

Analysis of Utility Interactive Photovoltaic Generation System using a Single Power Static Inverter

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Abstract: This paper presents the analysis of a static conversion system for treatment of the solar energy from photovoltaic panels. This system is interconnected with the commercial electric utility grid, contributing to the generation of the electrical energy. A current-fed push-pull converter, a buck converter, and a current inverter compose the power structure. The main features of the system are: simple control strategy, robustness and lower harmonic distortion of the current and natural isolation. The principle of operation, design procedure and experimental results are presented.

Keywords: Solar Energy, Photovoltaic Cells, Static Current Inverters, DC-DC Converter, High Frequency.

Introduction

Conventional energy sources, obtained from our environment, tend to be exhausted with relative rapidity due to their irrational utilization by humanity. This uncontrolled extraction of the natural energies, certainly will lead to instability of our ecological system. It is important to point out, that if it occurs the recuperation of this system will be practically impossible. As a consequence of this possibility, the apprehension for a diminution of the petroleum sources, natural gas and natural resources of coal has been intensified. For this reason, the effort to find new sources of energy, to permit reduction in the utilization of the natural resources of fuel, became a challenge for all scientific and technological areas in the world, and specially for the electrical engineering area.

Within this context, solar energy appears as an important alternative to the increase of the energetic consumption of the planet, once that, the quantity of the energy from the sun, that arrives on the earth surface in a day, is ten times more than the total energy consumed for all the people of our planet during a year [1].

Through the photovoltaic effect the energy contained in the sunlight can be converted directly into electrical energy.

This method of energy conversion presents some advantages, such as:

- Simplicity;
- Does not require any moving mechanical part;
- Its modular characteristic offers large flexibility in the design and application of this kind of energy generator;
- Short time of installation and operation;
- High reliability, and low maintenance.

Besides, photovoltaic solar systems represent a silent, safe, not polluting, and renewable source of electrical energy greatly appropriated for the integration in the urban area, reducing almost completely the energy transmission losses due to the proximity between the generation and the consumption.

This kind of energy source, traditionally attractive in rural areas, begins now to be economically viable in utility grid connected applications. In that case, the photovoltaic panels are incorporated in the rooves or facades of commercial buildings and residential houses, delivering electric energy to the grid. Thus, the photovoltaic panels can operate as little power stations in parallel with the electric utility grid.

Considering the application mentioned above, this paper describes a static conversion system for treatment of the solar energy from photovoltaic cells. This is a grid-connected system, contributing to the generation of the electrical energy. The complete system consists of three stages composed by of a

current-fed push-pull converter connected to a *buck* converter, and in the output stage a *current fed inverter*. The control circuit strategy is very simple. It uses an average current control and a PWM modulation in the *buck* converter, for obtaining a rectified sinusoidal current.

Much work in this application area has been proposed in the technical literature [2]-[4]. Some of them are very interesting and important; however, the isolation of the power structure is not natural or is accomplished with low frequency, and their control strategies are somewhat sophisticated. The power structure proposed in this paper is particularly robust and naturally isolated. Its main features are: simple control strategy and lower harmonic distortion of current.

The *current fed push-pull* converter (first stage), the *buck* converter (second stage), and the *current fed inverter* (third stage), are very simple, well known and dominant structures in power electronics. By associating these converters and adopting an appropriate control strategy, we obtain the necessary requirements to connect the photovoltaic panels to the utility grid, keeping the quality of the energy and providing safe operation.

In photovoltaic panels the electric energy is available in its terminals at the same instant that the light reaches it. But most of the electric equipment of standard use cannot directly be connected. This is because the panel generates direct current (DC) at low voltage (generally between 12 and 68 volts, depending on the technology used in the panel construction) and

the majority of the electrical equipment operates at alternating current (AC), at higher voltages (110 or 220 volts in the case of Brazil). For this reason the system operates by connecting the panels to the electric grid. As a result any grid-connected equipment can receive the energy provided by the sun.

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

The association of these three converters provides the advantage to ally the galvanic isolation and voltage gain (*push-pull*) to the *buck* modulation simplicity and the *inverter* command and operation facility. The result is a simple system but with excellent results when applied to photovoltaic energy processing.

