University of Strathclyde
Energy Systems Research Unit
MSc "Energy Systems & the Environment"

MSc's Dissertation Title

LABORATORY EVALUATION OF DC / AC INVERTERS FOR STAND-ALONE & GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

The present research project has been supported from
the Center for Renewable Energy Sources
in Greece

Mr Ilias Tsagas
email: tsagasilias@hotmail.com

Introduction

The present dissertation is the result of my individual research activity during the third part of the Strathclyde University's MSc course "Energy Systems & the Environment". It includes experimental laboratory evaluation of a DC to AC stand-alone inverter as well as of a DC to AC grid-connected inverter, while the development of my experimental activity has been carried out at the Department of Photovoltaic Systems, in the Centre for Renewable Energy Sources (C.R.E.S) in Greece.

The first step of my work was the configuration of the inverters test circuits, at the Power Electronic Lab of the Photovoltaic Department. The necessary stuff was provided by C.R.E.S.

The first part of the experiment concerns the measurement of the Trace Engineering stand-alone inverter's (model 2524, 2.5 kW) efficiency. The inverter was connected firstly at its output terminals with a resistive load, in order to measure its efficiency, at the inverter's input voltage equal to the inverter's nominal input voltage. At the same input voltage, the no-load and standby losses of the inverter, the output current ripple and the total harmonic distortion (THD) of both current and voltage were also measured. Measurements have been carried out for many different power levels of the resistive output load, while in order to produce the necessary input voltage of the inverter; we used four batteries of 12 V each.

Efficiency of the inverter was measured after again, with a reactive load connected at the inverter's output terminals. Efficiency was namely measured with a load, which provides power factors 0.25, 0.50 and 0.75 and for many different power levels of the reactive output load. All the other sizes have been also measured as before.

The second part of the experiment concerns the measurement of the Total Energie grid-connected inverter (model Onbuleur Joule Prg, 2.5 kW). The previous experimental test circuit was used again, but now the inverter was connected at the grid and instead of batteries, power supplies were used. At three inverter's input voltages, equal to the manufacturer's minimum rated input voltage, the inverter's nominal voltage and the 90 % of the inverter's maximum input voltage respectively, the same sizes as in stand-alone inverter were measured again. At this case, the harmonic currents and voltages injected into grid by the inverter were further recorded.

The above work has been presented analytically at the next pages of this paper. Namely, the first chapter of the dissertation is an introduction about the inverters, in order readers to obtain a view of the subject. The second chapter describes step by step the measuring procedure that has been followed and the stuff that was used to set up the test circuits, while the third chapter includes the results of the experiment and author’s conclusions.

The present paper can be used in future from students and institutes, as a basis for the production of relative work.

Table of Contents

Chapter 1

INVERTERS: AN INTRODUCTION

What does an inverter do?

Inverters are power electronic devices, which convert DC (typically low voltage) into AC (at 230 V, 50 Hz) as required for conventional appliances. There are generally two types of photovoltaic inverter available: stand-alone and grid-connected.

A. STAND-ALONE INVERTERS

Stand-alone, or battery supplied, inverters are demand driven - they provide any power or current up to the rating of the inverter and assuming that there is enough energy in the battery.

These inverters are being used increasingly to operate household appliances and other “normal” 230 V equipment. The question as to the maximum size for which a single central inverter for all electrical devices is still the best solution, is a matter of philosophy. The central inverter must be in operation all the time. In this case, it is important that the inverter itself has a very low internal consumption.

Different types of inverter produce different AC waveforms and are suitable for different situations.

Square Wave Inverters

The square wave inverter derives its name from the shape of the output waveform (see figure 1).

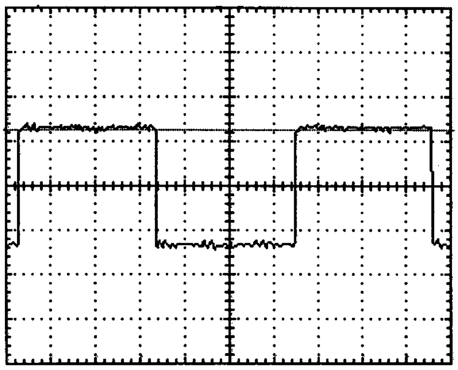


Figure 1- Square Wave Output Wave

Square wave inverters were the original "electronic" inverter. The first versions use a mechanical vibrator type switch to break up the low voltage DC into pulses. These pulses are then applied to a transformer where they are stepped up. With the advent of semiconductor switches the mechanical vibrator was replaced with "solid state" transistor switches. Nowadays, the most common circuit topology, which is used to produce a square wave output, referred to as "push-pull".

Square wave inverters run simple electric motors, but not much else, and will require a lot of energy to do so. Also, this kind of inverters is low quality. The price of better quality inverters is low enough to make the use of these unattractive.

Modified Square Wave Inverters

Modified square wave inverters (often referred to as modified sine wave inverters) use a push-pull topology as well as square wave inverters, with the addition of a few extra parts in their design. However, some modified square wave inverters use another one topology, which is called " H-Bridge". Their output has the shape of the waveform of the next page (see figure 2).

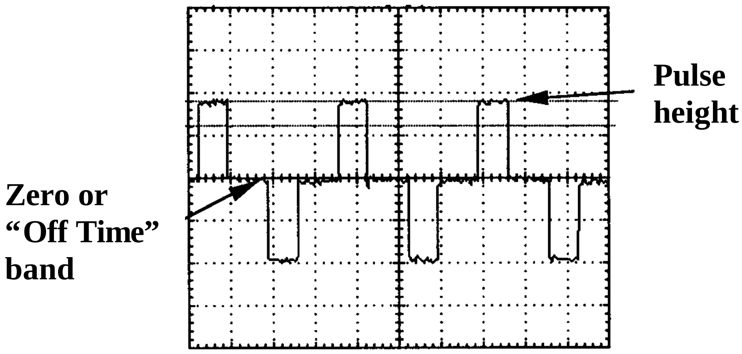


Figure 2- Modified Square Wave

These inverters are a good choice for a 'whole home' inverter since their high surge capacity lets them start motors whilst their high efficiency lets them run small appliances economically.

Most loads will run without trouble from a modified sine wave. It is suitable for a variety of applications such as induction motors (i.e. refrigerators, drill presses); resistive loads (i.e. heaters, toasters); universal motors (i.e. hand tools, vacuum cleaners) as well as microwaves and computers. However, some appliances will not operate or will run noticeably less well if not on a pure sine wave.

Problem loads: e.g. many laser printers, copiers, some computers, light dimmers and some variable speed tools may not operate; some TV's and some audio equipment will pick up interference or background buzz; some digital clocks may not keep time; microwave ovens will have longer cooking times; and some small battery chargers may fail. Central heating ignition systems can be problematic.

Sine Wave Inverters

A sine wave inverter puts out an AC equal to what you get from utility grid, a smooth sine wave. A 'mains' quality pure sine wave output is necessary for some applications such as running electronics or audio equipment.

Two common tolopogies that are used to produce sine wave output are push-pull and H-Bridge.

True sine wave inverters can run all types of load and are now available which are powerful, efficient and affordable! Their disadvantage is their cost, which is higher than the cost of the other kinds of inverters.

B. GRID-CONNECTED INVERTERS

Grid-connected inverters are supply driven - they provide all the power supplied from a DC source to the grid or mains. Therefore, in grid-connected systems, the solar inverter is the connecting link between the solar generator and the AC grid, while the characteristics of the inverter have a decisive influence on the performance of the grid-connected photovoltaic system.

Generally, grid-connected inverters operate at a higher DC voltage than stand alone inverters.

Grid-connected inverters should NOT be connected to batteries and stand-alone inverters should NOT be connected directly to PV or the grid.

Smaller systems with few appliances may have only DC power, but recent advances in inverter design, efficiency, and reliability have increased the potential of solar systems considerably.

With the use of modern high efficiency AC lighting the majority of, if not all, loads can be operated on AC especially in larger installations.

We can use both AC & DC where each is most effective and economical - many DC appliances use less power than their AC equivalents (especially refrigeration, lighting & electronics) - but DC appliances tend to be harder to find and more expensive.

How do they work?

The grid-connected inverter must convert the direct current from the solar modules to alternating current synchronous with the grid.

It must also be optimally matched to the I-V characteristic of the solar generator. Therefore, in PV applications the inverter will automatically adjust the PV array loading to provide peak efficiency of the solar panels by means of maximum power point tracking (MPPT).

Inverters automatically shutdown in the event of:

- High/Low grid AC-voltage
- High/Low grid frequency
- Grid Failure
- Inverter malfunction

Technicalities

Connection of a photovoltaic electrical system to the electricity grid must have local electricity company approval and installation method and protection must meet their safety requirements and appropriate standards.

There are costs associated with connection and metering to/from the grid. Also, the rate paid for electricity generated is usually considerably less than that charged for electricity consumed. Thus, the best economics are obtained if all the power generated can be consumed on site.

Types of grid-connected inverters

There are several basic types of grid-connected inverters, which all have different properties:

- grid-commutated inverters (thyristor devices)
- self-commutated inverters (pulse width modulation and LF transformer)
- self-commulated inverters (pulse width modulation and HF transformer)

Grid-commutated inverters are relatively inexpensive, because their components are derived from existing thyristor devices for drive unit technology. These inverters are simple and robust. They normally supply three-phase power to the grid. Inverters for the higher power range (>100 kW) are almost all constructed according to this principle.

These inverters have the characteristics of a current source, while the grid voltage is needed for commutation. They also have high harmonic content, because the electricity is supplied to the grid in blocks (rectangle or trapezium). Reactive power is drawn from the grid, because the current is out of phase with the grid voltage (ignition angle).
As a result of their operating principle, the power factor of this type of inverters lies in the range of 0.6 to 0.7 and must be increased, if required, with external devices.

Self-commutated inverters with pulse width modulation and a 50 Hz transformer can be used in stand-alone operation as well. The final power block is equipped with fast semiconductor switches (transistors), while the grid voltage is not needed to switch off the power semiconductors.
Small PV systems with a power of 1.5 to 5 kW are often equipped with single-phase solar inverters with a 50 Hz toroidal transformer.
The self-commutated inverters achieve their sinusoidal form of the output current by pulse width modulation with a high frequency. As a result of the switching principle, the power factor is close to 1.

Self-commutated inverters with pulse width modulation and an HF transformer are a further attempt to reduce the internal consumption of this category of inverters.

Ferrite transformers ensure the galvanic separation of the grid and the solar generation here.

The switching concept of these inverters requires three stages with power semiconductors. This means two more stages than for pulse width modulated solar inverters with an LF transformer. However each additional stage can cause further losses if it is not optimised. That is a main reason why the original aim to increase the efficiency by incorporating HF technology has not succeeded convincingly.

C. WHERE DOES ANY EXCESS ENERGY GO?

This depends on whether the system is stand-alone or whether it is grid-connected.

Storage batteries are the heart of all stand-alone PV or inverter electrical systems.
By storing excess energy when the sun is strong, they offer a reliable source of electricity, which can be used when solar power is not available.

Their function is therefore to balance the outgoing electrical requirements with the incoming energy supply.

Batteries are also able to provide short-term power output, many times higher than the charging source output.

For grid-connected inverters, energy is fed back into the grid.

D. WHO NEEDS A GENERATOR?

In typical domestic situations, for most of the day, loads are very small - perhaps a few lights and other appliances.

For a small proportion of the time, however, large loads such as washing machines, electric kettles, etc. must be powered.

Sizing a renewable energy system to meet this peak demand is, in most cases, prohibitively expensive (at least initially).

The optimum way to incorporate a solar energy is for this to supply the low loads required for most of the day, and allow a generator to start up automatically to meet the small proportion of loads for which a large capacity is required.

In such systems, batteries allow power to be available 24 hrs/day but means that the generator need only run for short periods to charge the battery.

E. EFFICIENCY

Modern electronic inverters are very efficient over a wide range of outputs, but some power is required simply to keep the inverter running (the standing losses) and they are less efficient when running small loads.
Consequently, sizing the inverter for its required purpose is extremely important.

- ☑ If it is undersized, then there will not be enough power - demanding more than their limit will shut them off.

- ☑ If it is oversized, it will be much less efficient (due to the standing losses) and more costly to buy and run.

A load seeking circuit is normally included to ensure that battery power is conserved for useful purposes by automatically switching the inverter on and off as loads are applied or discontinued.

F. SIZING

In inverter sizing the most important factor is peak power consumption: the peak power demand should not exceed the rated peak output of the inverter.

This is difficult when it is possible for many devices to consume power at the same time, and is further complicated by any electric motors in the system.

Some types of electric motors require three times as much power to start them as is required to run them. If two or more motors are started at the same time the surge power demand is much higher than the average demand. Consequently, the inverter should be sized to be able to at least start the largest motor in the system and measures taken to ensure that all motors do not start at the same time.

Proper energy management can reduce peak demand, and so the inverter can be sized closer to the average power demand, thereby increasing the system's efficiency and reducing hardware costs.

G. SITING

Inverters should be located in a dry, non-condensing, clean, ventilated environment.

Vented lead acid batteries can produce corrosive vapors and when on charge produce an explosive mixture of hydrogen and oxygen. So, good ventilation is required for the battery, particularly at a high level to allow any hydrogen to disperse.

Preferably, the battery should be in it's own cubicle, vented to the outside. If this is not practicable, we don't mount the inverter directly above the battery or directly adjacent to it.

In order to minimize the voltage drop in the connecting cables to the battery, these should be kept as short as possible and of sufficient size.

Chapter 2

EXPERIMENT WE DO

The main **activity** of the present project was to measure the efficiency of two different types of inverters, which are used in stand-alone and utility-interactive photovoltaic systems, respectively. Further tests, in order to measure the no-load and stanby losses of the inverters have been made, while the harmonic currents and harmonic voltages, which are injected into grid by the grid-connected inverter, are measured as well.

The **goal** was after we complete our tests and based on the measurements, to be able to have a clear view of the performance of the specific models of inverters.

The **procedure** for measuring the efficiency of the inverters, which are used in stand-alone and utility-interactive photovoltaic systems, is based on the International Electrotechnical Commission's Standard 61683 "Photovoltaic systems-Power Conditioners-Procedure for measuring efficiency".

A. PROCEDURE FOR MEASURING EFFICIENCY

A1. DEFINITIONS

For the purposes of the present project (as well as of the IEC 61683), the following definitions apply. All efficiency definitions are applied to electric power conversion alone and they do not consider any heat production.

- **rated output efficiency:** ratio of output power to input power, when the inverter is operating as its rated output.

- **partial output efficiency:** ratio of output power to input power, when the inverter is operating below its rated output.

- **no-load loss:** input of the inverter, when its load is disconnected or its output power is zero.

