A DC/AC Converter For Single-Phase Grid-Connected Photovoltaic Systems – IECON'02

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***Abstract* – This work proposes a static DC/AC system for grid-connected PV systems. The converter is made of an inverter, a high frequency transformer and a cycloconverter. Both converters operate with constant switching frequency and duty-cycle. The design, principle of operation, control circuits and the characteristics of the system is presented. In addition to the theoretical analysis, simulation results are shown to validate the principle of operation of the converter as part of a grid-connected system.**

I. INTRODUCTION

The solar energy is today a clean and viable source of electricity. It has been used as the main source for electrical loads in rural areas away from the grid or grid-connected in distributed energy production. Used only in satellite and space applications in the past, photovoltaic systems have come down to Earth, and its use is spreading all over the world. Although the cost of such systems is still regarded as high, the continuous research in power electronics and in the physics of semiconductors has pointed towards cost reduction of PV systems.

The large use of PV systems to produce electric energy since 1990 in countries like Germany, Denmark, Japan and USA has made the photovoltaic energy to be part of the national grid. Grid-connected PV systems have increased with an annual rate over 25%. This is related to the ever increasing use of small grid-connected systems as part of reduction of load demand from the grid. Within the PV market the one for grid-connected applications is the fastest spread one.

Grid-connected PV systems can be of two types: centralized generation or integrated to urban building. In the first case, the photovoltaic plant is located away of urban centers due to the necessity of relatively large areas. In the second case the systems are integrated to urban buildings commonly located on roofs.

Grid-connected PV systems neither require batteries or to be oversized to attend peak demands because the grid is a large storage energy system. If the PV system generates energy in excess to the residential load, the excess is sold to the grid. When the PV system generates less energy than the value required by the load, the grid supplies the extra value. Grid-connected PV system, due to its modularity, short period between the installation of the plant and the beginning of operation, could be very attractive for the utility [3].

In urban areas the intense use of air conditioning to climatise rooms has a straight relation with high solar irradiation. This means more photovoltaic energy generation. In that case, grid connected PV systems are na advantage for the local utility which can alleviate high peaks of demand, thus increasing the capacity of the transmission systems and distribution and postponing the great investments and long periods of installation of new lines.

Several papers have been published related to the application of static converters in PV systems. In [6] it is presented a 5kW grid connected system which power processing unit is composed by a DC-DC series resonant converter, a high frequency transformer and a full-bridge inverter. Even though, with a capacity of processing high power, this converter has the disadvantage of the use of a large number of power switches.

A conversion system made of two full-bridge inverters, without a transformer, for grid-connected PV system in introduced in [7]. The absence of the transformer is justified by a higher efficiency and lower weigth and volume. However, the PV array is not isolated from the grid.

Many others papers have been published in the field of grid-connected PV systems [2, 3, 4 e 5]. They are very interesting however in which either the power stage or the insulation stage operates in low frequency. Other works found in the literature deal with PV systems with many power stages, which compromise the efficiency of the system. It is with the objective to reduce or even to solve such problems that in this work it is presented a simple, robust and naturally insulated structure. It is composed by an inverter connected to a cycloconverter through a high frequency transformer. Both converter operate with a switching frequency of 40kHz and fixed duty cycle of 0.5. The output PWM modulation is obtained by shifting the drive signals to the inverter and to the cycloconverter.

II. THE PROPOSED DC/AC CONVERTER

Aiming a high frequency operation converter, and at the same time to fulfill the necessity of a high efficiency system, a dc/ac converter, based on the inverter presented in [1], is shown in Fig.1.

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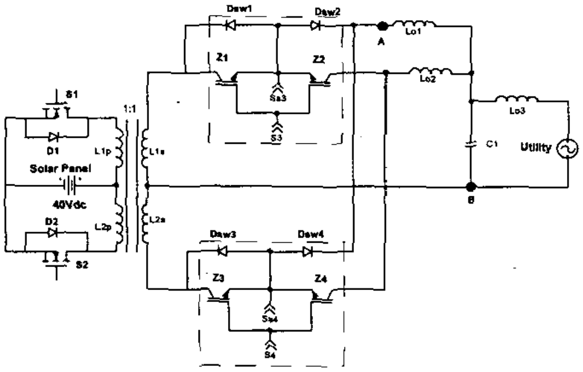

Figure 1. DC/AC converter.

