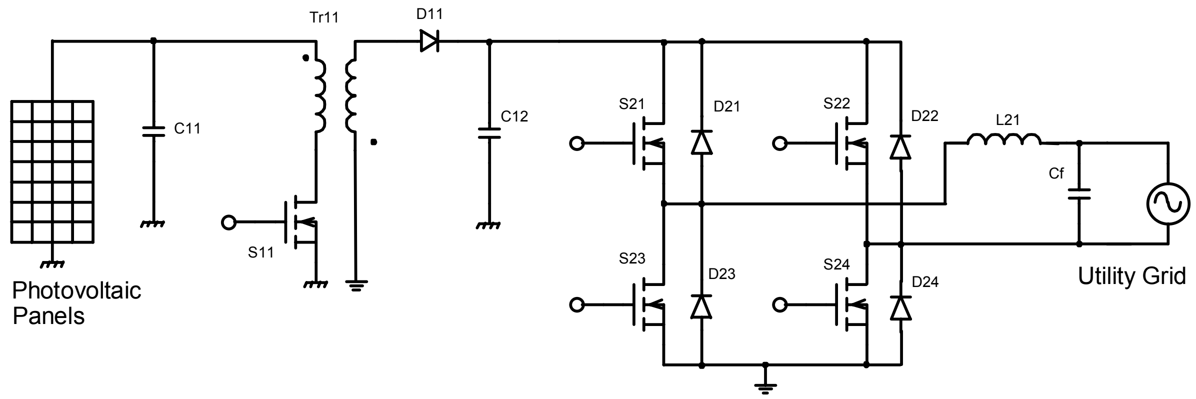

Fig. 1: Representation of the utility connected two stages power circuit.

Both stages operate at 25 kHz frequency. Then the storing energy components (capacitors and inductors) and the transformer have small dimensions, yielding reduced weight and size to the system. The inverter output, whose the modulation is made in two levels, is connected directly to the electric power supply.

III. Mathematical Study

C. Flyback Converter

The voltage static gain of the flyback converter is given by the equation:

$$\frac{Vi}{Vpfv} = a \cdot \frac{D}{1-D} \tag{1}$$

The duty cycle D is defined by:

$$D = \frac{tc}{Ts} \tag{2}$$

The switching period is defined by

$$Ts = \frac{1}{fs} \tag{3}$$

where:

Vi	→	Flyback output voltage;
$Vpfv$	→	Photovoltaic panel voltage;
a	→	Turns ratio transformer;
D	→	Duty cycle;
tc	→	S_{11} switch conduction time;
Ts	→	Switching period;
fs	→	Switching frequency.

D. Full Bridge Voltage Inverter

The current modulation used in this stage makes the matching for instantaneous values of the output current and generates an adequate PWM signal. The full bridge voltage inverter output characteristic with current output, for half cycle of the grid, is similar to the buck converter, whose output characteristic is:

$$\frac{Vo}{Vi} = D \tag{4}$$

In this converter the input voltage is constant but the output voltage has sinusoidal full wave shape.

For half period of the AC voltage it can be written:

$$Vo(\theta) = Vm \cdot \sin\theta \tag{5}$$

Applying (5) in (4) results

$$D(\theta) = \frac{Vm}{Vi} sen\theta \tag{6}$$

where:

Vo	→	Inverter output voltage;
Vm	→	Buck converter output peak voltage;
θ	→	Sine wave angle;
$D(\theta)$	→	Duty cycle (variable in function of the angle).

It can be seen that the duty cycle varies in function of the output voltage angle. A grid voltage sample is used. So the modulation of duty cycle D occurs in sinusoidal mode. The switching frequency is constant and is defined in 25 kHz. The current variation (Δi_{L21}) through the L_{21} inductor also varies as a θ angle function as it can be seen in Fig. 2.

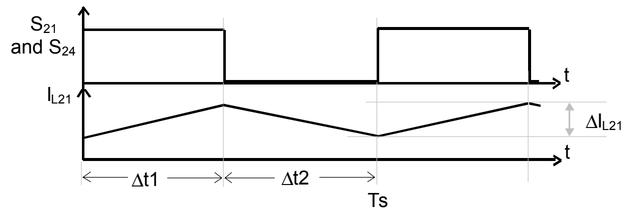

Fig. 2: Switch S_{21} e S_{24} command voltage and inductor L_{21} current.

The command voltage of the S_{22} and S_{23} switches is the complement of the S_{21} and S_{24} command voltage.

