# Modeling and simulation of a single phase photovoltaic inverter and investigation of switching strategies for harmonic minimization

ST. KOURTESI[1] L. EKONOMOU[1] A. NAKULAS[2] G.P. FOTIS[3] E. ZOULIAS[3]

[1]Hellenic Public Power Corporation S.A., 22 Chalcocondyli Str., 104 32 Athens
[2]National & Kapodistrian University of Athens, 11 Asklipiu Str., 153 54 Athens
[3]National Technical University of Athens, 9 Iroon Politechniou Str., 157 80 Athens
GREECE

*Abstract:* The aim of this paper is to build an EMTDC model of a single phase photovoltaic inverter and to investigate switching strategies for harmonic minimisation. For the simulation of this model, the PSCAD/EMTDC software package was used and the waveforms of interest were taken for further examination and discussion on the performance of the model. A low rating, mains connected device was designed and was later used to demonstrate that real and reactive power can flow in the desired direction just by changing the phase shift or the voltage magnitude. The inverter device is intended for domestic use and will allow users to exploit voltage from photovoltaic cells. This a.c. converted voltage will be useful for feeding small house appliances or by employing appropriate techniques, real and reactive power exported from the inverter can reinforce the main power stream in the "Distribution Grid".

*Key-Words:* Single-phase photovoltaic inverter, EMTDC model, harmonic minimization

## 1. Introduction

In recent years the need for renewable energy has become more pressing. Among them, the photovoltaic system (PV) such as solar cell is the most promising energy [1]. In literature, several models have been developed for the modelling and simulation of the different components of PV power systems [2-5], based on simulation approaches, which performed in various programming environments such as Pspice, Matlab Simulink and Labview [6, 7].

The aim of this work is to build an EMTDC model of a single phase photovoltaic inverter and to investigate switching strategies for harmonic minimization. The inverter device was intended for domestic use and would allow users to exploit voltage from photovoltaic cells.

For the simulation of this model, the PSCAD/EMTDC software [8, 9] package was used and the waveforms of interest were taken. A low rating, mains connected device was designed and was later used to demonstrate that real and reactive power can flow in the desired direction just by changing the phase shift or the voltage magnitude. An inverter model that would convert the d.c. voltage supplied from a battery into an a.c. voltage was designed, offering the capability of feeding this into the grid through an inductance.

## 2. Technical background information

An inverter is a d.c. to a.c. converter i.e. it can convert d.c. voltage into a.c. for feeding into an a.c. utility network. It is possible to obtain a single-phase, or a three-phase output from such a device, but in this work only the behaviour of a single-phase inverter was studied. An inverter system consists of the d.c. input, the power circuit and the control circuit. The inverter finds very useful applications in standby power supplies or uninterruptible power supplies (UPS) and also in a.c. motor control.

The d.c. input voltage into an inverter can be obtained in various ways. In UPS systems, it is almost invariably obtained from a storage battery. In a.c. motor control, the d.c. link voltage is obtained from rectified mains. For the case described in this work, the voltage-source inverter (VSI) was powered from a stiff, low impedance d.c. voltage source provided in the form of a battery. The choice of the main devices depends on factors such as the d.c. link voltage, the load current, the maximum operating frequency, etc. The devices need to be force-commutated devices with high switching frequencies for example Insulated Gate Bipolar Junction Transistors (IGBTs), power MOSFETS or Gate-Turn-Off thyristors (GTOs) that can provide natural turn-off facilities.

# 3. Simulation package PSCAD/ EMTDC

EMTDC and PSCAD [8, 9] are a group of related software packages which provide the user with a very flexible power systems electromagnetic transients tool. PSCAD enables the user to design the circuit that is going to be studied. EMTDC enables the user to simulate the circuit performance under any conditions or disturbances of a complicated or non-linear model or process. The operation of such a model can be tested by subjecting it to disturbances and parameter variations and the stability of its response can be observed.

The EMTDC provides the facility that already available models can be interfaced with an electric circuit or control system. It cannot alone provide the user with a complete analysis of the power system under study so the analysis is assisted by some auxiliary programs. Graphics plotting of output of any desired quantity can be provided in the package. Fourier analysis of any desired output is possible, using an auxiliary program known as EMTFS. Another capability of the EMTFS program is the synthesizing of an EMTDC output representing the response to some complicated model, up to a fourth order linear function using an optimization technique.