Photovoltaic Panel Features

The photovoltaic panels transform the sunlight energy directly to electrical energy. Figure 1 shows the typical output current-voltage characteristic of a photovoltaic panel, for two different levels of solar insolation, with a constant temperature. Curve 1 corresponds to the highest insolation level. For the lowest insolation level we have curve 2. For each solar

irradiation level that reaches the photovoltaic panel, exists one point of maximum power (*mpp*).

Despite the first stage operating in an open loop, studies are being made for the implementation of a *mppt* system (maximum power point tracker - system that searches the maximum power point) with the aim to improve the energy collected from the panels.

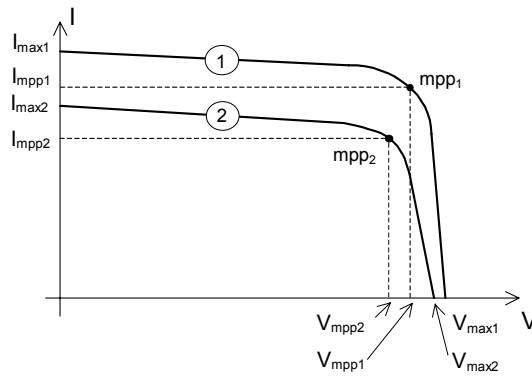


Figure 1. Typical output current-voltage characteristic of a photovoltaic panel, for two different levels of solar insolation.

Principle of Operation

In the engineering view, the interconnection between the solar panels and the grid must follow some prerequisites, so that the energy delivered to the grid will have high quality and the system will have to offer high reliability and safety.

For that, the proposed power static conversion system must provide some important items, to produce high quality energy to the grid. These items are shown in Figure 2, and they

can be considered as the principal objectives of the proposed circuit.

The proposed static conversion system for treatment of the solar energy is composed of three stages. The power structure diagram is presented in Figure 3.

In the first stage we have the photovoltaic panels connected to the *current-fed push-pull converter*. The objectives of this stage consist of providing the isolation between the panels and the grid and increasing the voltage for the next stage. The output voltage of this stage is approximately 400V. This stage operates in high frequency (20kHz), with the aim to reduce the volume of the transformer.

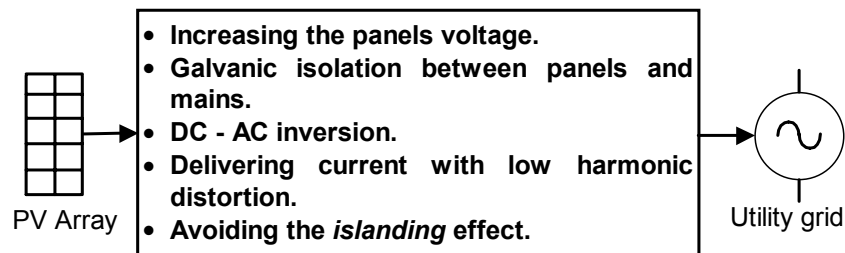


Figure 2. Principal objectives of the static conversion system.

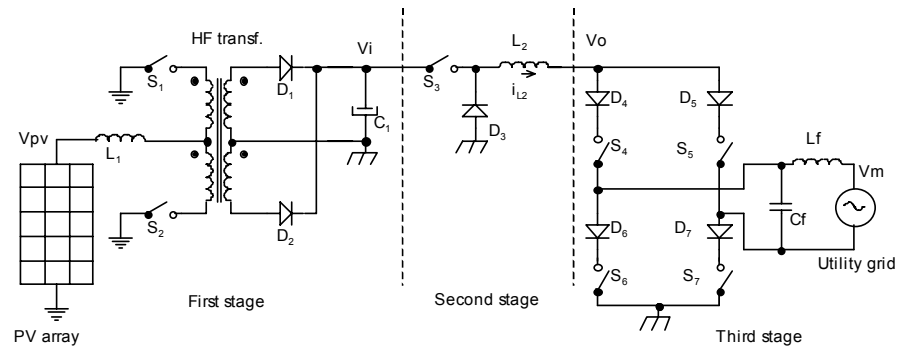


Figure 3. Proposed power structure diagram.