- **standby loss:** for a utility interactive inverter, power drawn from the utility grid when the inverter is in standby mode. For a stand-alone inverter, d.c. input power when the inverter is in standby mode.

A2. EFFICIENCY MEASUREMENT CONDITIONS

Efficiency of the inverters has been measured under the below conditions:

- **DC power source for testing**

For inverters operating with fixed input voltage, the d.c. power source was a storage battery or constant voltage power source to maintain the input voltage.

- **Temperature**

According to the IEC 61683 standards, all measurements are to be made at an ambient temperature of 25 °C ± 2 °C. However, there wasn’t control of the temperature during our measurements. The ambient temperature in our case was the typical room temperature.

- **Output voltage and frequency**

The output voltage and frequency was being maintained at the manufacturer’s stated nominal values.

- **Input voltage**

Measurements were repeated at three inverter’s input voltages:

a) manufacturer’s minimum rated input voltage;
b) the inverter’s nominal voltage;
c) 90 % of the inverter’s maximum input voltage.

In the case where an inverter is to be connected with a battery at its input terminals, only the nominal or rated input voltage may be applied.

A3. READINGS TO BE RECORDED

A3.1 Ripple and distortion

For both of stand-alone and grid-connected inverters, we record the input voltage and the current ripple for each measurement.

For stand-alone inverters, we record furthermore, the output voltage, the current distortion (THDi) and the voltage distortion (THDv), while for grid-connected inverters, we record the output voltage and the current distortion (THDi).

A3.2 Resistive loads / utility grid

For both of stand-alone and grid-connected inverters, at unity power factor ($\cos\varphi=1$), we measure the efficiency for power levels of 10 %, 25 %, 50 %, 75 % and 100 % of the inverter’s rating.

A3.3 Reactive loads

For stand-alone inverters, we measure the efficiency with a load, which provides a power factor equal to 0,25 and at power levels of 25 %, 50 %, and 100 % of rated kW. We repeat for power factors of 0,5 and 0,75 (we do not go below the manufacturer's specified minimum PF) and power levels of 25 %, 50 % and 100 % of rated kW.

A3.4 Loss measurement

For both of stand-alone and grid-connected inverters, we measure the no-load and standby losses.

A3.5 Harmonic Components

At the grid-connected inverter's input voltage, equal to the inverter's nominal voltage, we measure the harmonics of current and the harmonics of voltage.
The harmonics of current will be compared to limits for harmonic current emission for equipment input current ≤ 16 A per phase, which have been taken from the International Electrotechnical Commission's standard IEC 1000-3-2, EMC: Part 3, Section 2.

A4. EFFICIENCY CALCULATIONS

- **Rated output efficiency**

Rated output efficiency will be calculated from measured data as follows:

$$\mathbf{n_R = (Po / Pi) * 100} \qquad \mathbf{(1)}$$

where

n_R is the rated output efficiency (%);

Po is the rated output power from the inverter (kW);

Pi is the input power to the inverter at rated output (kW).

- **Partial output efficiency**

Partial output efficiency will be calculated from measured data as follows:

$$\mathbf{n_{par} = (Pop / Pip) * 100} \qquad \textbf{(2)}$$

where

n_{par} is the partial output efficiency (%);

Pop is the partial output power from the inverter (kW);

Pip is the input power to the inverter at partial output (kW).

B. EFFICIENCY TEST CIRCUITS

B1. TEST CIRCUITS

Figure 1 shows the test circuit, which will be used to measure the efficiency of the stand-alone inverter, while figure 2 shows the test circuit, which will be used to measure the efficiency of the grid-connected inverter.

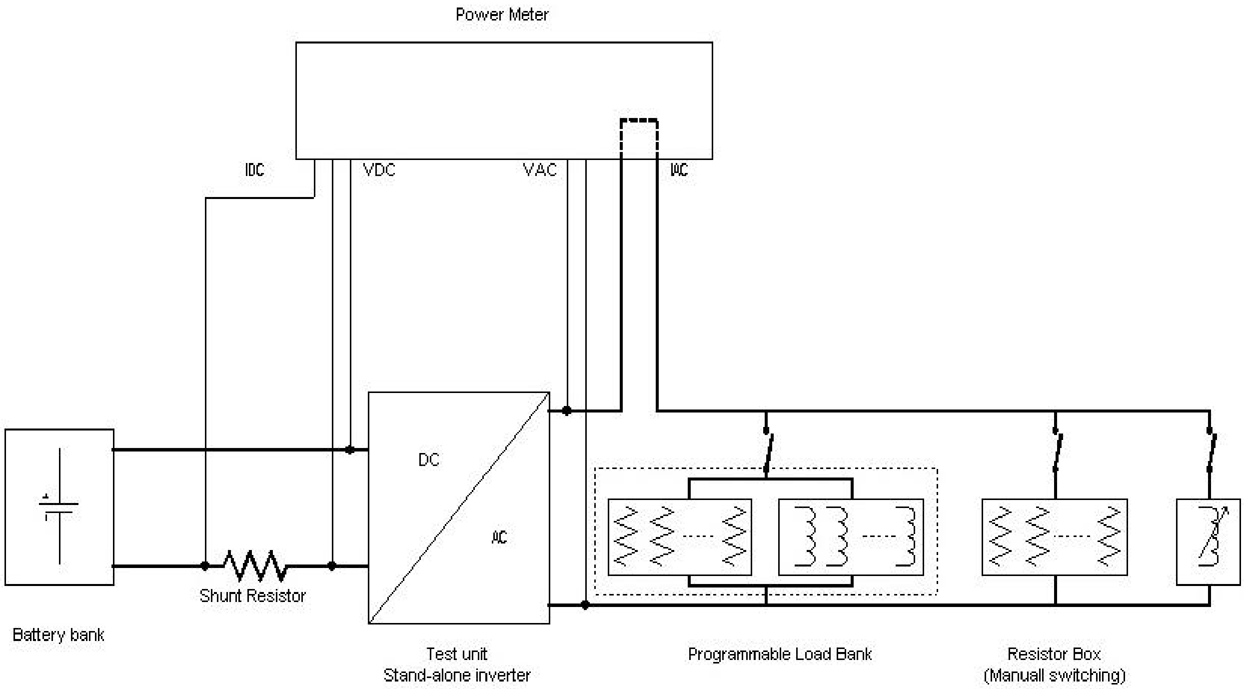


Figure 1- Experimental set-up for testing of stand-alone inverter

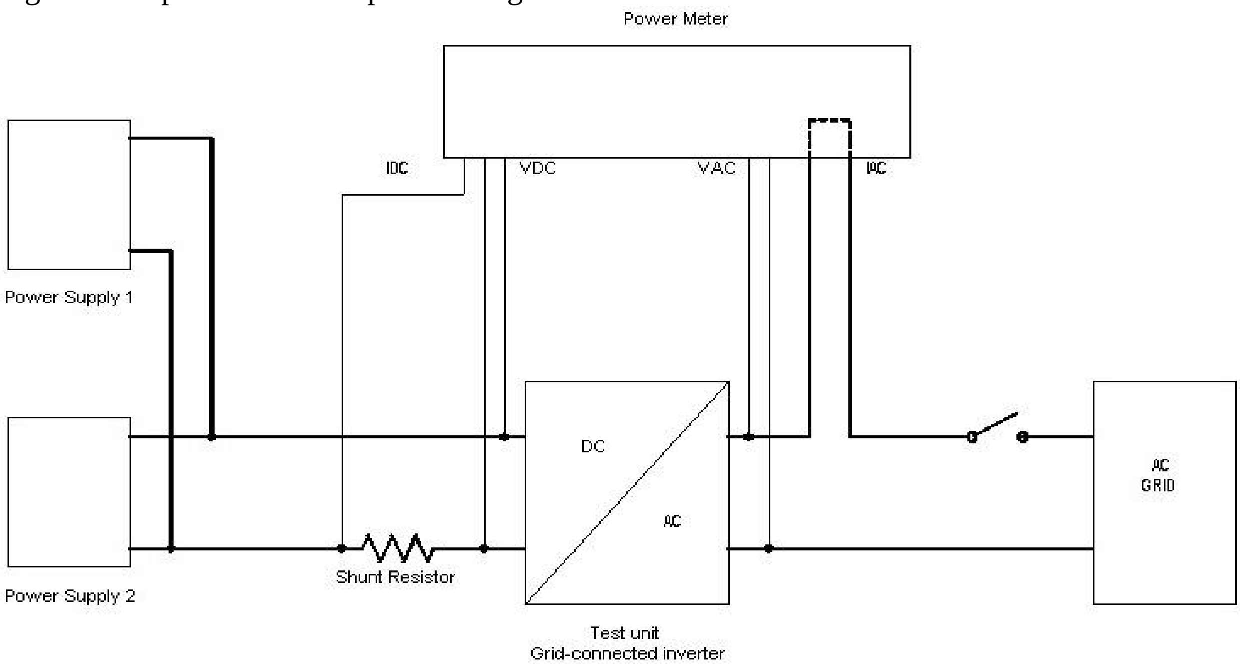


Figure 2- Experimental set-up for testing of grid-connected inverter

B2. EQUIPMENT OF THE TEST CIRCUITS

B2.1 Equipment of the stand-alone inverter's test circuit

The devices that are used to set up the circuit for the stand-alone inverter's test (figure 1) are listed below:

Four batteries of 12 V, 75 AH each. Dynasty Technologies	
YOKOGAWA digital power meter Model WT 2030	
Electronic device consisted of an "external shunt" resistor	
Electronic device consisted of 7 resistances 1 kΩ each & 3 resistances 200 Ω each.	
Regulating autotransformer 5 kVA, 50/60 Hz	
Froment Proofloader Reactive Load	
Load Bank Capacity 103 kVar / 0 kW 400 Volts 3 phase 50 Hz	Auxiliary Supply 230 Volts 4 Amperes 1 phase 50 Hz
Froment Proofloader Resistive Load	
Load Bank Capacity 103 kW / 0 kVar 400 Volts 3 phase 50 Hz	Auxiliary Supply 230 Volts 4 Amperes 1 phase 50 Hz

Note 1: The digital power meter can be used as wattmeter, voltmeter, ammeter, frequency meter and power factor meter as well. So, instead of using many different meters, we use only the above digital power meter, which provides us, all the necessary measurements. However, a problem is presented. The YOKOGAWA digital power meter can accept only until 20 A, at its input terminals. In order to face this problem, we add an electronic device at the input terminals of the YOKOGAWA meter, which is consisted of a resistance, called “external shunt”. When external shunt accepts 150 A, at its input terminals, it shows 60 mV, as its output. So the YOKOGAWA meter accepts voltage and it’s able to work.

Note 2: The reactive load, which is connected in parallel with the resistive load, is needed to provide a power factor, equal to 0.25, 0.50 and 0.75 and at power levels of 25 %, 50 % and 100 % of the inverter’s rated kW. In order to succeed these values of the power factor as well as the necessary values of the output inverter’s active power, we use two devices, which are connected in parallel with the resistive and the reactive loads.

The first device is a regulating autotransformer (5 kVA, 50/60 Hz), which is used as a variable coil. Using this device, we change the value of the power factor, preferably.

The second device is consisted of 7 resistances of 1 kΩ each and 3 resistances of 200 Ω each. The output power of a resistance 1 kΩ is 50 W, while the output power of a resistance 200 Ω is 25 W. Using this device properly, we are able to adjust the inverter’s output power.

Note 3: Sometimes, we use further an oscilloscope (Tektronix, model TDS 3054) and an ammeter (Tektronix, model TM 5003), in order to take the graphs of the input voltage and the input current of the inverter, as well as the output voltage and the output current of the inverter. These devices are used properly, for both of the above test circuits.

B2.2 Equipment of the grid-connected inverter's test circuit

The devices that are used to set up the circuit for the grid-connected inverter's test (figure 2) are listed below:

Two ELCAD s.r.l Power Transformers (made in Romania) Model Ta3P5K-a/e 380/240 V, 5 kVA
Two ELGAR Sorensen (DHP Series) variable voltage-current d.c. power supplies Model No. DHP 200-25 Volts 200-240 VAC, 3W+PE Amps 21-18, 50/60 Hz
YOKOGAWA digital power meter Model WT 2030

Figure 3- Inverter's test circuit.
Center for Renewable Energy Sources in Greece
Department of Photovoltaic Systems

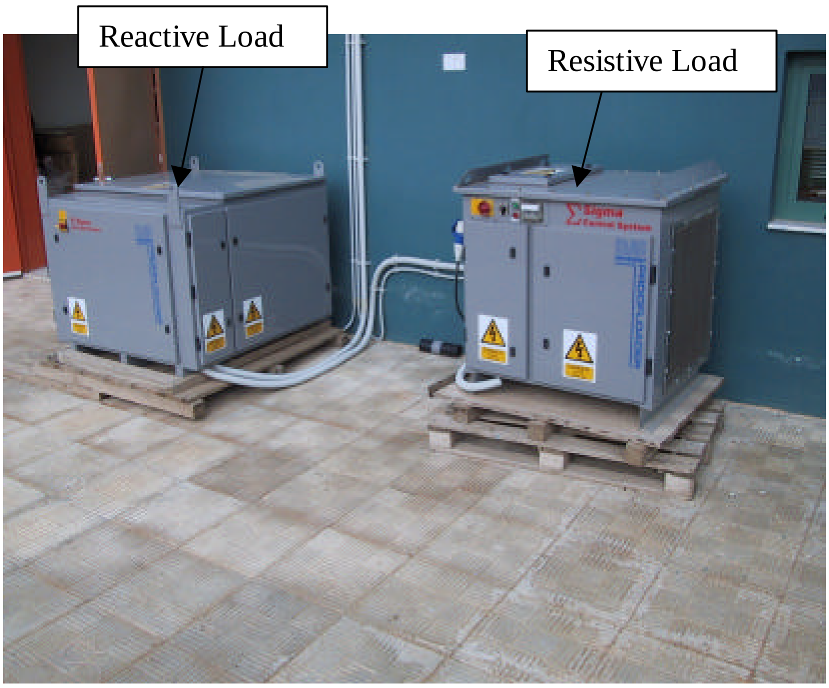


Figure 4- Resistive & Reactive Loads of the test circuits.
Center for Renewable Energy Sources in Greece
Department of Photovoltaic Systems

B2.3 Measurement procedure

a) Efficiency is calculated with equation (1) or (2) –see pages 19 & 20 respectively-, using measured Pi, Po or Pip, Pop. DC input power Pi, Pip can be measured by digital power meter or determined by multiplying the inverter's input voltage and the inverter's input current, both measured by digital power meter. Output power Po, Pop is measured by digital power meter as well.

b) DC input voltage, which is measured by digital power meter, will be varied in the defined range where the output current, which is also measured with digital power meter, is varied from low output to the rated output.

c) Power factor (PF in per cent) can be measured by the digital power meter.

d) The inverter's output current and the inveretr's output voltage will be measured by the the digital power meter as well as the THD of current and the THD of voltage.

e) Based on the graph of the output current, which is shown at the monitor of the oscilloscope, we can evaluate each time, the current ripple of the inverter's output current.

f) In case of grid-connected inverter, we further measure the harmonics of voltage and the harmonics of current injected into grid, by using the digital power meter, shown in figure 2, page 21.