# 4. Simulation results

## 4.1 Inverter design procedure

The whole design of the inverter circuit was implemented using Gate-Turn-Off thyristor (GTO) models. These GTO models are normally used as controlling switches in H.V. devices with large power ratings, whereas in this design they are just used to provide the switching pulses and finally produce the output. The inverter circuit is given in Fig. 1.

The inverter device was intended for use alongside a PV controller that would act as the supply to the circuit. A "triggering" block was used to provide the appropriate gate triggering pulses which when applied to the gate terminals of the thyristors would result in a square wave output. This triggering block has one input (I/P) and five outputs out of which only four are used. The input to this triggering block was a square-pulse of magnitude varying between 0 and 1 and the outputs are the four triggering pulses for the four thyristors. The output of the thyristor was a square wave.

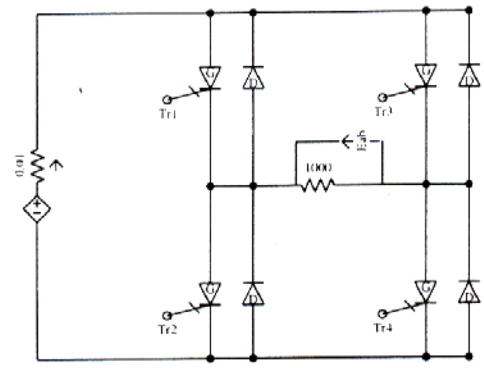

Fig. 1: The inverter circuit

## 4.2 Representation - generation of the grid voltage

Once the correct output from the inverter was obtained, a sinusoidal wave for representing the grid voltage had to be generated. It was simple and easy to represent this grid voltage using the output of a low impedance a.c. source. This a.c. source was to be used as the supply for obtaining a 50 Hz, 230 V rms sinusoid that would represent the grid voltage. The initial parameters of this source, i.e. magnitude and frequency were respectively set to 230 V rms and 50 Hz. Once this output was generated it was coupled in the circuit as the grid voltage.

## 4.3 Coupling of the two circuits

After designing and implementing the inverter device and the a.c. source equivalent circuit, the two circuits were coupled together through an inductance. An inductance of value 67.35 mH was used to couple the two circuits together.

Another adjustment needed to be considered was "locking" the phase of the inverter output voltage onto that of the grid voltage. This means that the phase of the inverter voltage had to be made equal to the phase of the grid voltage. It is possible to achieve this task in various ways such as using a Phase-Locked-Loop (PLL), but in this work a much simpler implementation technique was employed. This technique used a duplicate of the grid voltage source and used its output after being passed through a Zero-Crossing-Detector (ZCD) to trigger the thyristors in the inverter device. The ZCD, as its name implies detects zero crossings on the input waveform and triggers at each zero crossing. In this way a sinusoidal input is easily converted into a square wave.

The ZCD output was used as the input to the triggering block. Applying a square-pulse generated from the grid voltage sinusoid at the input of the triggering block, the triggering pulses obtained will eventually produce a square-wave output that will be in phase with the grid voltage. This phase compatibility is shown in Fig. 2 but in order to have the two voltages in phase the triggering pulses had to be swapped around.

### 4.4 Power measurements

With appropriate phase manipulation between the two voltages and voltage magnitude manipulation the respective transfer of real and reactive power is feasible. In order to measure real and reactive power, the complex power (S) had to be measured first. The complex power at any point in the system can be found by multiplying the corresponding voltage (V) and current (I) at that point.