Due to the current-fed characteristics, the switches S_1 and S_2 cannot be kept up open simultaneously. The drives control voltages of these switches are shown in Figure 4.

The *push-pull* converter operates in continuous conduction mode with constant frequency and its duty cycle D is defined by (1), where T_s represents the switching period of the converter and Δta is energy accumulation interval in L_I inductor.

$$D = \frac{2 \cdot \Delta ta}{T_s} \quad (1)$$

Since the average voltage in L_I inductor is equal to zero during a complete switching period T_s ($T_s = 2\Delta ta + 2\Delta td$) it can be written:

$$V_{L_{med}} = 2 \cdot \frac{1}{T_s} \left[\int_0^{\Delta ta} V_{pv} \cdot dt + \int_0^{\Delta td} (V_{pv} - V_{rp}) \cdot dt \right] = 0 \quad (2)$$

where Δtd is the interval of energy sent to the secondary side of the transformer.

$$\text{Observing that} \quad \Delta t_a = \frac{T_s}{2} D \quad (3)$$

$$\text{and} \quad \Delta t_a + \Delta t_d = \frac{T_s}{2} \quad (\text{see Figure 4}) \quad (4)$$

we resolve (2) obtaining

$$\frac{V_{rp}}{V_{pv}} = \frac{1}{1-D} \quad (5)$$

where V_{pv} is the photovoltaic panels voltage and V_{rp} is the secondary side voltage transformer referred to the primary side.

The equation (5) is the *current fed push-pull converter* output characteristic, operating in continuous conduction mode.

We can observe that increasing the duty cycle, the converter voltage gain is also increased. Another important verification is that the V_{rp} e V_{pv} relation, according to (5), is not dependent to any parameter, only the duty cycle D . In other words the output voltage can be perfectly stabilized through D since

$$V_i = \frac{V_{rp}}{a} \quad (6)$$

where V_i is the *push-pull* output voltage and a is the *push-pull* transformer turns ratio.

We can observe that for this stage a control circuit is not necessary simplifying its construction.

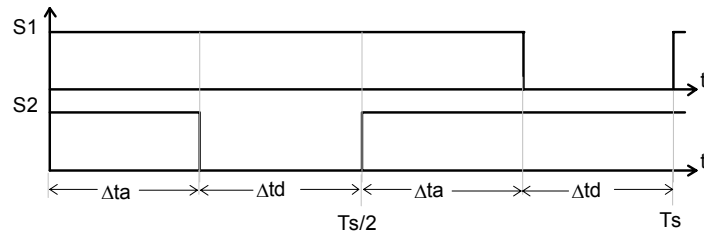


Figure 4. Drive control voltage of switches S_1 and S_2 .

The second stage is formed from the *buck* converter. In this stage the control circuit strategy is very simple, where a current feedback loop is imposed. It uses an average current control and a pulse width modulation (PWM), with 20 kHz switching frequency, for attaining a output rectified current of 120 Hz. The reference sinusoidal voltage is obtained from the grid power supply, so that, in the absence of the grid voltage the photovoltaic system does not work, avoiding the *islanding* effect.

The current modulation is based on the following equations:

$$V_o(\theta) = V_m = V_p \cdot \sin\theta \quad (7)$$

where V_o is the *buck* output voltage, V_m is the grid voltage, V_p is the grid peak voltage and θ is the grid voltage phase angle.

$$V_o(\theta) = V_i \cdot D(\theta) \quad (8)$$

$$D(\theta) = \frac{V_p}{V_i} \cdot \sin\theta \rightarrow \text{Duty cycle of the } \textit{buck} \text{ converter.} \quad (9)$$

The current ripple in L_2 is given by:

$$\Delta i_{L_2} = \frac{[V_i - V_p \cdot \sin \theta]}{L_2 \cdot f_s} \cdot D(\theta) \quad (10)$$

$$\Delta i_{L_2 \max} = \frac{V_i}{4 \cdot L_2 \cdot f_s} \quad (11)$$

where f_s represents the switching frequency.