The inductor's voltage is considered constant during a switching period because the *fs* frequency (25 kHz) is very higher that the utility grid frequency (60 Hz).

$$\Delta i_{L_{21}}(\theta) = \frac{V_{L_{21}}(\theta)}{L_{21}} . \Delta t1 \tag{7}$$

Since

$$V_{L_{21}}(\theta) = Vi - Vo(\theta) \tag{8}$$

and

$$D = \frac{\Delta t1}{Ts}, \tag{9}$$

the inductor current ripple will be

$$\Delta i_{L_{21}}(\theta) = \frac{[Vi - Vm.sen\theta]}{L_{21}.fs} D(\theta) \tag{10}$$

IV. EMPLOYED CONTROL STRATEGY

The employed control strategy is shown in Fig. 3.

A sample of the utility grid voltage is used to produce a modulation in the voltage inverter and to get at the output a current with the same contour of the original voltage. The current injected in the utility grid will follow its voltage wave shape, even this voltage is a distorted signal. Then, in both cases an unitary power factor of the voltage and current will be achieved.

In cases of utility voltage failure the system stops to feed the grid because there isn't reference to generate the output current. This is a desirable feature since electric utility grid connected systems of energy production must halt the generation in order to avoid the "islanding effect" [5], where parts of the utility grid are energised even with the total disconnection of the electrical system by the utility.

For the operation of this system it was made a consideration that the utility grid voltage is steady, that is, does not suffer variations in its RMS value. To compensate eventual variations of this voltage they are being studied some possible strategies to be used. A solution that can be employee, among others, is the inclusion of a second control loop to make the compensation of the variations of the utility grid voltage RMS value. The first stage operates in open loop, however studies are being made for the implementation of a m.p.p.t. system (maximum power point tracker - system that searches the maximum power point) with the aim to improve the energy collected from the panels.

V. SIMULATIONS RESULTS

Simulations were made in order to verify the behaviour of the system and validation of the mathematical study. Some results are presented to follow.

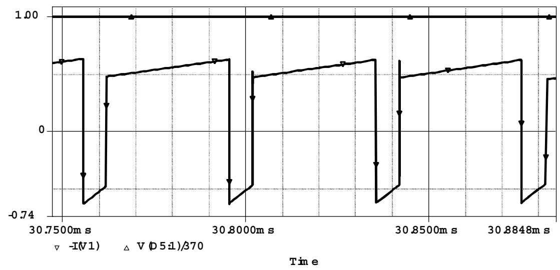

Fig. 4: Inverter input voltage and current.

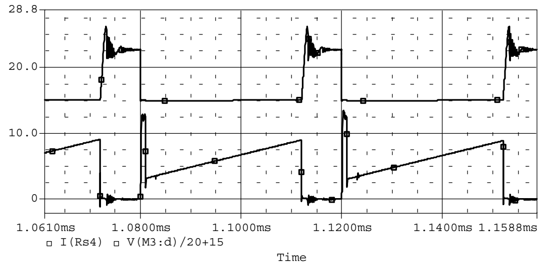

Fig. 5: Switch S_{11} drain voltage and current.

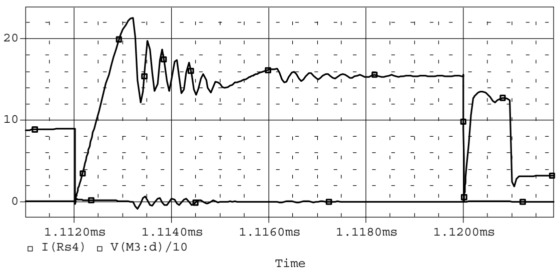

Fig. 6: Switch S_{11} drain voltage and current. Switching detail.

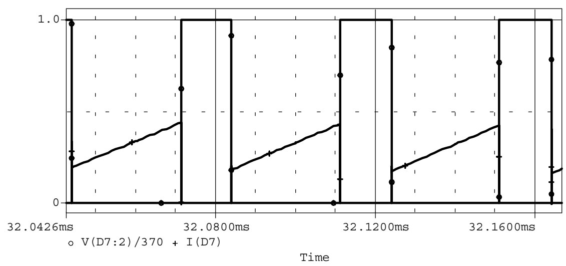

Fig. 7: Switch S_{23} drain voltage and current.