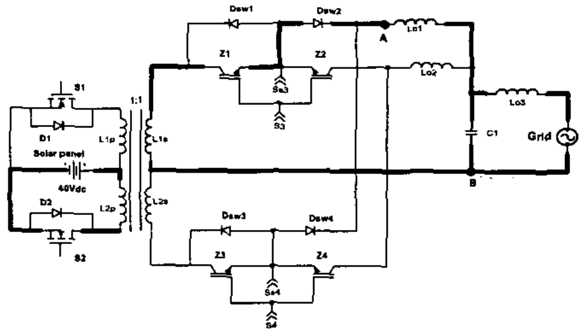

Figure2 First stage

This converter is made of two stages. Two switches, S_1 and S_2 connected between the PV modules and the primary of a high frequency transformer, represent one stage. That stage operates as a high frequency push-pull inverter with a duty cycle of 0.5 supplying a square waveform high frequency voltage to the primary of the transformer.

Two bi-directional, in voltage and current, switches formed by a set of IGBT and diodes, connected between the secondary of the high frequency transformer and the grid, represent the second stage. The two bi-directional switches operate like a cycloconverter with fixed switching frequency and duty cycle. The output current modulation is obtained by shifting the drive signals to the inverter and to the cycloconverter.

The LC passive filter attenuates the high frequency current harmonics giving at the output a current waveform at the desired low frequency.

III. STEADY-STATE ANALYSIS OF THE CONVERTER

For the purpose of this analysis the converter is considered to be in steady-state condition, fixed phase shifting, the switches are ideal and the transformer is an ideal one with a 1:1 transformer relation.

The stages of operation are described as follows:

First stage (t_0,t_1): During this stage the switches S_2, Z_1 e Z_2 are enable to conduct. The current flows through S_2, Z_1 and Dsw_2, and the voltage at the input of the LC filter is +E. That stage ends when Z_1 and Z_2 are turned off and Z_3 e Z_4 turned on.

Second stage (t_1,t_2): This stage begins when Z_3 starts to conduct the current flowing through S_2, Z_3 and Dsw_4. Voltage V_{AB} change to –E. This stage ends when S_2 is driven off and S_1 is driven on.

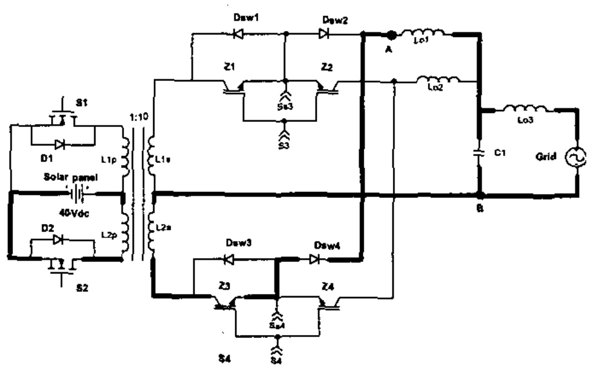

Figure3 Second stage

Third stage (t_2,t_3): At t_2, switch S_1 conducts the transformer primary current. The secondary current flows through Z_3 e Dsw_4. The output voltage changes it polarity back to +E. That stage ends when Z_3 and Z_4 are turned off and Z_1 e Z_2 turned on.

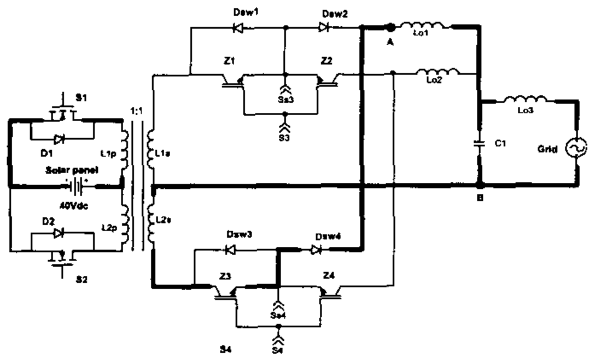

Figure 4 Third stage.