Eq. (11) represents the biggest ripple current during a utility grid period. Thus, defining Δi_{L_2} as the maximum ripple acceptable, it is possible to find the minimum L_2 inductor, for the appropriate operation of this stage.

Figure 5 represents the *buck* output current, obtained via numerical simulation.

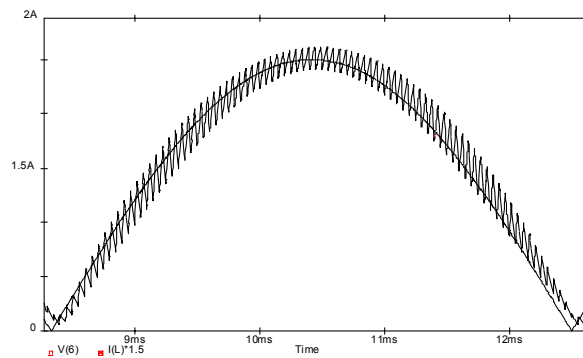


Figure 5. Output current in the second stage.

In the third stage we have a *current fed inverter*, which permits us to obtain a sinusoidal current at the same frequency of the utility grid (60 Hz), but with a phase angle of 180° . This

current is injected into the grid, transferring energy from the sun to the electric utility (220 V / 60 Hz).

This *inverter* is composed of the $S_4 - S_7$ Mosfets, $D_4 - D_7$ diodes and by the high frequency harmonics filter L_f , C_f . The diodes $D_4 - D_7$ are connected in series with each Mosfet to avoid the grid short circuit, because in the *current fed inverter* the drive signals are superimposed. The operation of this stage occurs at low frequency, so the switches commutation losses are very small.

Figure 6 shows the whole structure diagram, including the control circuit strategy employed in this work.

Buck Converter Control

As can be seen in Figure 6 the control circuit uses three sensors to obtain the desired effect. The first is the *buck* input voltage sensor with the aim to maintain the input voltage near 400V. In this loop there is a voltage compensator (V Reg.). The second is the sensor that observes the shape and the rms value of the output voltage (grid voltage sample). The third sensor monitors the *buck* output current in order to perform the average current control in this converter. In this loop we have the current compensator (I Reg.).

The input voltage loop has the objective of maintaining constant the *buck* input voltage. As can be seen in Figure 6, this sensor is just a resistive divider that samples the voltage and

compares it to a reference voltage. The result is applied to V Reg. and sent to port *A* of the 3854 multiplier [5].

The second feedback loop has the objective to define the output current shape as well as to measure the output rms voltage (grid voltage) value, and then, make the output power corrections in function of the variations in this voltage.

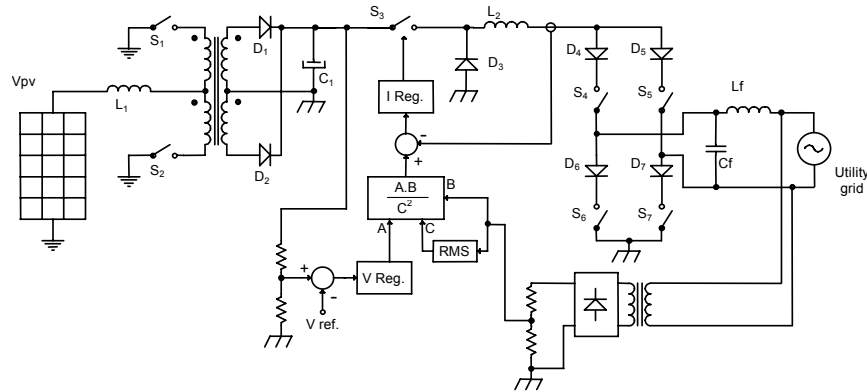


Figure 6. Power structure and its control strategy.

In order to maintain the processing energy quality it is necessary that the output current keep its shape close to the grid voltage. In most cases this voltage is not a perfect sinusoid. A little transformer (second sensor) gives the waveform information of the grid voltage and rectifies it via of a full bridge diode. The rectified signal is sent to the *B* input directly and, after the RMS block, to the *C* input.