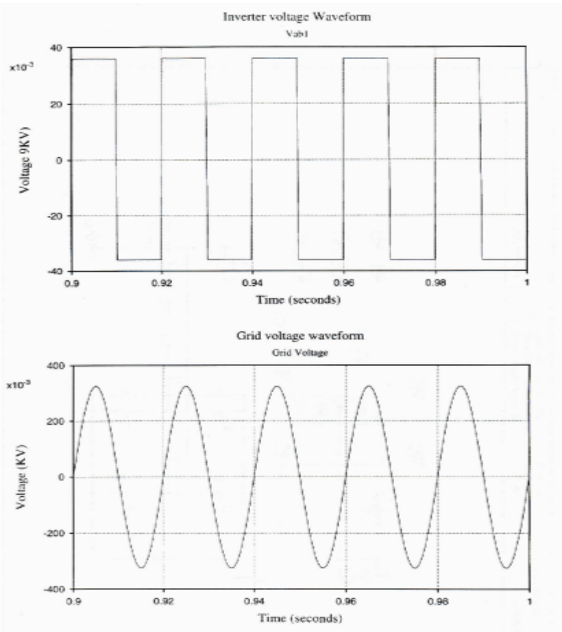


Fig. 2: Inverter output and grid voltage waveforms

The current was measured by using an ammeter connected in series in the circuit. The voltage was also measured. Multiplying graphically the waveforms of these two quantities the waveform corresponding to the complex power was derived and from that an rms value for the complex power can be deduced.

First, setting the d.c. supply to 250 V rms the current was limited between the acceptable limits and it actually had an rms value of 1.3 A. The current waveform was seen to be very distorted, containing all orders of harmonics. The inverter output waveform was also changed since the load became inductive and a "step" was observed in the waveform.

The complex power was measured using the current and voltage values. A two input-one output multiplier was used in order to obtain the complex power waveform simply by multiplying the voltage and current waveforms. The complex power waveform was seen to be distorted due to the contribution from the current waveform. The real power was measured by passing the complex power waveform through a first order control transfer function of the form $G/1+s\tau$, where G is the gain introduced between the input and the output and $\tau$ is the time constant of the system. This transfer function has no zeroes and has only one pole that being at $s=-1/\tau$.

The gain was set to 1 and the time constant $\tau$ was also set to 1 sec. The value of the time constant needed to be as large as possible. The instantaneous values would not be taken into account and the output waveform indicates that real power had reached a steady state value. For these measurements the magnitude of the fundamental of the inverter output voltage was set to 250 V rms resulting in a current flow of 1.3 A through the circuit.

The real power flow was monitored and relative graphs showing the voltage waveform $V_2$, the current $I_a$, the complex power waveform and the real power waveform were plotted. Measurements were taken with $V_{d.c.}$ = 250 V rms and phase shifts of +2 degrees and -2 degrees and the above waveforms were recorded each time. Fig. 4 gives the waveforms obtained for the leading mode of operation.

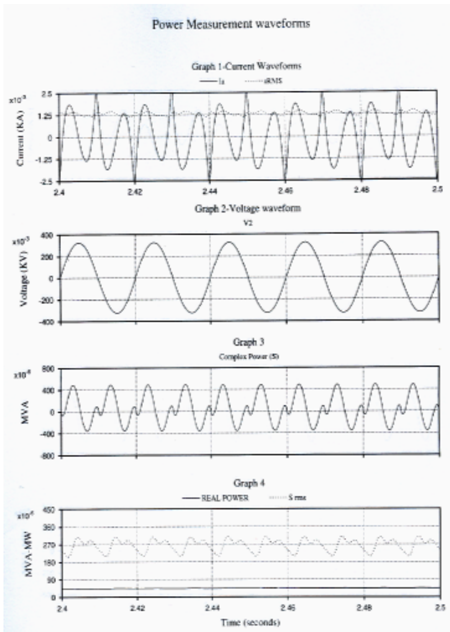


Fig. 4: Leading mode waveforms, $V_{d.c.}$=250 V

### 4.5 Voltage magnitude manipulation - reactive power flow

The magnitude of the fundamental of the inverter output voltage was set to 250 V rms and the magnitude of the grid voltage to 230 V rms. This had as a result a current of rms value 1.3 A flowing through the circuit. The current flow was due to the voltage difference between the a.c. side and the d.c. side and it was expected that a reactive power flow occurred in the same direction. There was no easy way to measure the reactive power Q so the flow of reactive power was demonstrated by inspection of the current waveshapes for different supply voltages that would increase or decrease the magnitude of the fundamental of the inverter output.

One set of measurements and graphs was obtained using a supply voltage of 250 V rms and a phase shift of +2 degrees leading. These graphs were given in Fig. 4 but they are given again in Fig. 5 to support the reactive power flow demonstration. Another set of graphs was taken this time using a supply voltage of 230 V rms and a phase shift of two degrees leading.