Loss measurement

No-load loss will be measured as follows.

- If the inverter is a stand-alone type, the reading of d.c. input voltage, output voltage and frequency is given with digital power meter and will be adjusted to the rated values.

  No-load loss is thus the indicated value of d.c. input power measured by power meter in figure 1, page 21, when the load is disconnected from the inverter.

- If the inverter is a utility-interactive type, the reading of d.c. input voltage, a.c. output voltage and frequency is given with digital power meter and will be agjusted to meet the specified voltages and frequency.

No-load loss is thus the indicated value of d.c. input power measured by digital power meter in figure 2, page 21, when the same digital power meter indicates a zero value as the value of the a.c. output voltage.

Standby loss will be measured as follows.

- If the inverter is a utility-interactive type, standby loss is defined as the consumption of utility power when the inverter is not operating, but is under stanby condition. Standby loss is indicated with digital power meter in figure 2, at the rated output voltage.

- If the inverter is a stand-alone type, standby loss is defined as the consumption from the d.c. source when the inverter is not operating, but is under standby condition. Standby loss is then the indicated value of d.c. input power measured with digital power meter in figure 1, without a.c. or d.c. output voltage.

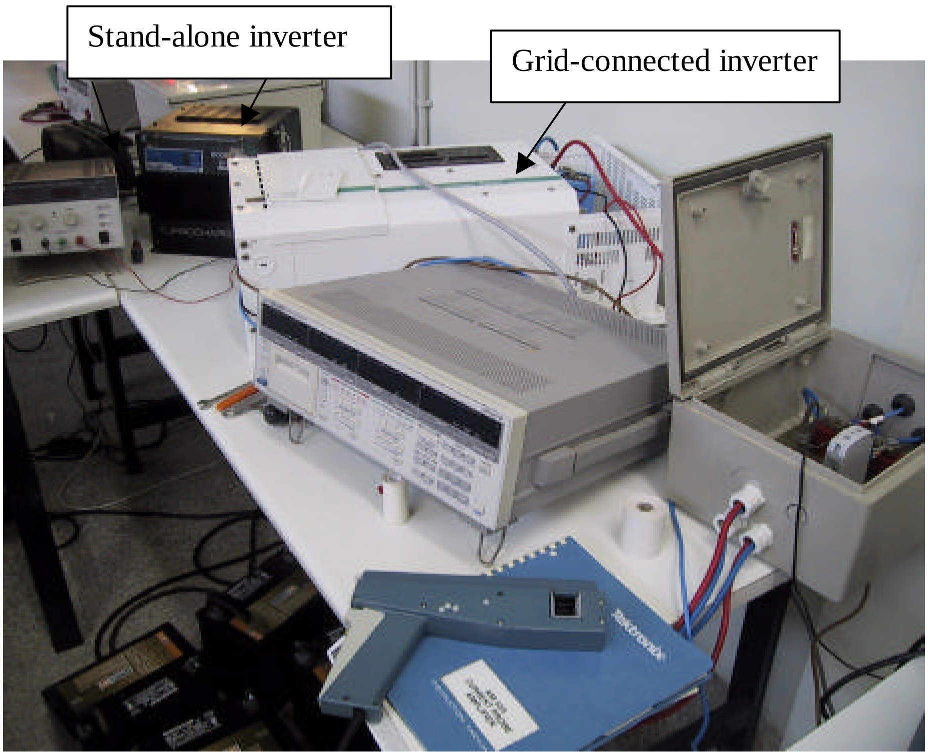


Figure 5- Part of the test circuits

Center for Renewable Energy Sources in Greece

Department of Photovoltaic Systems

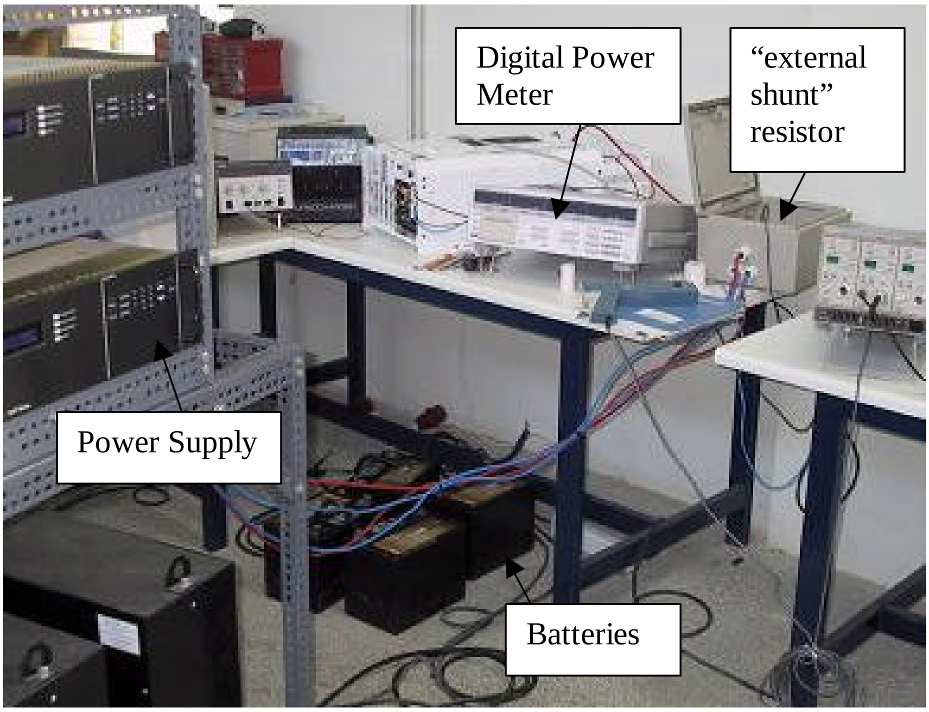


Figure 6- Part of the test circuits

Center for Renewable Energy Sources in Greece

Department of Photovoltaic Systems

C. INVERTERS, WHICH ARE TESTED

C1. STAND-ALONE TYPE

Trace Engineering inverter (made in U.S.A.)
Model 2524
2,5 kW
Nominal Input Voltage 24 VDC
Input Voltage Range 14,9 V - 30,7 V
Nominal output Range 220 VAC
50 Hz

The above model of Trace Engineering stand-alone inverter belongs to Trace 2500 series Inverters, which are modified square wave inverters.
The topology of this series of inverters is named push-pull topology and it's based on low frequency switching of the low voltage DC side, applying the resulting DC pulses to a step-up transformer.

Design and operation of the inverter

The basic theory of operation behind a **push-pull design** is as follows:

The top transistor switch closes and causes current to flow from the battery negative thriugh the transformer primary to the battery positive. This induces a voltage in the secondary side of the transformer that is equal to the battery voltage times the turns ratio of the transformer. Note: Only one switch at a time is closed.

After a period of approximately 8ms (one-half of a 60 Hz AC cycle), the switches flip-flop. The top switch opens and then the bottom switch closes allowing current to flow in the opposite direction. This cycle continues and higher voltage AC power is the result.

The above type of operation produces a square wave result. The addition of an extra winding in the transformer along with a few other parts allows output of a modified square wave.

So, at **modified square wave inverters**, as the model 2524 of Trace Engineering, the switching cycle is identical to that described above, except for one additional step. In the switching cycle, another step is added, which “clears” out the transformer reducing the problems associated with the sudden change in current direction. This is accomplished by the off time shorting winding shown in figure 7. As one switch opens and before the second switch closes, the switch across the shorting winding closes, effectively removing the current from the transformer. Off-time shorting provides a better zero crossing of the waveform, which equates to better ability to operate electronic devices. Improved efficiency is another one benefit.

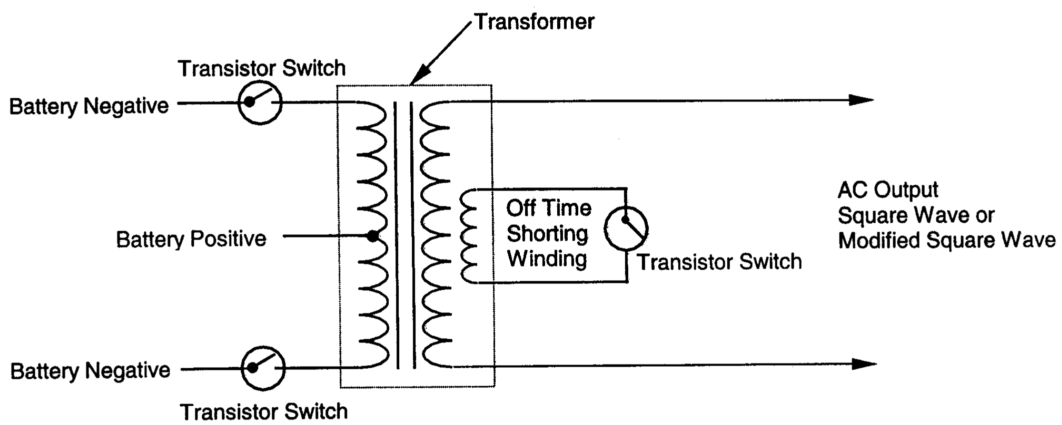


Figure 7- Push-pull topology with shorting winding

C2. GRID-CONNECTED TYPE

Total Energie inverter (made in France)
Model Onbuleur Joule Prg
2,5 kW
Single phase
Nominal Input Voltage 48 VDC
Input Voltage Range 44 V - 66 V
Nominal output Range 220 VAC
50 Hz

Total Energie inverter is based on the Trace Engineering SW series, which uses a combination of three transformers, each with its own low frequency switcher, coupled together in series and driven by separate interconnected micro-controllers. In essence it is three inverters linked together by their transformers. By mixing the outputs from the different transformers, a **stepped approximation of a sine wave** is produced. Shown in figure 8 is the output waveform from this kind of inverter. Notice the “steps” form a staircase that is shaped like a sine wave.

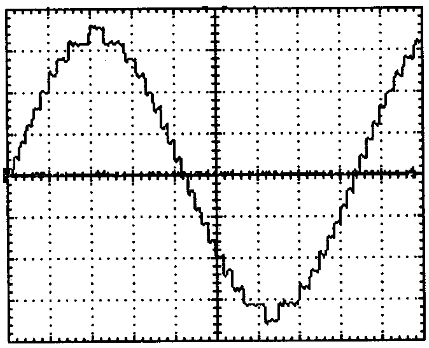


Figure 8- Output of the above type of grid-connected inverter

The multi-stepped output is formed by modulation of the voltage through mixing of the three transformers in a specific order. Anywhere from 34-52 “steps” per AC cycle may be present in the waveform. The heavier the load or lower DC input voltage the more steps there are in the waveform.

The main disadvantage to this type of approach is the complexity of accomlishing the task. However, once designed, this type of inverter has high efficiency and good voltage and frequency regulation.

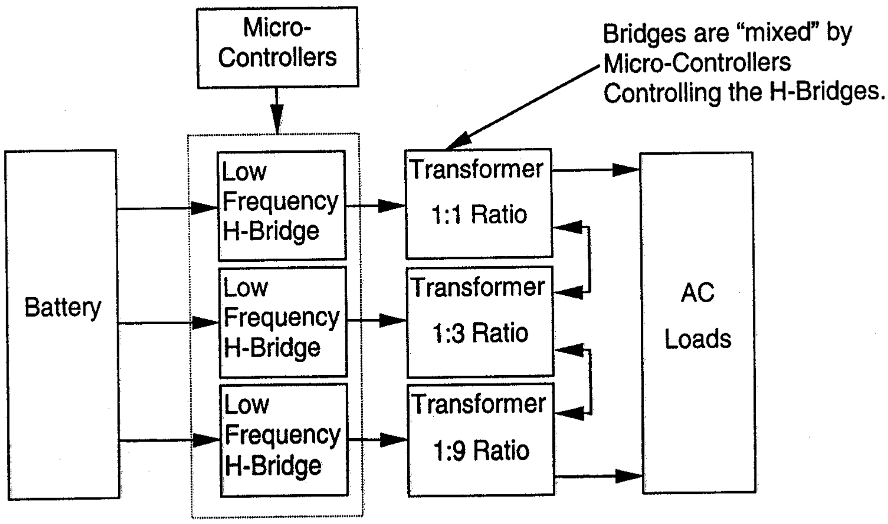


Figure 9- Inverter's topology & design

Chapter 3

RESULTS & CONCLUSIONS

A. STAND-ALONE INVERTER'S TEST RESULTS

A1. TEST WITH RESISTIVE LOAD- AT INVERTER'S NOMINAL INPUT VOLTAGE, 24 V.