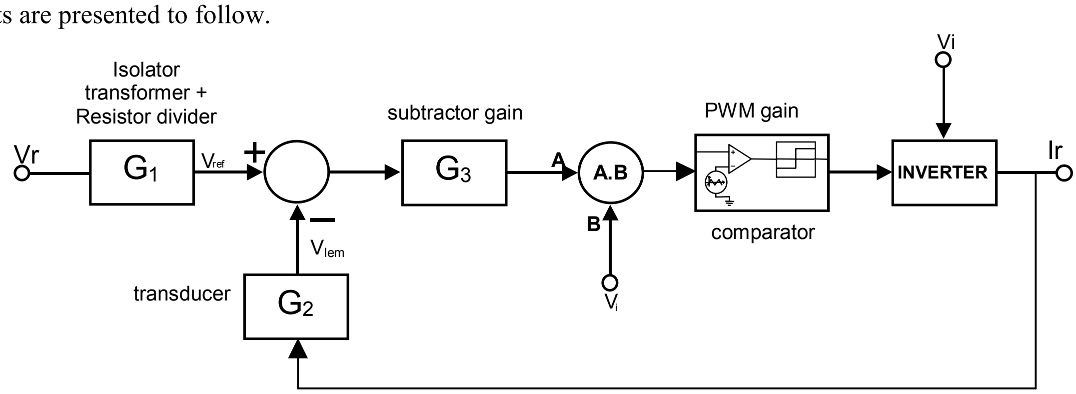

Fig. 3: Employed control strategy.

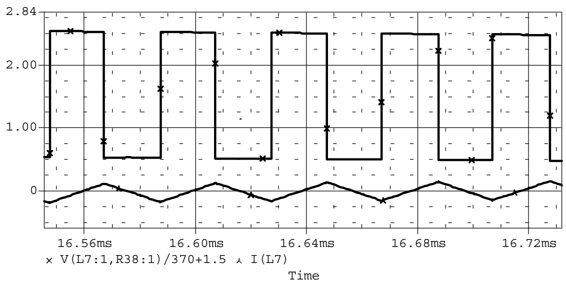

Fig. 8: Indutor L_{21} voltage and current.
High freqency.

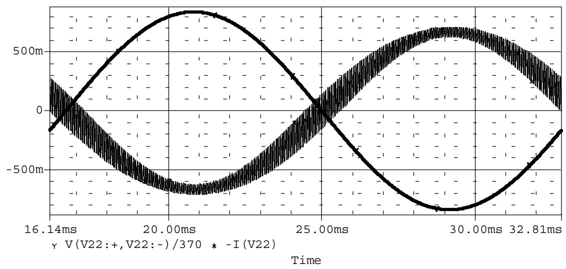

Fig. 9: Electric utility grid voltage and injected current.

VI. Experimental Results

A system prototype was constructed with the objective to confirm the operation verified in the simulations. One notices the experimental results of the flyback and the voltage inverter matches, respectively, to those obtained by simulations.

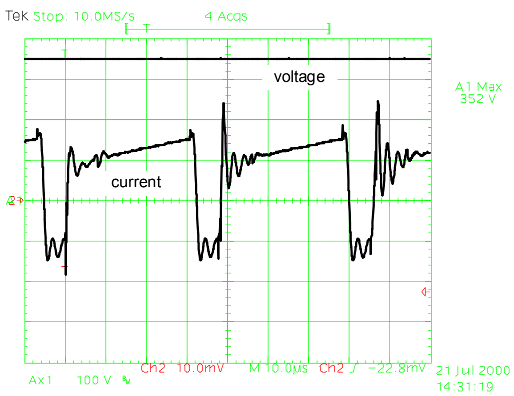

Fig. 10: Inverter input voltage and current. High frequency detail.
Scales: 100 V/div; 200 mA/div; 10 µs/div.

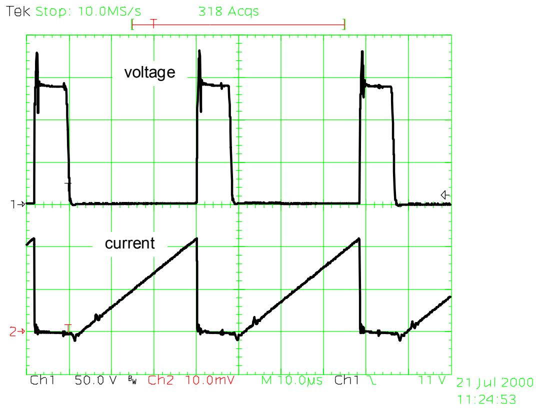

Fig. 11: Switch S_{11} drain voltage and current.
Scales: 50 V/div; 2 A/div; 10 µs/div.