Comparing the two current waveforms obtained for supply voltages $V_{d.c.}$=250 V rms, and $V_{d.c.}$= 230 V rms, is concluded that in the second case, where the supply voltage was reduced the current spikes seem to have reduced in terms of magnitude. The rms value of the current was increased.

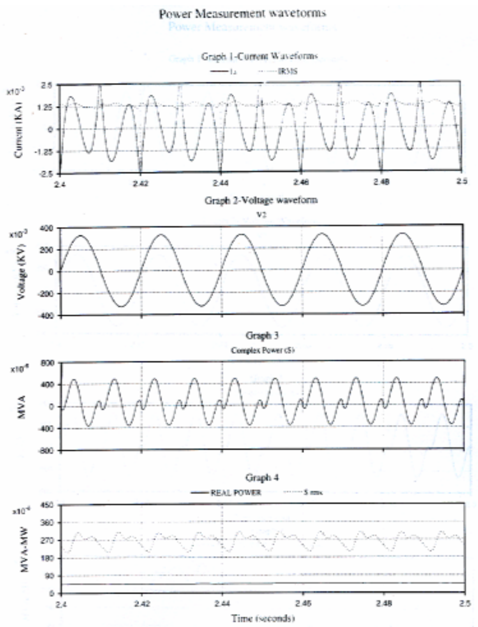

Fig. 5: Leading mode waveforms for $V_{d.c.}$=250 V

### 4.6 Harmonic injection into the grid voltage

The waveforms in Fig. 6a were obtained to demonstrate the effect that an increase of the series inductance of the a.c. voltage source, had on the grid voltage $V_2$. This inductance was increased from a value of 0.001 H to a value of 0.01 H i.e. by a factor of 10 and harmonic injection was evident on the grid voltage waveform $V_2$. Fig. 6 shows waveform $V_2$ containing harmonics, alongside the current waveforms, complex and real power waveforms for $V_{d.c.}$ = 250 V rms.

The reason for this harmonic injection is that the a.c. source is active for a frequency of 50 Hz, the pre-defined frequency of the pure sinusoid generated by this source. In the case of higher frequency and trying to simulate the circuit at the second harmonic the only "source" present would be the inverter which has an output containing this 2nd harmonic. At this frequency the a.c. source becomes short-circuited and the remaining circuit acts as a voltage divider, dividing the square inverter output between the series inductance and the coupling inductance. The larger the series inductance the more voltage containing harmonics will appear across it as voltage drop.

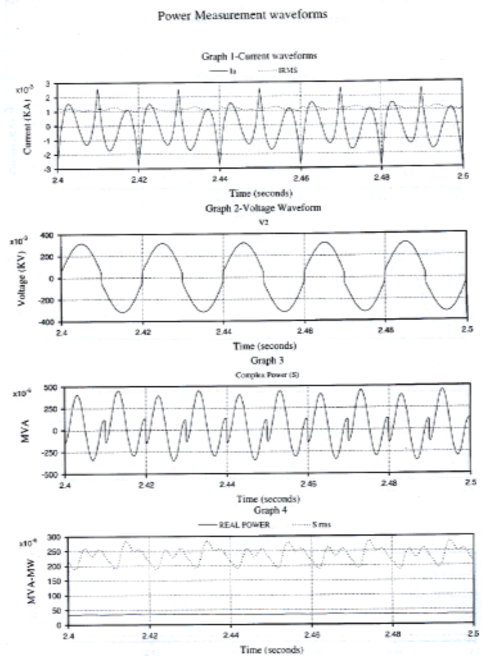

Fig. 6: Leading mode waveforms, harmonics injection in grid voltage $V_2$: $V_{d.c.}$=250 V

## 5. Conclusions

In this paper a model of a single photovoltaic voltage inverter was designed and simulated. The simulation was performed using the PSCAD/EMTDC simulation package. This inverter model was used in conjunction with an a.c. voltage source to show real and reactive power flow.

The operation of the inverter device showed the model's ability to both absorb and generate reactive power. It was shown that increasing the supply voltage at the input of the inverter resulted in exporting reactive power from the inverter, and decreasing it resulted in importing reactive power to the model. When the d.c. supply was increased, the magnitude of the fundamental of the inverter output was increased with respect to the grid voltage magnitude. Decreasing $V_{dc}$ leads to exactly the opposite effects i.e. absorption of reactive power by the inverter.