% of rated kW	Pout (W)	n (%)	Vin (V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)	Voltage Distrortion (THDv)
5 %	125	77,50 %	25,120	15	217,09	35,86 %	36,52 %
10 %	250						
	257	85,95 %	24,941	25	217,10	33,69 %	34,14 %
	435	88,95 %	24,810		217,13		
	622	89,36 %	24,541	50	217,27	28,94 %	29,10 %
25 %	625						
	786	89,11 %	24,337		217,52		
	1011	88,68 %	24,196		217,66		
50 %	1250						
	1248	87,70 %	23,973	75	217,91	27,79 %	27,84 %
75 %	1875						
	1885	84,75 %	23,420	110	218,99	36,12 %	36,18 %
	2492	80,18 %	22,809	100	206,30	41,19 %	41,23 %
100 %	2500						

% of rated kW	Pout (W)	Pin (W)
5 %	125	161
10 %	250	
	257	299
	435	489
	622	696
25 %	625	
	786	882
	1011	1140
50 %	1250	
	1248	1423
75 %	1875	
	1885	2224
	2492	3108
100 %	2500	

Figure 1a- Table of numerical results

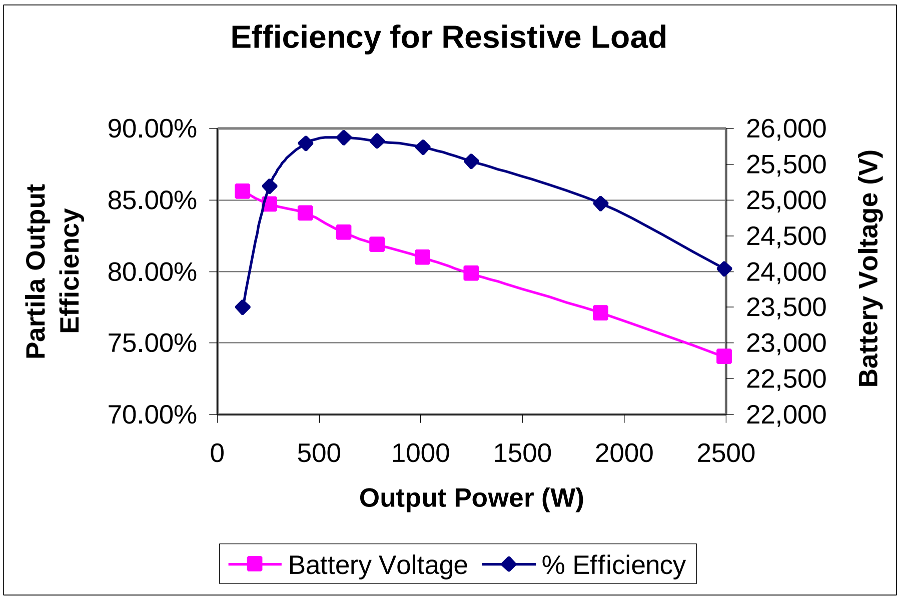


Figure 1b- Graph of the efficiency

Figure 1- Test Results of the stand-alone inverter with a load at unity power factor

Comments

- Based on the formula (1) that is presented in page 19 and using the numerical results of the figure 1a, the rated output efficiency of the Trace Engineering 2524 stand-alone inverter is measured as follows:

  $$\mathbf{n_R = (Po / Pi) * 100 = (2492\ W / 3108\ W) * 100 = 80{,}18\ \%}$$

  So, the rated power efficiency of the tested inverter at unity power factor is 80,18 %.

- Based on both of the numerical results of the figure 1a and the efficiency curve of the figure 1b, we extract the conclusion that the inverter's best partial output efficiency is taken for power level of 25 % of the inverter's rating. For power levels greater than this one, the efficiency values are decreased smoothly.
- Further, as much the output power is increased, the input voltage is decreased. That happens, because we use batteries to produce the input voltage of the inverter. When we use batteries, as much input power is taken from the inverter; the input current of the inverter is increased. Therefore, respectively, the input voltage of the inverter is decreased.

- In general, based on the results presented in figure 1a and 1b, we can say that the efficiency of the inverter as well as its whole behaviour at unity power factor (resistive load, $\cos\varphi = 1$) is very good.

Graphs

of the inverter's input voltage, output voltage, input current and output current

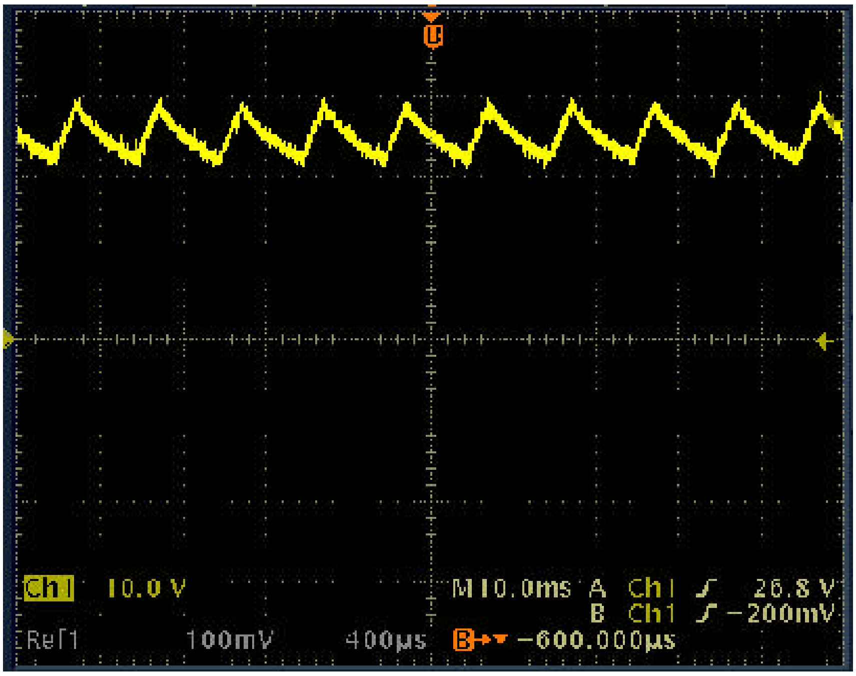
At unity power factor of the stand-alone inverter and under the conditions, which are presented in the array below, we extract the graphs of the inverter's input voltage, output voltage, input current and output current, using an oscilloscope.

Input	Output
Pin = 943 W	Pout = 884 W

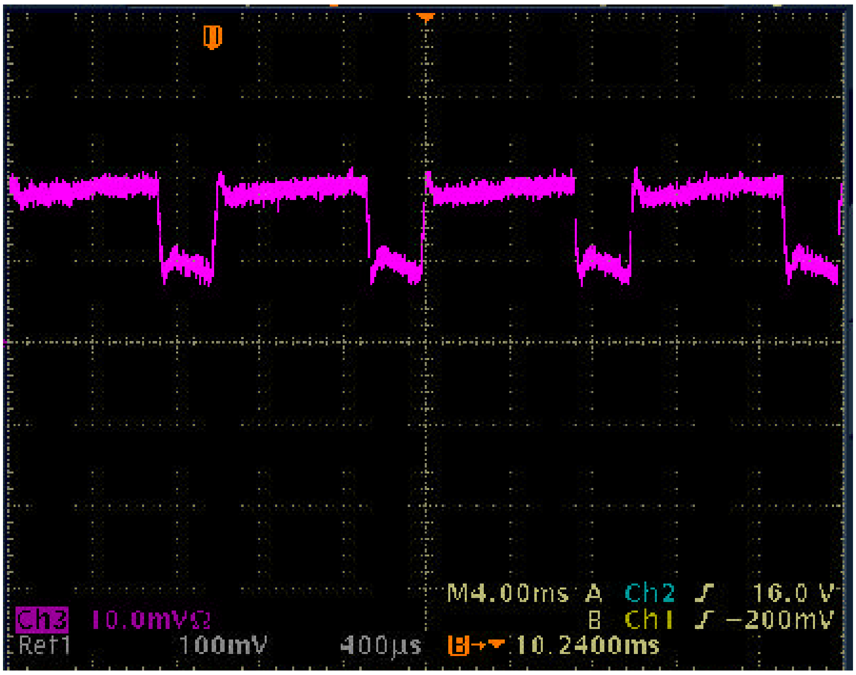
Figure 2- Inverter's conditions
when taking the graphs

The graphs are presented at the next figures.

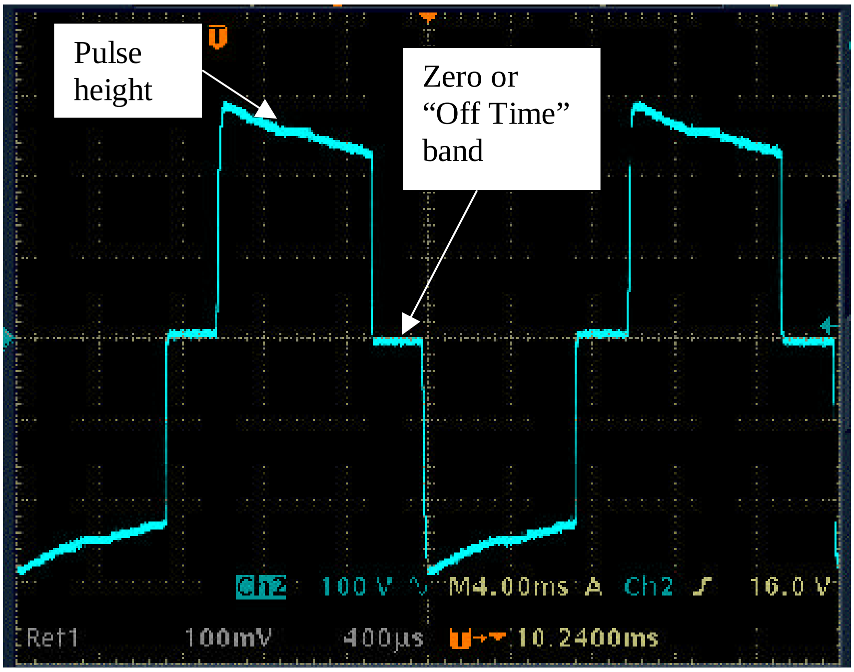
- **Graph No 1: inverter's input voltage**



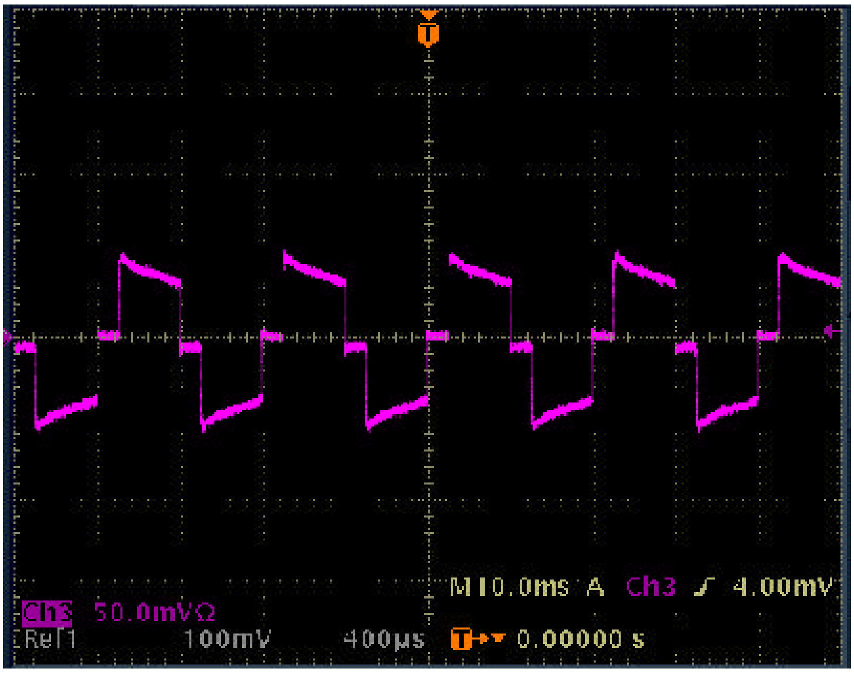
- **Graph No 2: inverter's input current**



- **Graph No 3: inverter's output voltage**



- **Graph No 4: inverter's output current**

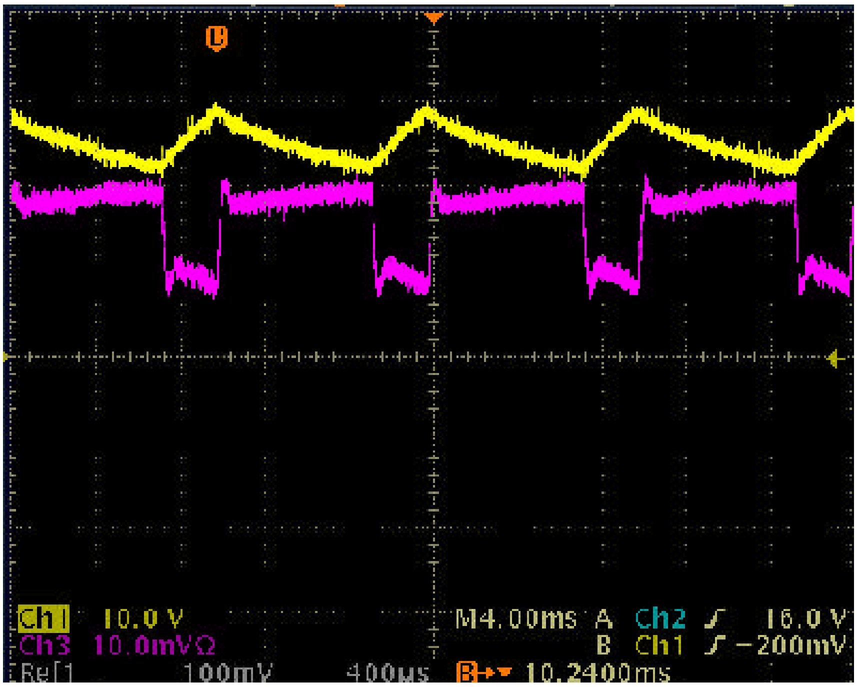


Comments

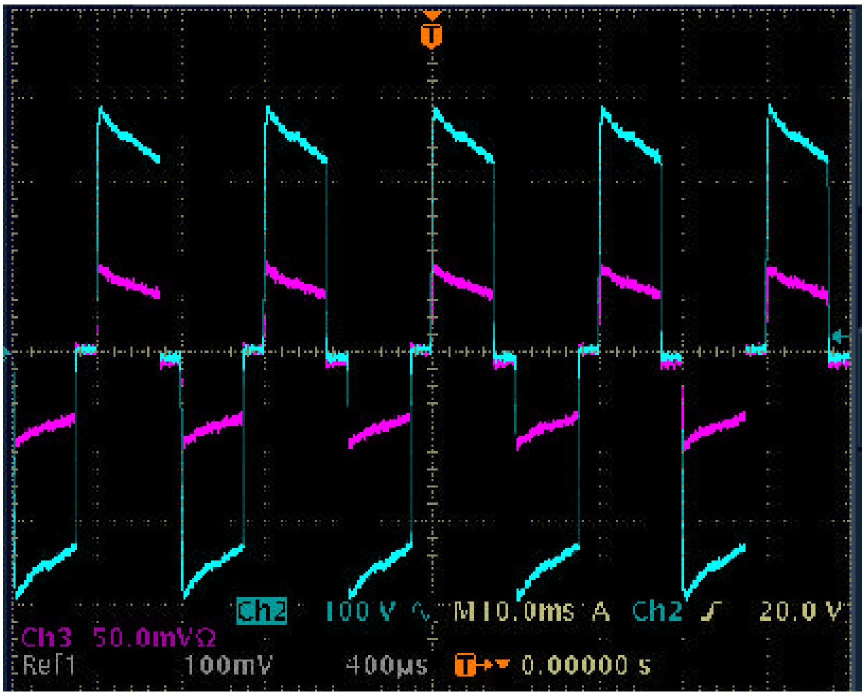
The output voltage of the Trace Engineering 2524 stand-alone inverter (graph No 3) shows that its output is a modified square wave (often referred to as modified sine wave). The graph of the output voltage is similar to the graph in figure 2, page 8, which according to the theory represents the output of a modified square wave inverter. The zero or "Off Time" band and pulse height have been shown with arrows up to the graph.