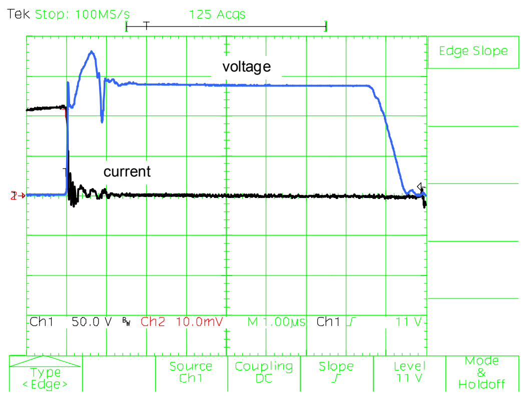

Fig. 12: Switch S_{11} drain voltage and current. Switching detail.
Scales: 50 V/div; 2 A/div; 1 µs/div.

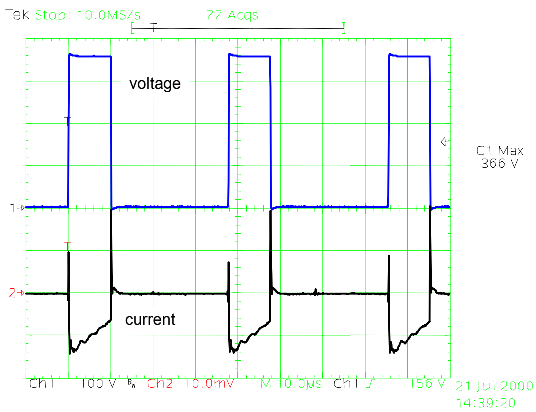

Fig. 13: Switch S_{23} drain voltage and current.
Scales: 100 V/div; 200 mA/div; 10 µs/div.

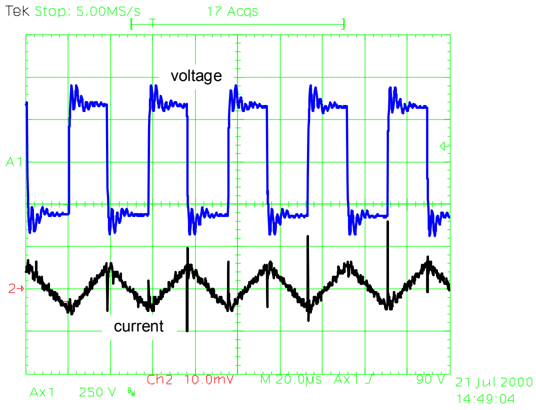

Fig. 14: Indutor L_{21} voltage and current.
Scales: 250 V/div; 200 mA/div; 20 µs/div.

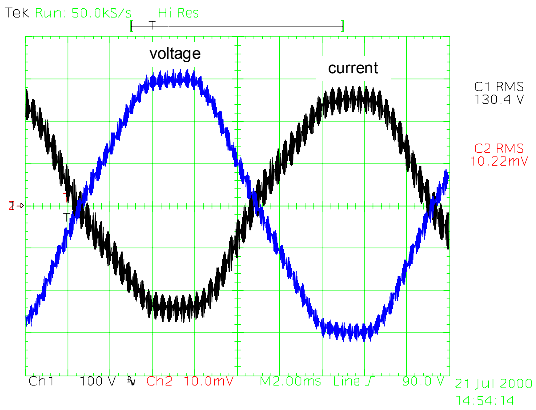

Fig. 15: Electric utility grid voltage and injected current.
Scales: 100V/div; 200mA/div; 2ms/div.

VII. Conclusion

A simple, however robust system was presented in this work, to be used with electrical energy generated by photovoltaic panels.

The system does not need batteries since it operates connected to electric utility grid. The energy supply occurs in periods where the sun light is present, being the system in wait state when it does not have light. An immediate application for this type of system can be made in places that need refrigeration due to the heat produced for the sun, for example, in air-conditioning system, where it has coincidence between the demand of energy for refrigeration and the generation of electric energy by the photovoltaic system.

The adopted control strategy allowed the production of a current with little harmonic distortion, simplifying and reducing the size and the number of components, as much of the control, as of the output filter. The high frequency operation allowed the reduction of the magnetic components and the capacitors.

This system presents some important positive features such as the natural insulation between the panels and the utility grid, robustness operation, simplicity in the power stages and in the control strategy, possibility of interconnection with other units (connection in parallel) and wide useful life, since no mobile part exists.

This system operates with commercially available panels being necessary no adaptation of these to be connected.

VIII. References

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