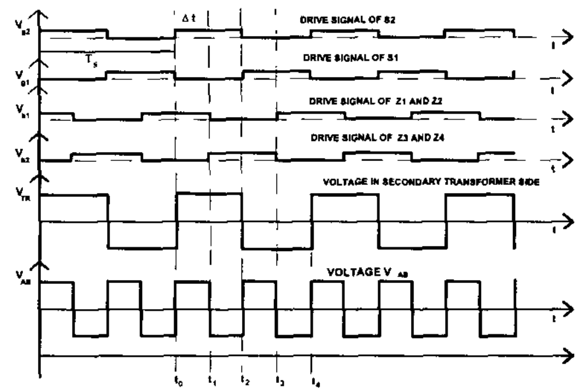

Figure 6 Waveforms for the converter with a fixed phase shift.

Fourth stage (t_3, t_4): The current at the secondary of the transformer flows through Z_1 e D_{SW2}. The output voltage V_{AB} changes once more to –E.

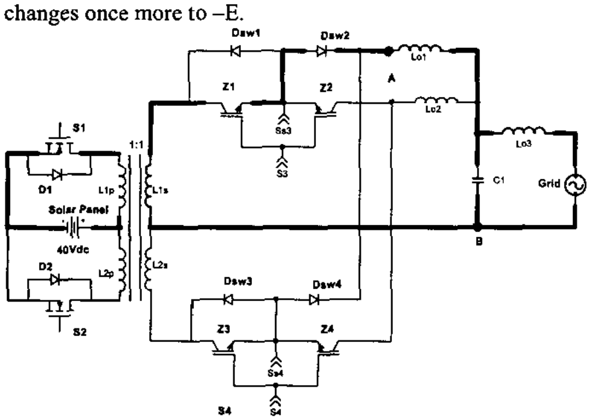

Figure 5 Fourth stage.

Fig.6 shows the main waveforms for the converter operating with a fixed phase shifting between the drive signals of the inverter and the drive signals of the cycloconverter.

The width of the magnitude of the voltage V_{AB}, showing in Fig.6, is the same of the time interval Δt. This time depends on the phase shift between the drive signals of the inverter at the primary of the high frequency transformer and the drive signals of the cycloconverter at the secondary side. Considering Δt as the width of a PWM signal which period is twice the switching frequency, a theoretical duty cycle, Dk is defined in Eq.1.

$$Dk = \frac{2 \cdot \Delta t}{T_S} \qquad \text{(Eq.1)}$$

As it can be observed in Fig.6 voltage V_{AB} at the output filter of the converter has a frequency equal to twice the switching frequency, and its average value is controlled by the theoretical duty cycle Dk as shown in Eq.2.

$$V_{AB_{avg}} = E \cdot (2Dk - 1) \qquad \text{(Eq.2)}$$

As the time interval Δt varies sinusoidaly, imposed by the control circuit shown in Fig.10, the average value of V_{AB} also varies in the same way, guaranteeing the sinusoidal PWM modulation at the voltage across the capacitor C_1.

The converter has an important characteristic in relation to the specification of the elements of the filter. It can be noted from Fig.6, that the output voltage V_{AB} is symmetrical and its frequency is equal to twice the switching frequency, so, the capacitor and the inductor of the output filter can be designed for a frequency equal to twice the switching frequency.

IV. CYCLOCONVERTER OUTPUT INDUCTANCES

Two bi-directional switches and two inductors compose the cycloconverter stage shown in Fig.7.

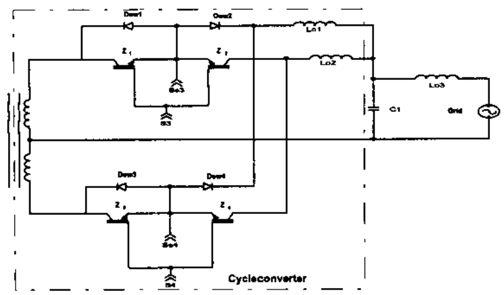

Figure7 Cycloconverter

The two bi-directional switches work with a small conduction time overlap to make sure that always there will be a path for the inductor current to flow.

The inductors behave like a current source at the switching frequency, so the secondary of the transformer will not suffer a short circuit during the switches overlap.