The next graphs (graph No 5 and graph No 6) show the inverter's input voltage and current together, as well as the inverter's output voltage and current together.

- **Graph No 5: inverter's input current and voltage**



- **Graph No 6: inverter's output current and voltage**



A2. TEST WITH REACTIVE LOAD-
AT INVERTER'S NOMINAL INPUT VOLTAGE, 24 V.

A2.1 For Power factor ($\cos\varphi$) 0,25

% of rated power	Pout (W)	n (%)	Vin (V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)	Voltage Distrortion (THDv)
5 %	125						
	155	58,05 %	24,797	100	216,59	75,14 %	34,39 %
10 %	250						
	270	53,35 %	24,503	175	216,71	82,29 %	30,68 %
	299	50,33 %	24,398		216,58		
	337	78,19 %	22,889		220,32		
	356	61,16 %	23,180	150	220,19	13,12 %	32,49 %
25 %	625						
	648	42,88 %	23.791	230	218,72	59,87 %	23,54 %
	755	42,25 %	23,565		218,58		
50 %	1250	-	-	-	-	-	-
100 %	2500	-	-	-	-	-	-

% of rated power	Pout (W)	Pin (W)
5 %	125	
	155	267
10 %	250	
	270	506
	299	594
	337	431
	356	582
25 %	625	
	648	1511
	755	1787
50 %	1250	-
100 %	2500	-

Figure 3a- Table of numerical results

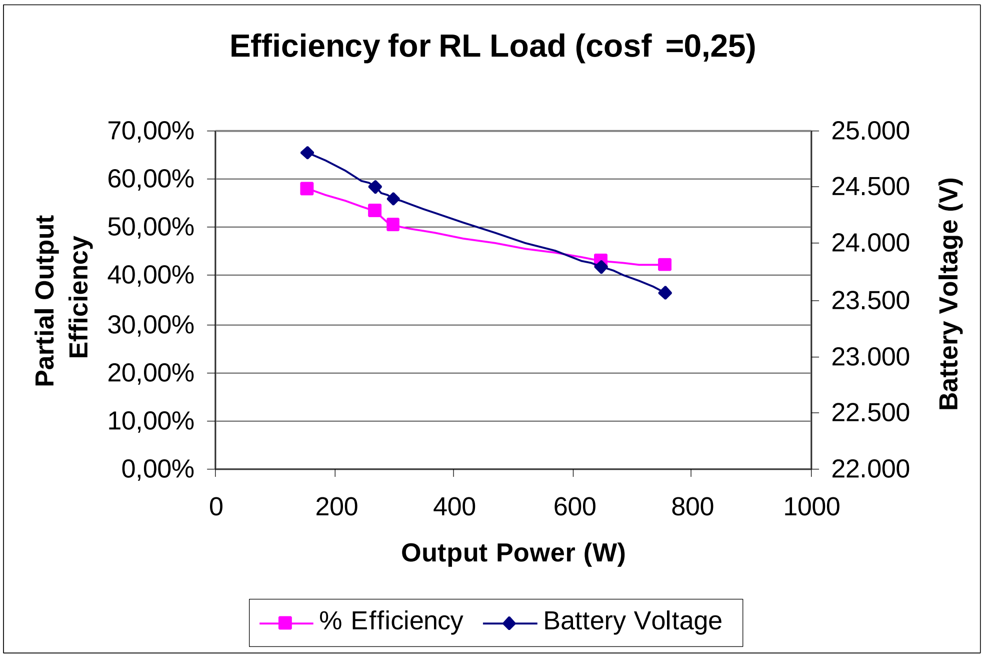


Figure 3b- Graph of the efficiency

Figure 3- Test Results of the stand-alone inverter with a load at power factor of 0,25

Comments

- For the above conditions (reactive load, cosφ=0.25) of the experiment, we were not able to succeed an output power more than 755 W. In fact, the highest value of the inverter's output power, which has been succeeded, is 755 W, equal to a power level of 30.2 % of the inverter's rating. After this value, the inverter couldn't work.
- The inverter cannot produce an output power more that 755 W at power factor of 0.25, because the input current is increased so much, that the inverter cannot work.
- The rated output efficiency of the stand-alone inverter cannot be measured at this case, because we were not able to measure the inverter's output power for the power level of 100 % of the inverter's rating.
- Based on the figure 3b, we are not able to extract a general conclusion for the efficiency of the tested inverter at power factor 0.25, because the efficiency curve is limited, just between the power levels of 6.2 % and 30.2 % of the inverter's rating. However, we can see that a load, which provides a power factor 0.25, is not the ideal condition for the inverter's operation.

A2.2 For Power factor (cos j) 0,50

% of rated power	Pout (W)	n (%)	Vin (V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)	Voltage Distrortion (THDv)
10 %	250						
	263	74,08 %	24,518	75	217,18	54,37 %	31,81 %
	399	73,34 %	24,322		217,41		
	503	71,04 %	24,151		217,85		
	619	70,82 %	24,005	175	218,13	37,05 %	27,22 %
25 %	625						
	777	69,93 %	23,824	160	219,07	22,66 %	29,89 %
	1086	63,80 %	23,392	200	219,43	48,48 %	31,86 %
50 %	1250	63,22 %	23,225	240	219,40	56,03 %	34,75 %
	1485	63,00 %	22,962	250	213,51	53,34 %	35,50 %
	1606	63,35 %	22,926	225	210,76	47,74 %	38,64 %
75 %	1875	-	-	-	-	-	-
100 %	2500	-	-	-	-	-	-

% of rated power	Pout (W)	Pin (W)
10 %	250	
	263	355
	399	544
	503	708
	619	874
25 %	625	
	777	1111
	1086	1702
	1250	1977
	1485	2357
	1606	2535
50 %	1875	-
100 %	2500	-

Figure 4a- Table of numerical results

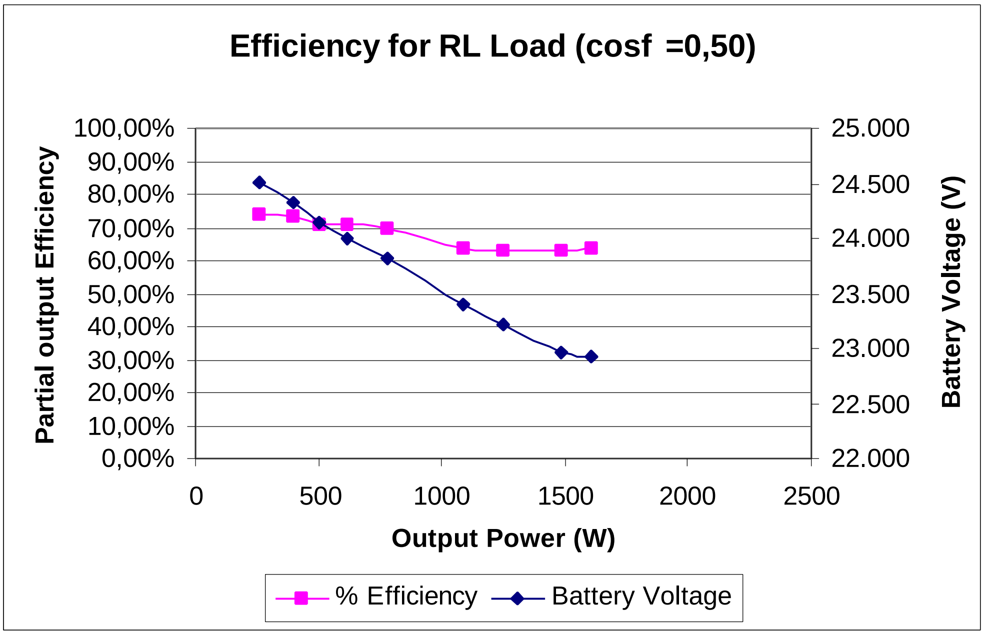


Figure 4b- Graph of the efficiency

Figure 4- Test Results of the stand-alone inverter with a load at power factor of 0,50

Comments

- As in the previous case of the load, which provides a power factor 0.25, here, where the load provides a power factor 0.50, we are not able to succeed an output power of the stand-alone inverter, equal to the inverter's rating power. Therefore, we are not able to measure the rated output efficiency of the Trace Engineering 2524 stand-alone inverter, at power factor 0.50.
- The highest value of the inverter's output power, which has been succeeded during our measurements, was 1606 W, equal to a power level of 64.24 % of the inverter's rating.
- The reason that the stand-alone inverter cannot produce an output power more than 1606 W is here the same, as in measurements with a load, which provides a power factor of 0.25. After the value of 1606 W, the input current was so high, that the inverter couldn't work. However, at the present measurements, we were able to extract a higher value of the output power than before. That happens because now, the power factor has been increased at the value of 0.50.
- The figure 4b shows that when the output power of the inverter is increased, then the voltage of the batteries is decreased. That is rational, because when the

inverter’s input power is increased, the input d.c curent of the inverter is increased as well. So, consequently, the inverter’s input voltage is decreased.

- Figure 4b shows that while the inverter’s efficiency begins at a high value, after it is decreased step by step. Namely, the highest partial efficiency value, which has been measured is 74,08 %, which is not of course an ideal value for the stand-alone inverter.

A2.3 For Power factor ($\cos\varphi$) 0,75

% of rated power	Pout (W)	n (%)	Vin (V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)	Voltage Distrortion (THDv)
	243	81,27 %	24,815	50	217,42	32,63 %	33,21 %
10 %	250						
	492	83,38 %	24,511		217,82		
25 %	625	82,78 %	24,362	105	217,90	24,53 %	28,12%
	673	82,17 %	24,324		217,78		
	845	81,17 %	24,241		218,37		
	924	80,06 %	24,048		218,88	20,82 %	29,09 %
50 %	1250						
	1276	82,80 %	23,873	170	220,25	27,28 %	29,99 %
	1593	79,65 %	23,544		220,84		
	1918	77,99 %	23,249	200	220,79	39,57 %	41,23 %
	2452	66,92 %	22,278	210	187,06	39,11 %	41,01 %
100 %	2500						

% of rated power	Pout (W)	Pin (W)
	243	299
10 %	250	
	492	590
25 %	625	755
	673	819
	845	1041
	924	1154
50 %	1250	
	1276	1541
	1593	2000
	1918	2459
	2452	3664
100 %	2500	

Figure 5a- Table of numerical results

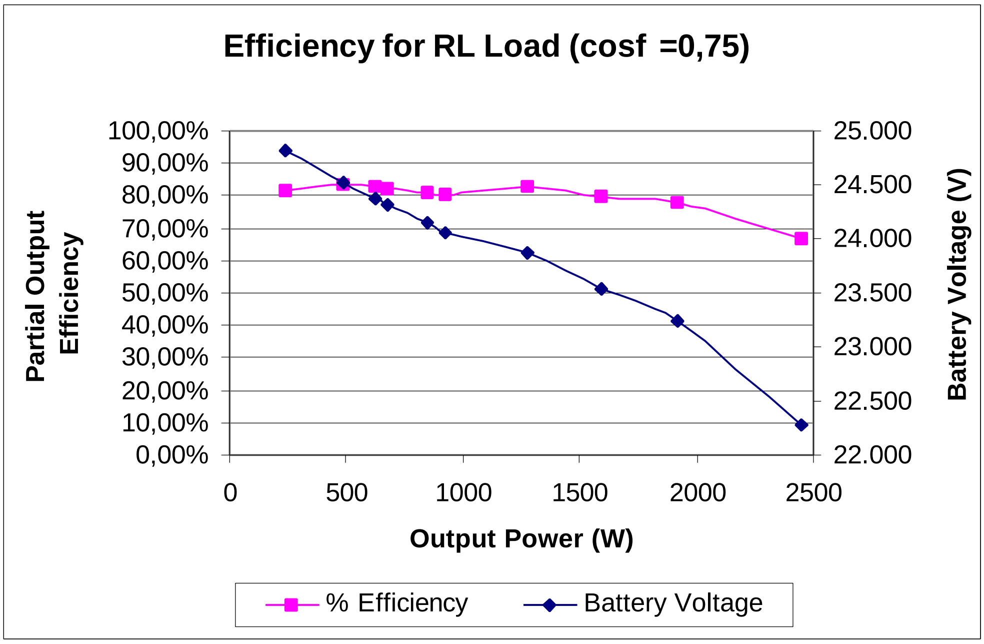


Figure 5b- Graph of the efficiency

Figure 5- Test Results of the stand-alone inverter with a load at power factor of 0,75

Comments

- Based on the formula (1) that is presented in page 19 and using the numerical results of the figure 1a, the rated output efficiency of the Trace Engineering 2524 stand-alone inverter is measured as follows:

$$\mathbf{n_R = (Po / Pi) * 100 = (2452\ W / 3664\ W) * 100 = 66{,}92\ \%}$$

So, the rated power efficiency of the tested inverter at power factor 0.75 is 66,92 %. This value is not of course the best that a modified stand-alone inverter can produce.

- The highest partial efficiency, which is measured is 83,38 %. This value is derived for an output power 492 W, equal to a power level of 19,68 % of the inverter's rating. After this value, the efficiency is decreased.
- The efficiency curve in figure 5b is not very smooth and of course in any case is not linear. The inverter's behaviour seems not to satisfy us completely.

Graphs

of the inverter's input voltage, output voltage, input current and output current

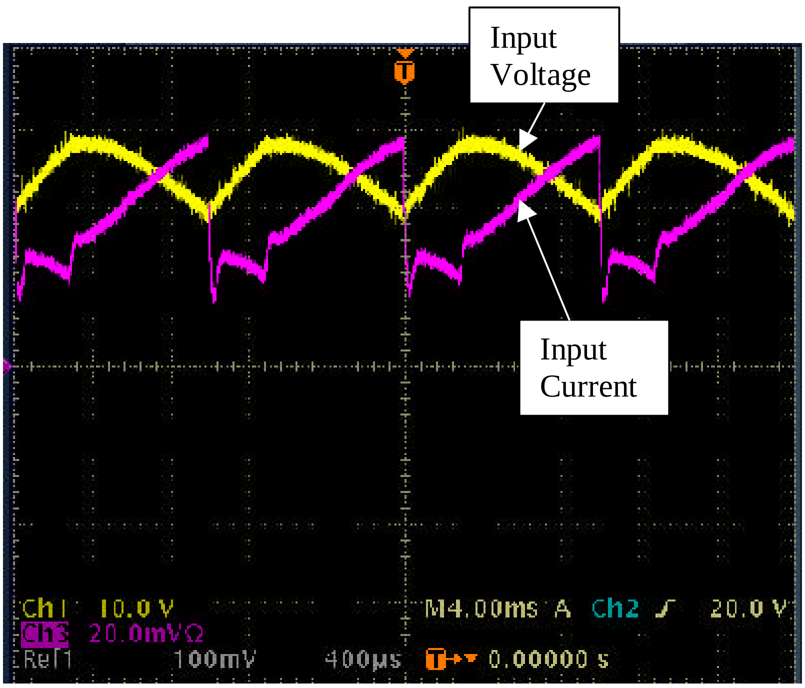
For the Trace Engineering 2524 stand-alone inverter, with a load, which provides a power factor equal to 0.8 and under the conditions, which are presented in the array below, we extract the graphs of the inverter's input voltage, output voltage, input current and output current, using an oscilloscope.