*References:*


[1] Y. Sukamongkol, S. Chungpaibulpatana, W. Ongsakul, A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads, *Renewable Energy*, 2002, No. 27, pp. 237-258

[2] E Koutroulis, K. Kalaitzakis, et al., Development of a microcontroller-based, photovoltaic maximum power point tracking control system, *IEEE Trans Power Electronics*, 2001, Vol. 16, No. 1, pp. 46-54

[3] F. Valenciaga, P.F. Puleston, P.E. Battiaiotto Power control of a photovoltaic array in a hybrid electric generation system using sliding mode techniques, *IEE Proc, Control Theory Appl*., 2001; Vol. 148, No. 6, pp. 448-455

[4] T. Noguchi, S. Togashi, R. Nakamoto, Short-current pulse-based maximum power point tracking method for multiple photovoltaic and converter module system, *IEEE Trans Industrial Electronics*, 2002; Vol. 49, No. 1, pp. 217-223

[5] D.P. Hohm, M.E. Ropp, Comparative study of maximum power point tracking algorithm using an experimental, programmable, maximum power point tracking test bed, *Photovoltaic Specialists Conference*, 2000, pp. 1699-1702

[6] D.F. Hasti, Photovoltaic power system application, IEEE Power Engineering Review, *Sandia National Laboratories*, 1994, pp. 8-19

[7] E. Koutroulis, K. Kalaitzakis, Development of an integrated data-acquisition system for renewable energy systems monitoring, *Renewable Energy*, 2003, Vol. 28, pp. 139-52

[8] PSCAD/MTDC Power System Simulation Software, User's Manual, Manitoba HVDC Research Centre, Winnipeg, Canada, EMTDC version 2, 1994 release.

[9] Manitoba HVDC Research Center, PSCAD/EMTDC Power System, Simulation Software User's Manual, Version 3, 1998 release.



**Stavroula Kourtesi** was born on April 23, 1981 in Athens, Greece. She has received her diploma in Electrical and Computer Engineering in 2004 and her Master in Energy Generation and Management in 2005 from the National Technical University of Athens. She is currently working in Hellenic Public Power Corporation S.A. as an electrical engineer. She is member of the Technical Chamber of Greece since 2005.

**Lambros Ekonomou** was born on January 9, 1976 in Athens, Greece. He received a Bachelor of Engineering (Hons) in Electrical Engineering and Electronics in 1997 and a Master of Science in Advanced Control in 1998 from University of Manchester Institute of Science and Technology (U.M.I.S.T.) in United Kingdom. In 2006 he received a Ph.D. from the National Technical University of Athens (N.T.U.A.) in Greece. Currently he is working in the Hellenic Public Power Corporation S.A. as an electrical engineer.

**Angelos Nakulas** was born on February 9, 1970 in Kilkis, Greece. He received a Bachelor from Hellenic Army Academy in 1992, a Master in Computer Science in 1999 from University of Athens - Department of Informatics, a Master in Business Administration in 2002 from Athens University of Economics and Business - Departments of Operation Research and Marketing and a Master in Information Systems in 2007 from Athens University of Economics and Business- Department of Informatics. Currently he is working in the Hellenic Army General Staff as a senior officer in research and Informatics. His research interests concern computer and network security, information systems, and software engineering.

**Georgios P. Fotis** was born on July 26, 1977 in Athens, Greece. He received his diploma and his Ph.D. in Electrical Engineering from the National Technical University of Athens in 2001 and 2006, respectively. He is currently a research associate in the N.T.U.A.'s High Voltage Laboratory. His research interests concern high voltages, electromagnetic compatibility and electrostatic discharges. He is member of IEEE and the Technical Chamber of Greece. Dr Fotis is the author of 17 papers in scientific journals and conferences proceedings.

**Emmanouil Zoulias** was born in Piraeus in 1973 and gained his first degree from National Technical University of Athens, Department of Electrical and Computer Engineers in 1996. He gained his M.Sc. in 1997 from University of Dundee in the field of Biomedical Instrumentation Engineering. Currently he is an employee of the National Health System of Greece as a Computer Engineer. In parallel he is a Postgraduate student (PhD) in the field of Data Mining.