V. PHASE SHIFT CIRCUIT

Fig.8 shows the circuit that generates the time shifting between the inverter switches drives signals and the cycloconverter drive signals.

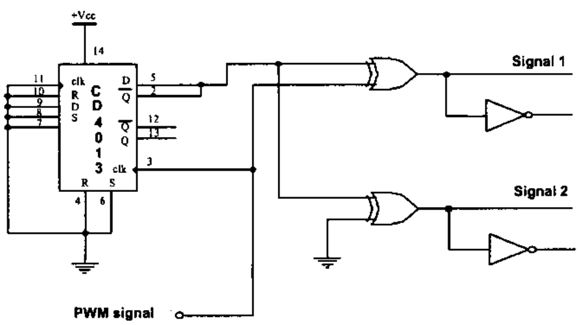

Figure..8 Circuit that generates the time shifting between the two converters

The sinusoidal PWM signal generated from the current control circuit shown in Fig.10 has a carrier frequency of 80kHz. In the circuit shown in Fig.8 that PWM signal is decomposed in two signals (signal 1 and signal 2 in Fig.8) of half the frequency, fixed duty cycle of 0.5 and a phase shift between them equal to the width of the original PWM signal. As the original PWM signal is a sinusoidal one, so will be the phase shift. The circuit shown in Fig.9 is based on a D-type flip-flop. It is worthwhile to point out that the drive signal to the inverter switches (signal 1) and the drive signal (signal 2) to the cycloconverter switches are generated from the same signal.

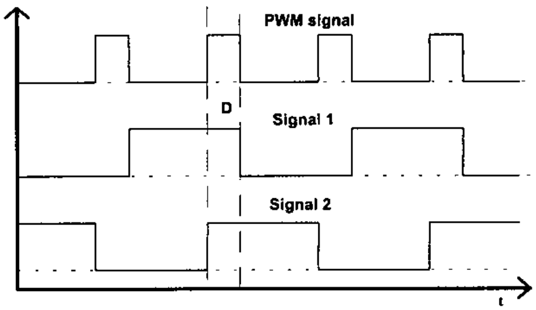

Figure 9 Waveforms of the circuit

VI. CONTROL CIRCUIT

Fig.10 shows the circuit used to control the converter output current. The circuit is a PI controller which transfer function is determined in accordance to the chosen cut frequency and poles and zeros allocation.

The converter output current is controlled by a reference signal which is a sample of the grid voltage waveform. So, the power factor at the point of common connection is near unit. The harmonic distortion will depend on the values of the frequency of commutation and the output filter inductance.

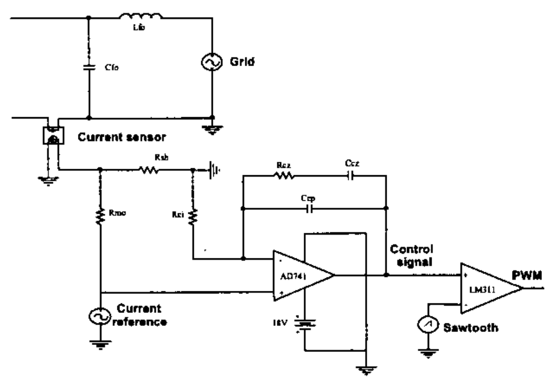

Figure 10 Control circuit

VII. SIMULATION RESULTS

The results presented here were obtained for the following design specification.

E = 40V	Voltage supplied by the solar panels
Es = 400V	Voltage in the secondary transformer side
Pout = 300W	Output power
fo = 60Hz	Output current frequency
fs = 40kHz	Switching frequency

The circuit presented in Fig.2 was simulated in the software OrCAD Pspice version 9.1.

The Fig.11 shows the current injected directly in the grid. The Fig.12 shows the waveforms of the current injected in the grid (with a gain of 50) and of the grid voltage. As it can be observed, the current is 180° out of phase in relation to the voltage, thus proving that all the energy flows from converter to the grid. The voltage V_{AB} is shown in Fig.13.