Input	Output
Pin = 1.013 kW	Pout = 907 W

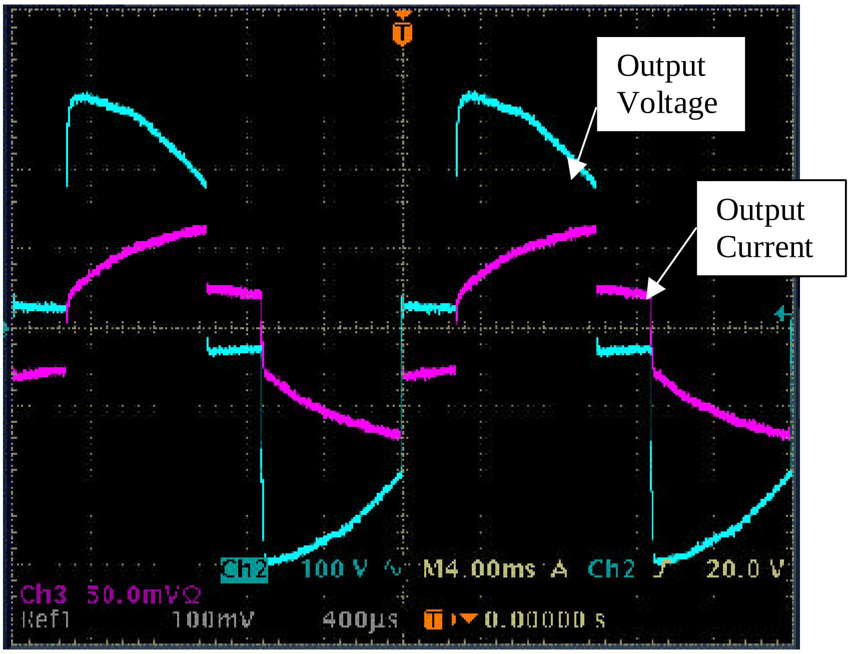
Figure 6- Inverter's conditions
when taking the graphs

The graphs are presented at the next figures.

- **Graph No 1: inverter's input current and voltage**



- **Graph No 2: inverter's output current and voltage**



A3. LOSS MEASUREMENT TEST RESULTS

NO-LOAD LOSS & STANDBY LOSS

As we read in page 26, if the inverter is a stand-alone type, no-load loss is the indicated value of d.c. input power, measured by digital power meter in figure 1 –see page 21-, when the load is disconnected from the inverter, while standby loss is the indicated value of d.c. input power, measured by digital power meter in figure 1, without a.c. or d.c. output voltage.
So, as we can understand, at this case, no-load loss and standby loss have the same value.

The measured data showed that:

Input:
Pinput = 0,007 kW

Therefore, no-load loss is 0,007 kW as well as standby loss is 0,007 kW.

These values are adequately low.

A4. CONCLUSIONS

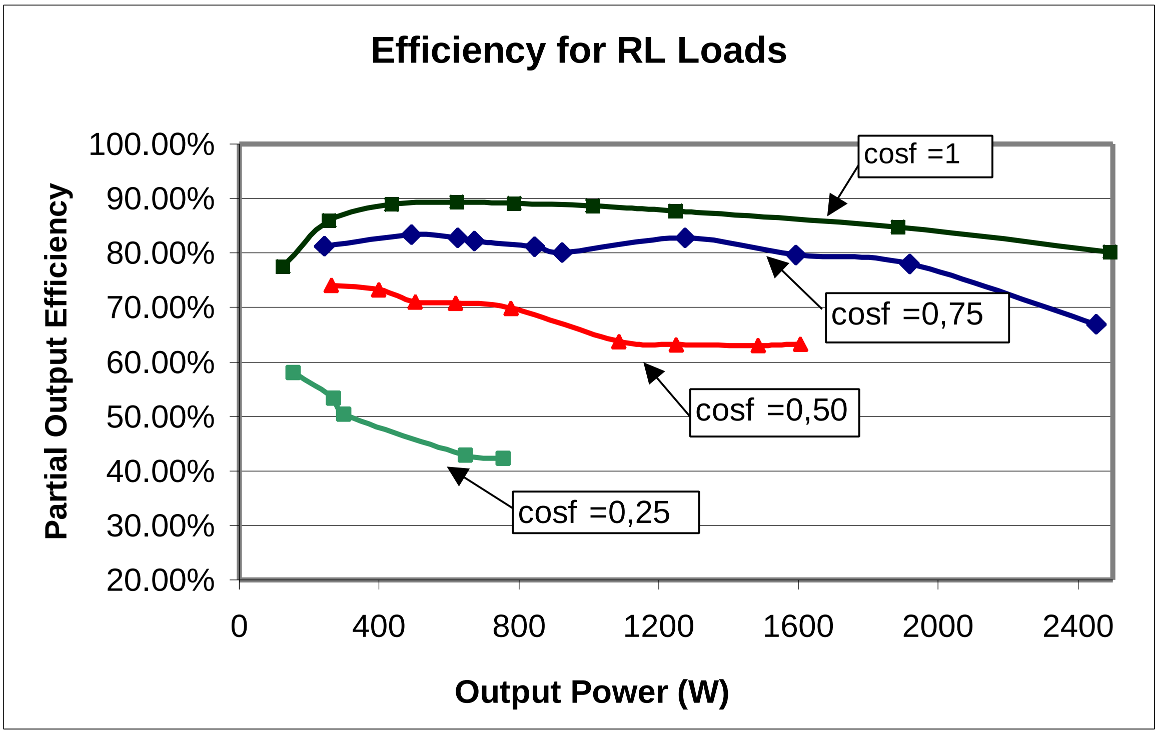


Figure 7- Efficiency curves of the Trace Engineering 2524 stand-alone inverter with a load at power factor of 0.25, 0.50, 0.75 and 1 respectively.

- Based on the above graph, we can easily extract the conclusion that the Trace Engineering 2524 stand-alone inverter has the highest values of partial efficiencies, at unity power factor (cosφ=1). Namely, as much the power factor is increased, as the best for the efficiency of the inverter.
- We realize further, that the inverter's efficiency curve is smoother at unity power factor than the efficiency curves of the inverter at lower power factors. There is no case of linear efficiency curve of course, but as much the power factor is increased, as smoother the curves seem to be.
- In general, the results of the Trace Engineering 2524 stand-alone inverter do not satisfy the up-to-date requirements. The model 2524 of Trace Engineering stand-alone inverter is about five years old now and since the last five years, plenty of other models of modified square wave inverters have appeared –some of Trace Engineering too-, with a more improved efficiency. However, the

opinion that the modified square wave inverters are suitable for resistive loads, which has been written in the introduction of this paper –see page 8, Chapter 1- is verified here, by the results of our experiment.

B. GRID-CONNECTED INVERTER'S TEST RESULTS

B1. AT INVERTER'S MINIMUM RATED INPUT VOLTAGE

Table 1: Input voltage 44 V (Inverter's Minimum Rated Input Voltage)

% of rated kW	Pout (W)	n (%)	Vin(V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)
	142	71,35 %	36,58		228,29	
10 %	250	79,87 %	40,46	7	227,19	44,60 %
	400	83,68 %	42,53		227,33	
25 %	625	89,41 %	43,05	8	228,20	40,10 %
	796	91,17 %	41,70		227,33	
50 %	1250	92,92 %	42,48	10	228,11	33,41 %
	1501	92,59 %	42,77		227,81	
75 %	1875	92,54 %	42,32	12	228,07	24,60 %
	1956	92,48 %	42,41		227,96	
100 %	2500	-	-	-	-	-

% of rated kW	Pout (W)	Pin (W)
	142	199
10 %	250	313
	400	478
25 %	625	699
	796	873
50 %	1250	1345
	1501	1621
75 %	1875	2026
	1956	2115
100 %	2500	-

Figure 8a- Table of numerical results

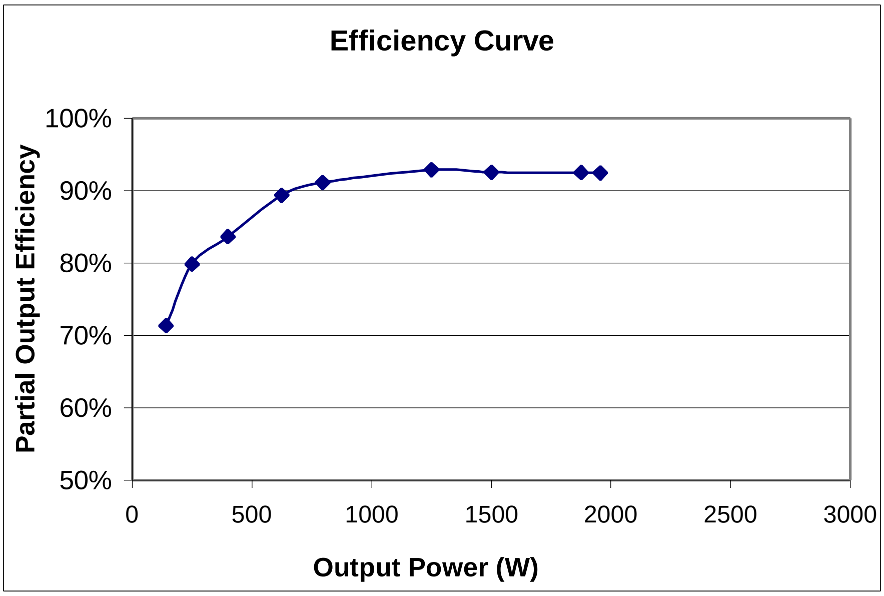


Figure 8b- Efficiency curve

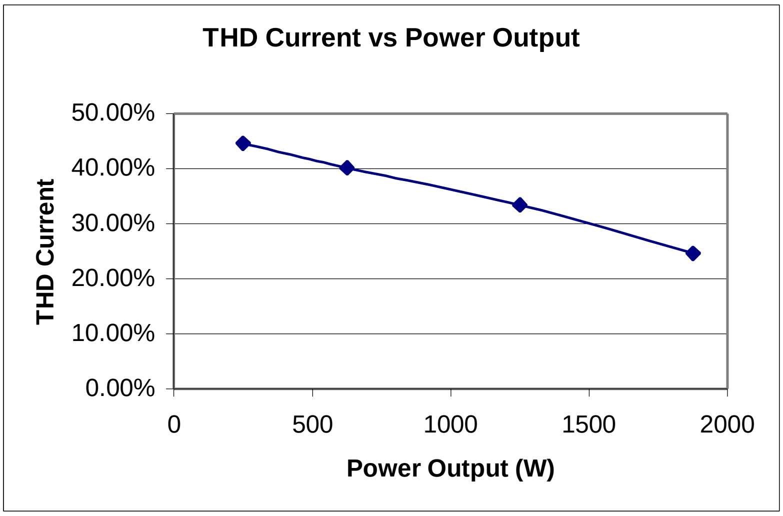


Figure 8c- Graph of THDi vs Power Output

Figure 8- Test Results of the grid-connected inverter at input voltage 44 V

Comments

- Based on both of the numerical results of the figure 8a and the efficiency curve of the figure 8b, we extract the conclusion that the inverter's best partial output efficiency has been derived for power level of 50 % of the inverter's rating. However, for power levels greater than 50 %, the values of the partial output efficiency are not so much different. In general, the efficiency of the grid-connected inverter, for power levels greater than 50 % of the inverter's rating, remains at the same almost values. That is a very important characteristic of the inverter, because after it succeeds an output power equal to 1250 W, it follows an almost constant performance.
- In order to produce an inverter's input voltage equal to 44 V, we used two power supplies, as it is shown in figure 2 of the second chapter, (see page 21). The power supplies were manually programmable. So, each time, the power supplies were programmed to provide an output voltage of 44 V, equal to the inverter's input voltage. However, as we can see in figure 8a, the power supplies were not able to provide a total output voltage equal to 44 V. So, the input voltage of the grid-connected inverter was increasing, only when the output power of the inverter was increasing as well. Namely, at this part of the experiment, the power supplies were able to provide a final maximum output voltage, equal to 42,41 V.
- After the value of 42,41 V, the power supplies couldn't work. So, the rated output efficiency of the grid-connected inverter could not be measured at this case, as we were not able to measure the inverter's output power for the power level of 100 % of the inverter's rating.
- The distortion of the output current (THDi) is decreased as the output power and the partial output efficiency of the grid-connected inverter are increased.

Graphs

of the inverter's input voltage, output voltage, input current and output current

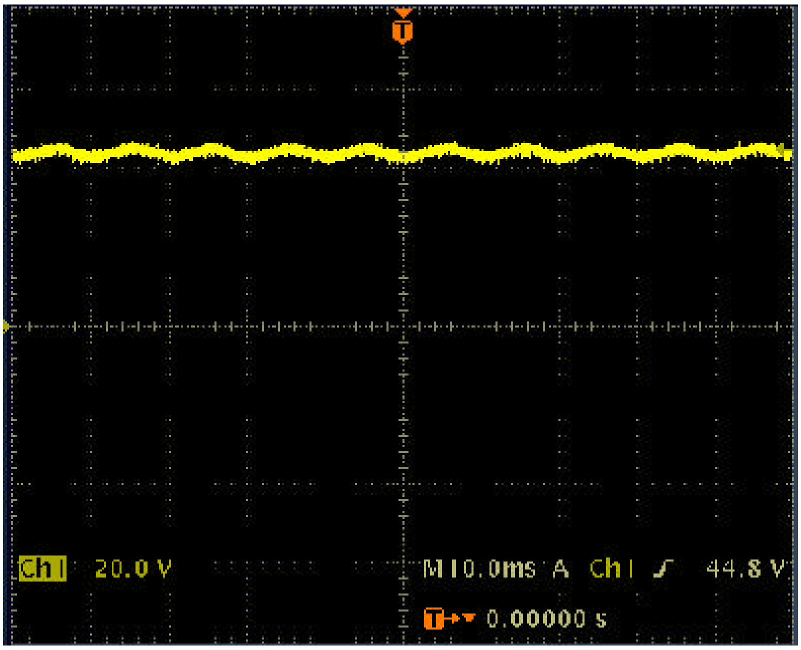
At an input voltage of the grid-connected inverter equal to its minimum rated input voltage and under the conditions, which are presented in the array below, we extract the graphs of the inverter's input voltage, output voltage, input current and output current, using an oscilloscope.