The third feedback loop watches the *buck* output current in order to achieve the average current control. The feedback is negative. In this loop we have the third sensor that observes de

current. This sensor is just a shunt resistor and the voltage that appears, when a current flows, is applied to the 3854 I Reg.

Design Procedure and Example

1. Input data

- $D = 0.7 \rightarrow$ duty cycle of the *push-pull*;
- $f = 60\text{Hz} \rightarrow$ grid frequency;
- $f_s = 20\text{kHz} \rightarrow$ switching frequency;
- $P_o = 300\text{W} \rightarrow$ grid delivery power;
- $V_{pv} = 14\text{V} \rightarrow$ *push-pull* input voltage;
- $D = 0.7 \rightarrow$ duty cycle of the *push-pull*;
- Grid voltage: single-phase 220 V / 60 Hz.

2. Inductance L_I

The inductance L_I can be obtained from the following equations:

$$L_I = \frac{V_{pv} \cdot D}{2 \cdot f_s \cdot \Delta I_{L_I}} = 114 \mu\text{H} ;$$

where
$$\Delta I_{L_I} = 0.1 \cdot \left(\frac{P_o}{V_{pv}} \right)$$

3. Transformer turns ratio (a).

$$a = \frac{V_{pv}}{V_i} \cdot \frac{1}{1-D} = 0.12, \text{ where } V_i = 400 \text{ V (buck input voltage);}$$

4. Capacitor C_1

The capacitor C_1 is given by:

$$C_1 = \frac{Po/V_i}{2 \cdot fs \cdot \Delta Vi} \cdot D = 3.28 \mu F ; \text{ where } \Delta Vi = 1\% \cdot Vi$$

5. Inductance L_2

$$L_2 = \frac{Vi}{4 \cdot fs \cdot \Delta i_{L_2 \max}} = 12.96 mH ;$$

$$\Delta i_{L_2 \max} = 0.2 \cdot i_{L_2 \text{ peak}} ,$$

$$\text{where } i_{L_2 \text{ peak}} = \frac{2 \cdot Po}{V_p} \quad \text{and} \quad V_p = \sqrt{2} \cdot 220 .$$

6. Output filters (C_f , L_f).

For the output filters the conventional design was used.
So, the following values were obtained:

$$C_f = 560 nF \quad ; \quad L_f = 2.0 mH$$

Results

A prototype rated at 300 W was built to evaluate the proposed circuit performance. The input data are given in the previous item.

1. Specifications

The specifications of the components used in the experimental analysis are shown below:

First stage

- $S_1, S_2 \rightarrow$ MOSFET IRF250;
- $D_1, D_2 \rightarrow$ MUR4100 - 4 A, 1000 V, ultra fast diode;
- $L_1 \rightarrow$ 120 μ H inductor, 17 turns;
- Transformer \rightarrow a = 0.11 (turns ratio), primary 3+3 turns, secondary 27+27 turns;
- $C_1 \rightarrow$ 5 μ F high frequency capacitor.

Second stage

- $S_3 \rightarrow$ MOSFET IRFP460;
- $D_3 \rightarrow$ MUR450 – 4 A, 500 V, ultra fast diode;
- $L_2 \rightarrow$ 12mH inductor, 133 turns;
- Control CI \rightarrow UC3854 Unitrode.

Third stage

- $S_4 - S_7 \rightarrow$ MOSFET IRFP460;
- $D_4 - D_7 \rightarrow$ Low frequency rectifier diode.
- $L_f \rightarrow$ 2,0mH inductor, 84 turns;
- $C_f \rightarrow$ 560nF, 400V, high frequency capacitor.

Figure 7 presents the current and voltage in the Mosfet of the *push-pull* converter. We can observe a small high frequency oscillations on S_1 switch drain current. The same occurs in S_2 . These oscillations are caused by the leakage inductance of the

push-pull transformer and reverse recovery phenomenon of the D_1 and D_2 diodes. However these oscillations do not affect significantly the *push-pull* operation.