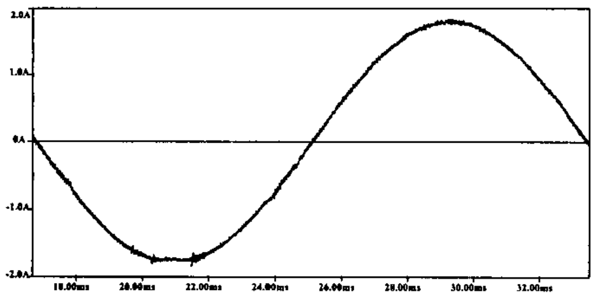

Figure 11 Output current converter.

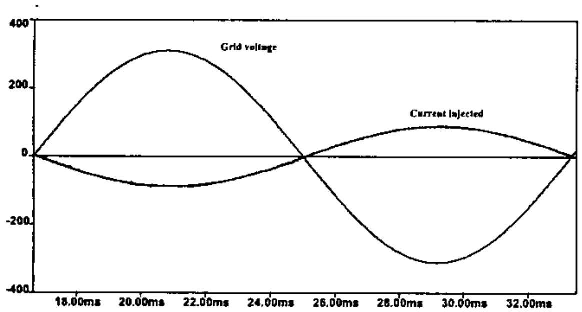

Figure 12 Current and voltage in the main power supply.

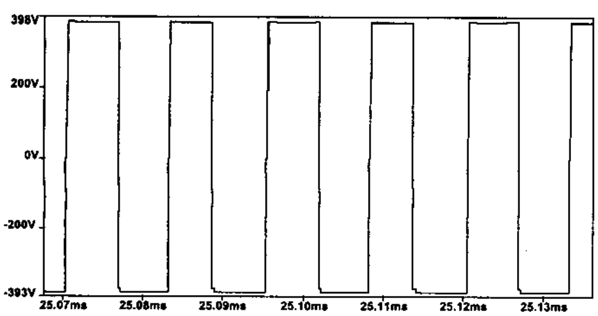

Figure 13 Voltage V_{AB}.

The voltage and current in the first bi-directional set (Z_1, Z_2, Dsw_1 e Dsw_2) of the cycloconverter and in the switch S_1 of the push-pull inverter are shown in the Fig. 14 and Fig. 15.

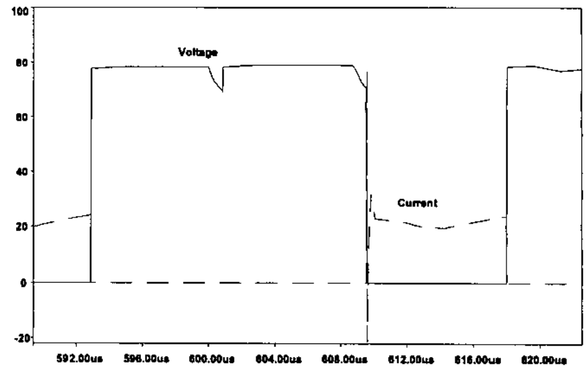

Figure 14 Voltage and current in the first bi-directional set of the cycloconverter.

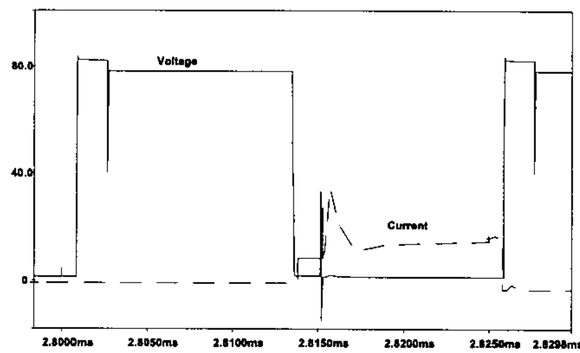

Figure 15 Voltage and current in switch S1 of the push-pull.

VII. CONCLUSION

This paper has presented the analysis of a static converter system able to process photovoltaic energy and feed it to the grid. The converter uses fewer switches when compared to similar ones presented in the literature. The converter presents low harmonic distortion at the point of coupling connection, and galvanic isolation from the grid.

Other important features are: it robustness to shot circuit, simple control strategy and low cost technology.

Due to its modularity many systems can be connected to the grid in a distributed generation.

VIII. ACKNOWLEDGEMENT

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