Input	Output
Pin = 2026 W	Pout = 1875 W

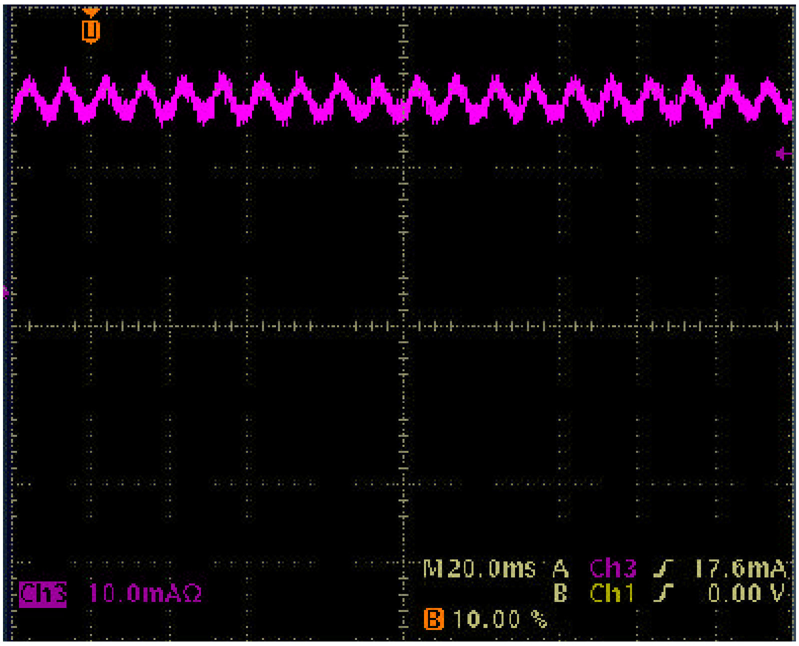
Figure 9- Inverter's conditions
when taking the graphs

The graphs are presented at the next figures.

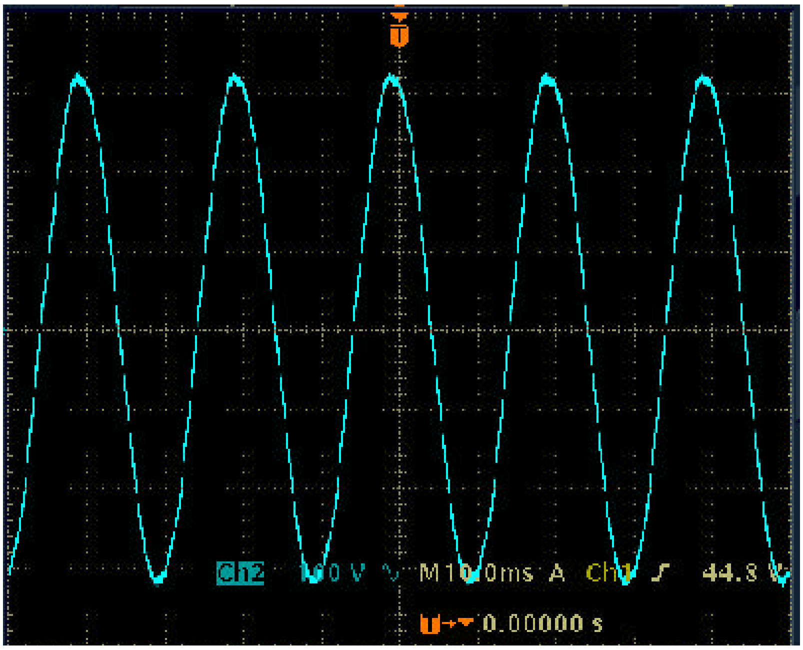
- **Graph No 1: inverter's input voltage**



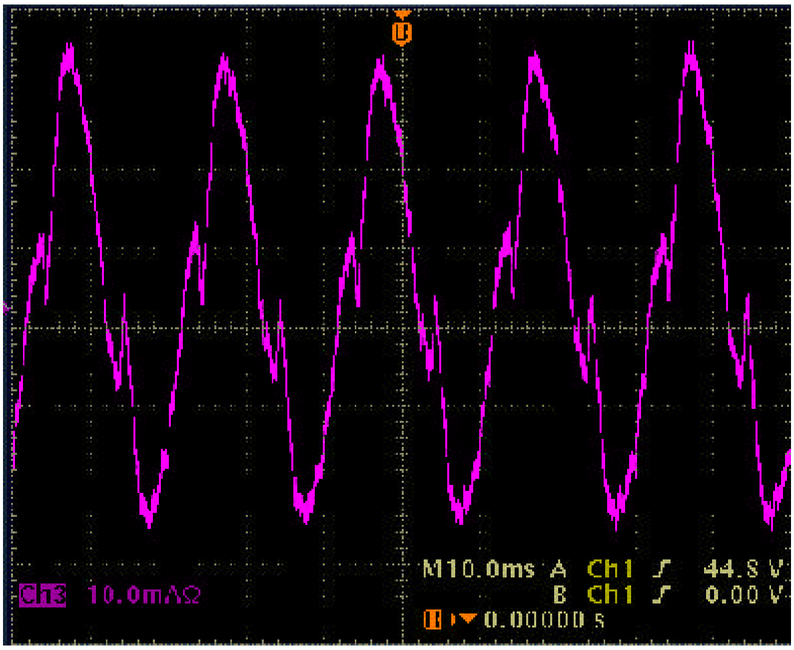
- **Graph No 2: inverter’s input current**



- **Graph No 3: inverter’s output voltage (grid)**



- **Graph No 4: inverter’s output current**



B2. AT INVERTER'S NOMINAL INPUT VOLTAGE

Table 2: Input voltage 48 V (Inverter's Nominal Input Voltage)

% of rated kW	Pout (W)	n (%)	Vin(V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)
	160	75,11 %	39,04		225,24	
10 %	250	79,81 %	43,79	7	225,54	43,80 %
	402	83,75 %	46,94		225,38	
25 %	625	89,12 %	47,41	8	225,82	41,14 %
	1014	91,93 %	46,87		226,25	
50 %	1250	92,57 %	47,22	12	226,17	34,60 %
	1402	92,90 %	47,27		225,13	
75 %	1875	92,59 %	45,10	10	225,22	24,60 %
	2094	92,45 %	42,40		225,07	
100 %	2500	-	-	-	-	-

% of rated kW	Pout (W)	Pin (W)
	160	213
10 %	250	313
	402	480
25 %	625	701
	1014	1103
50 %	1250	1347
	1402	1509
75 %	1875	2025
	2094	2265
100 %	2500	-

Figure 10a- Table of numerical results

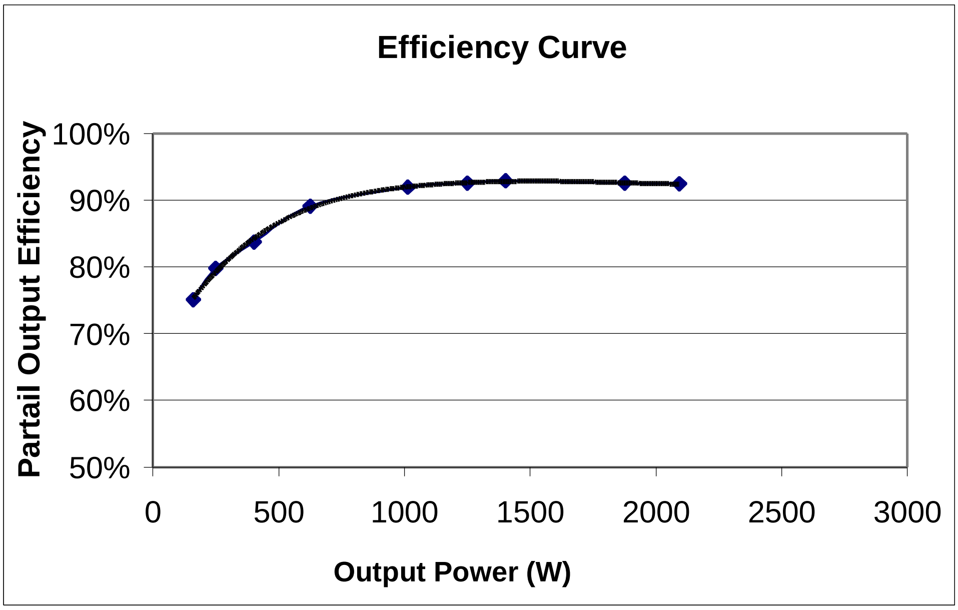


Figure 10b- Efficiency curve

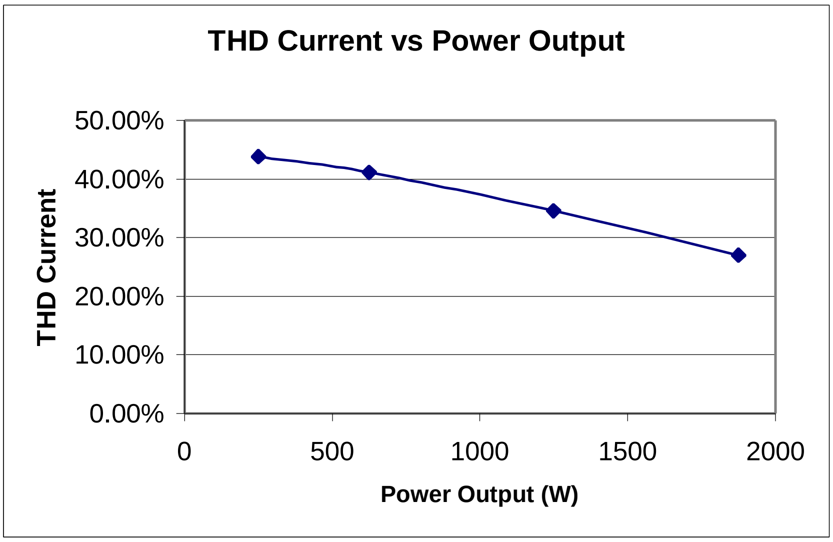


Figure 10c- Graph of THDi vs Power Output

Figure 10- Test Results of the grid-connected inverter at input voltage 48 V

Comments

- Based on both of the numerical results of the figure 10a and the efficiency curve of the figure 10b, we extract the conclusion that the inverter's best partial output efficiency has been derived for power level of 56,08 % of the inverter's rating.
- In general, the efficiency of the grid-connected inverter, for power levels greater than 50 % of the inverter's rating, remains at the same almost values. It happened the same, at an input voltage equal to the inverter's minimum rated voltage. So, as we mentioned in the comments of the last test, that is a very important characteristic of the inverter, because after the inverter succeeds an output power equal to 1250 W, it follows an almost constant performance.
- For the same reason that we explained in the comments of the previous test at an input voltage equal to 44 V, here the power supplies were not able to provide a final output voltage equal to 48 V. Namely, at this part of the experiment, the power supplies were able to provide a final maximum output voltage, equal to 45,40 V, while they were programmed from us, to provide an output voltage of 48 V.
- After the value of 45,40 V, the power supplies couldn't work. So, as in the previous test, the rated output efficiency of the grid-connected inverter could not be measured at this case, because we were not able to measure the inverter's output power for the power level of 100 % of the inverter's rating.
- Figure 10c shows that the distortion of the output current (THDi) is decreased, as the inverter's output power and partial output efficiency are increased.

Graphs

of the inverter's input voltage, output voltage, input current and output current

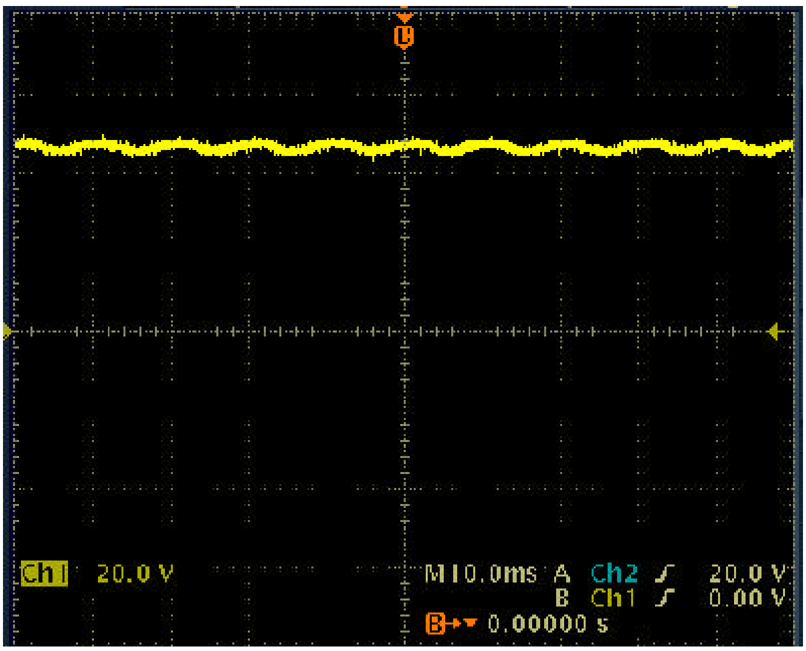
At an input voltage of the grid-connected inverter equal to its nominal input voltage and under the conditions, which are presented in the array below, we extract the graphs of the inverter's input voltage, output voltage, input current and output current, using an oscilloscope.

Input	Output
Pin = 2025 W	Pout = 1875 W

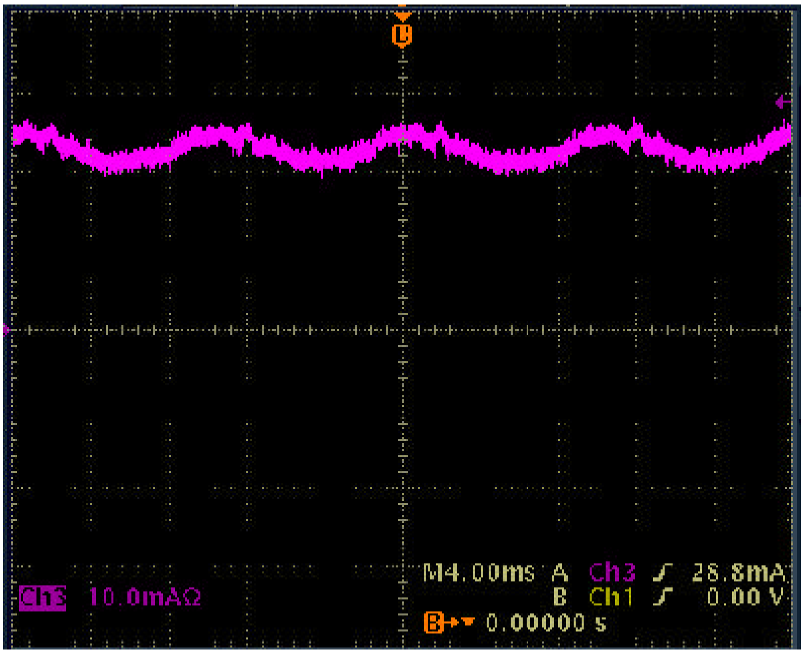
Figure11- Inverter's conditions
when taking the graphs

The graphs are presented at the next figures.