The voltage and the current in the Mosfet of the *buck* converter are shown in Figure 8. In the beginning of the *buck* Mosfet conduction, the current peak is superior to 2A. This peak is caused by the reverse recovery energy of the *buck* D_3 diode. It does not cause any damage to the Mosfet because its duration is very short and the total area involved is very small.

The frequency of the voltage and current is 60Hz, so the Mosfets commutation losses are very small. The voltage waveform is produced by the control system in the second stage, which must be as close as possible to the voltage waveform.

Figure 9 shows the voltage and current in the switch S_4 .

The drive signals of the *current fed inverter* are given in Figure 10. These signals are applied to the $S_4 - S_7$ Mosfets. They are low frequency signals (60Hz).

Figure. 11 presents the voltage and current transferred to the grid.

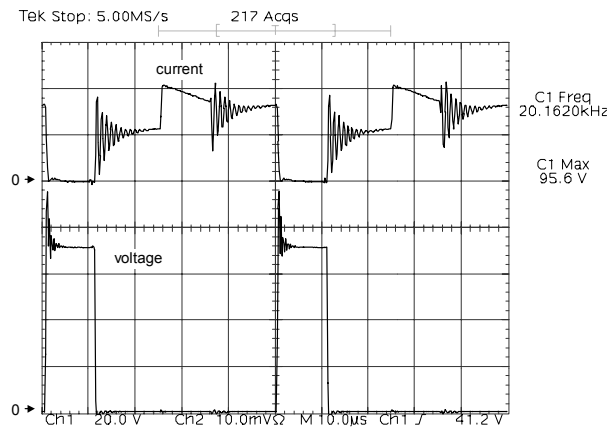


Figure 7. Current and voltage in switch S_1 .
20V/div; 10A/div; 10μs/div.

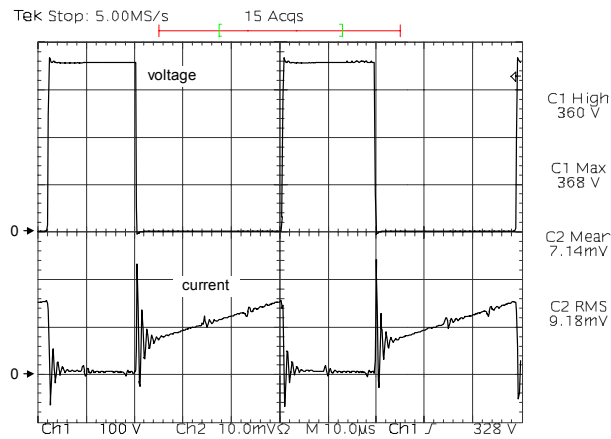
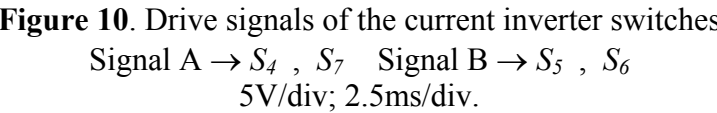
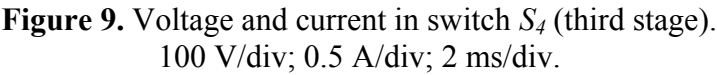


Figure 8. Voltage and current in switch S_3 .
100V/div; 1A/div; 10μs/div.



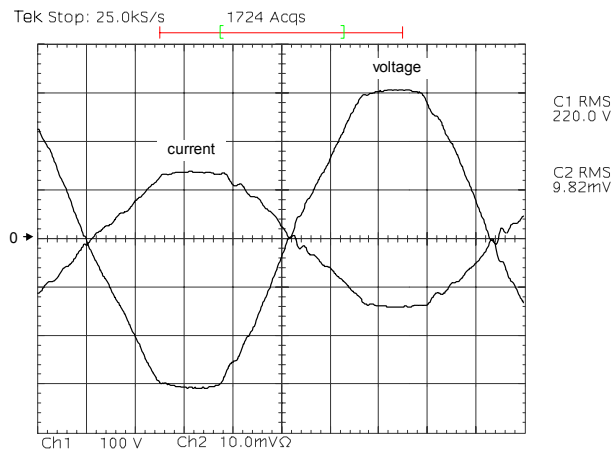


Figure 11. Voltage and current in the grid.
100 V/div; 1 A/div; 2 ms/div.

We can observe that the waveform of the grid voltage and the current injected in to the utility grid are very similar, showing that the relative harmonic distortion between them is very low. There is a phase shift of 180° between the voltage and current of the grid, indicating that the utility grid is receiving energy from the photovoltaic system.

Comparing Figure 11 and Figure 9 we can observe that the high frequency component of the output current was eliminated by L_f and C_f high frequency filter.

Figure 12 and Figure 13 show the total harmonic distortion (THD) of the voltage and current respectively.

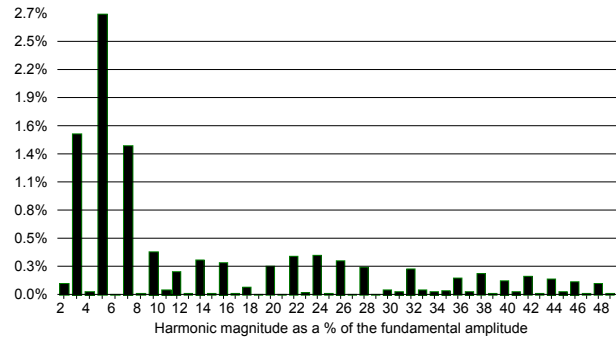


Figure 12. Voltage harmonic analysis of the grid.

$$\text{THD} = 3.69\%.$$

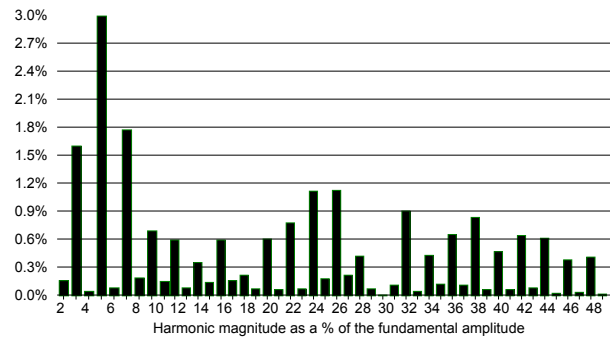


Figure 13. Current harmonic analysis of the grid.

$$\text{THD} = 4.89\%, \text{ phase} = -175^\circ.$$

It is important to observe that the THD of the commercial utility grid voltage is 3.69%. This happens due the non-linear loads connected to many points of the grid. So, the current waveform follows this distortion insuring a unity power factor.

An efficiency of 91% was obtained at full load conditions.

Conclusions

This paper has presented the analysis of a static conversion system for treatment of solar energy from photovoltaic cells. This system is interconnected with the electric utility grid, contributing to the generation of commercial electrical energy.

According to the results obtained we have a DC-AC static conversion system with the following features:

- It is particularly robust;
- It has a simple control strategy;
- It uses low cost technology;
- Does not present *islanding* problem in the voltage grid failure;
- Many systems can be associated in parallel;
- Simple installation;
- Lower harmonic distortion of current;
- Natural isolation.

This system can be applied in residential or commercial buildings, for low or high power. Therefore, the authors believe that this technology can be very useful for some residential and/or industrial applications.

References

- [1] Rüther, R. (1998) Use of the Photovoltaic Solar Energy. *Seminar-Non-Conventional Energy Sources*, **1**, pp. 9-25.

- [2] Calais, M. and Agelides, V.G. (1998) Multilevel Converters For Single-Phase Grid Connected Photovoltaic Systems, *IEEE - ISIE '98*, **1**, pp. 224-229.
- [3] Chiang, S. J., Chang, K. T., and C. Y. Yen (1998) Residential Photovoltaic Energy Storage System, *IEEE Trans. on Industrial Electronics*, **45**(3), pp. 754-759.
- [4] Kobayashi, H. and Takigawa, K. (1998) Islanding Prevention Method For Grid Interconnection of Multiple PV Systems, *2nd World Conference on Photovoltaic Solar Energy Conversion*, **2**, pp. 837-842.
- [5] High Power Factor Preregulator (2002) *Application Information UC 3854*, Unitrode.