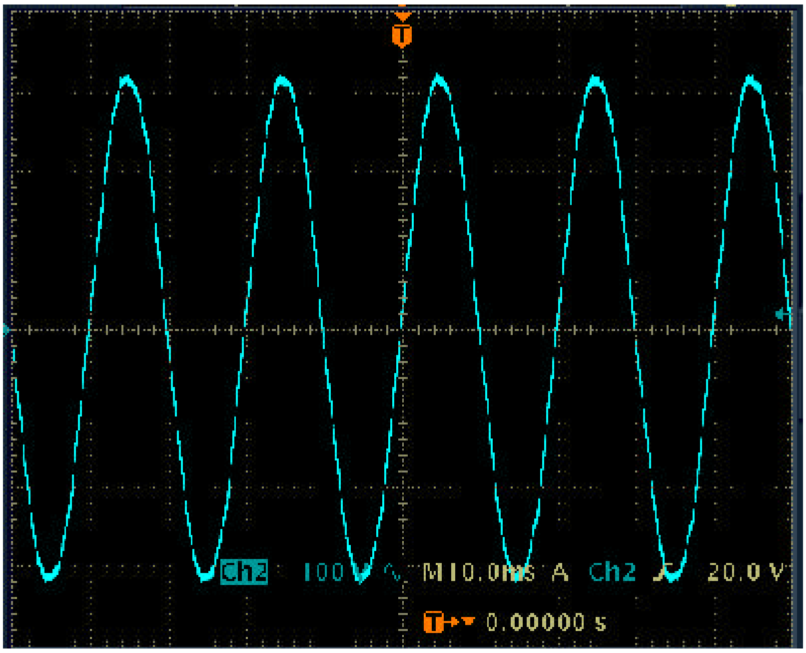
- **Graph No 1: inverter's input voltage**



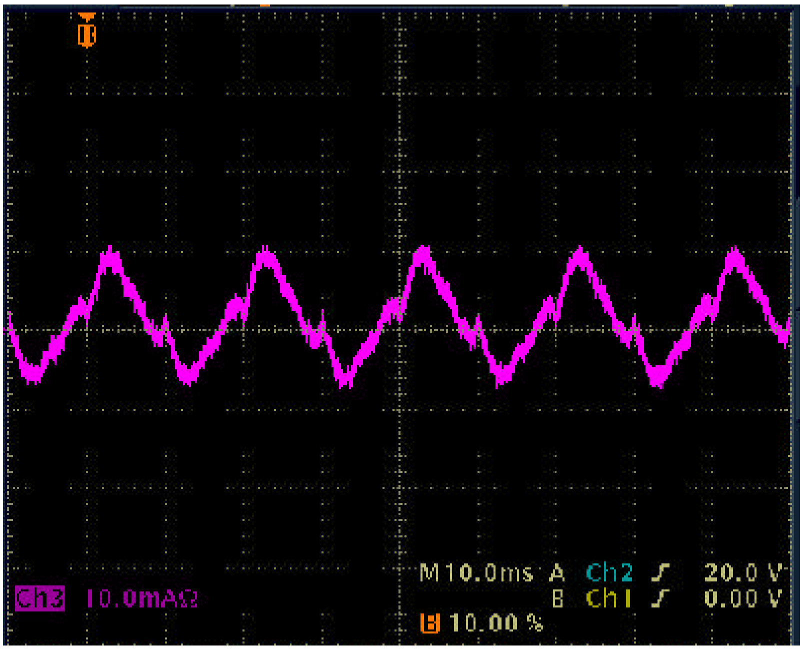
- **Graph No 2: inverter's input current**



- **Graph No 3: inverter's output voltage (grid)**



- **Graph No 4: inverter's output current**



B3. AT INVERTER' MAXIMUM INPUT VOLTAGE

Table 3: Input voltage 59,4 V (Inverter's Maximum Input Voltage)

% of rated kW	Pout (W)	n (%)	Vin (V)	Current Ripple (A)	Vout (V)	Current Distortion (THDi)
	102	58,60 %	50,33		224,64	
10 %	250	75,52 %	54,83	8	224,73	50,40 %
	294	75,38 %	56,18		223,91	
	424	81,38 %	56,48		224,16	
25 %	625	85,96 %	56,58	9	226,38	47,78 %
	1002	89,70 %	57,50		227,41	
50 %	1250	91,44 %	56,65	10	227,52	39,70 %
	1555	91,74 %	57,38		228,33	
75 %	1875	92,08 %	57,76	12	227,31	29,44 %
	2004	91,96 %	57,88		226,65	
100 %	2500	91,20 %	57,72	12	227,43	23,12 %
	2630	91,28 %	57,74		226,36	

% of rated kW	Pout (W)	Pin (W)
	102	174
10 %	250	331
	294	390
	424	521
25 %	625	727
	1002	1117
50 %	1250	1367
	1555	1695
75 %	1875	2036
	2004	2179
100 %	2500	2741
	2630	2881

Figure 12a- Table of numerical results

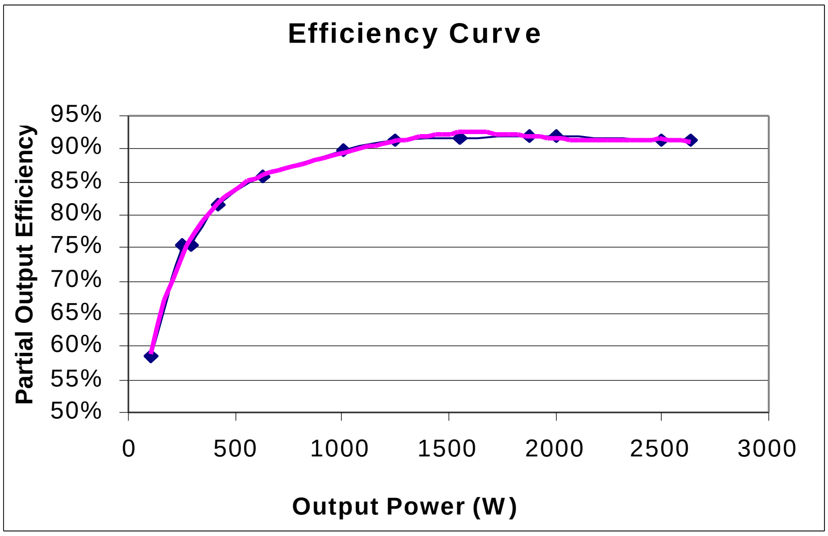


Figure 12b- Efficiency curve

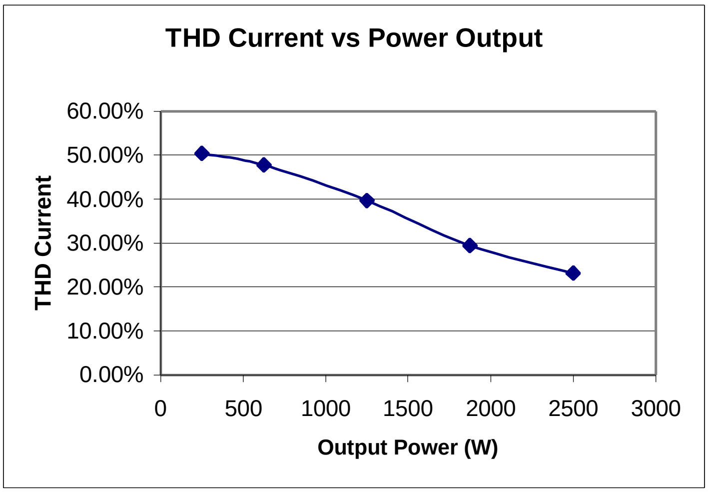


Figure 12c- Graph of THDi vs Power Output

Figure 12- Test Results of the grid-connected inverter at input voltage 59,4 V

Comments

- Based on the figures 12a and 12b, we extract the conclusion that the inverter's best partial output efficiency has been derived for power level of 75 % of the inverter's rating.
- The rated output efficiency of the tested grid-connected inverter at input voltage equal to 90 % of the inverter's maximum input voltage, is calculated based on the formula (1), which is presented in chapter 2, page 19, and using the numerical results of the figure 12a, as follows:

  n_R = (Po / Pi) * 100 = (2500 W / 2741 W) * 100 = 91,20 %

  Therefore, the rated power efficiency of the tested inverter at input voltage equal to 59,4 V is 91,20 %.
  Of course, writing that the inverter input voltage is equal to 59.4 V, we mean that the power supplies have been programmed by us, to provide an output voltage of 59,4 V, while actually, they were able to provide only a maximum voltage equal to 57,74 V.
- The inverter's partial output efficiency, after the power level of 50 % of the inverter's rating, remains almost the same. Namely, firstly it is increased a little, until to succeed its maximum value at output power equal to 1875 W, while after it is decreased, until the value of 91,28 %, at the inverter's output power of 2630 W.
- The distortion of the output current (THDi) has a value of 50,40 % for power level of 10 % of the inverter's rating, while this value is reduced at 23,12 % for power level of 100 % of the inverter's rating. Figure 12c shows that the current distortion is decreased, while the output power and the partial output efficiency of the tested grid-connected inverter are increased.

B4. LOSS MEASUREMENT TEST RESULTS

NO-LOAD LOSS

As we wrote in page 26, if the inverter is a grid-connected type, no-load loss is the indicated value of d.c. input power measured by digital power meter in figure 2 –see page 21-, when the same digital power meter indicates a zero value as the value of the a.c. output voltage.

Namely, the device that we measured, showed:

Input:	Output:
Pinput = 0,023 kW	Poutput = 0 W

Therefore, the no-load loss is 0,023 KW.

STANDBY LOSS

If the inverter is a utility-interactive type, standby loss is also indicated with digital power meter in figure 2 –see page 21-, at the rated output voltage.

So, the device that we measured, showed:

Output:
Poutput = 0,039 kW

Therefore, standby loss is 0,039 KW.

The values of the no-load and standby losses are adequate low.

B5. HARMONICS

With an ideal inverter, the electricity supplied to the grid would consist only of the 50 Hz fundamental frequency. With real inverters, the solar electricity has a certain harmonic content. However, electronic devices, which are connected to the low-voltage grid, must comply with the general regulations for harmonics.

Harmonic currents

The digital power meter, which is used in the test circuit of the grid-connected inverter, -see figure 2, page 21-, is able to provide a list of the harmonic currents of the inverter. Thus, for power level of 25 % of the inverter's rating, we extract the results of the first and second columns of the array below. The third column consisted of the limits for harmonic current emission (equipment input current ≤ 16 A per phase), which are based on harmonics standard IEC 1000-3-2.

Harmonic Order	Harmonic Amplitude	Limits for Harmonic Current
2	0.463	1.08
3	1.536	2.3
4	0.127	0.43
5	1.369	1.14
6	0.086	0.3
7	0.674	0.77
8	0.023	0.23
9	0.322	0.4
10	0.042	0.184
11	0.406	0.33
12	0.014	0.153
13	0.266	0.21
14	0.019	0.131
15	0.282	0.15
16	0.013	0.115
17	0.067	0.132
18	0.007	0.102
19	0.11	0.118
20	0.007	0.092
21	0.142	0.107
22	0.016	0.083
23	0.036	0.097
24	0.01	0.076
25	0.15	0.09
26	0.018	0.07
27	0.028	0.083
28	0.006	0.065
29	0.033	0.077
30	0.002	0.061
31	0.06	0.072
32	0.006	0.057
33	0.052	0.068
34	0.019	0.054
35	0.042	0.064
36	0.01	0.051
37	0.034	0.06
38	0.004	0.048
39	0.046	0.057
40	0.025	0.046
41	0.07	
42	0.01	
43	0.012	
44	0.008	
45	0.025	
46	0.002	
47	0.026	
48	0.016	
49	0.044	
50	0.002	

Figure 13- Harmonic currents for power level 25 % of the inverter's rating.

Based on the array of the previous page, we draw the next graph.

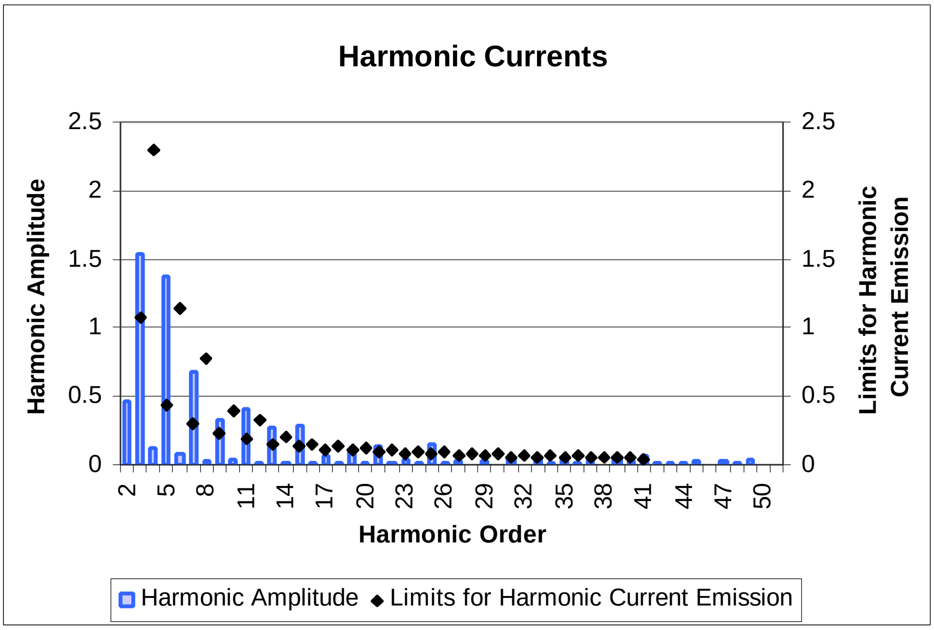


Figure 14- Current Harmonics of the tested grid-connected inverter at Pac=625 W compared to limits of IEC 1000-3-2.

By the same way, we measure the harmonic currents of the Total Energie inverter, for power levels of 50 % and 84,2 % of the inverter's rating. The results are represented at the next two graphs, respectively.

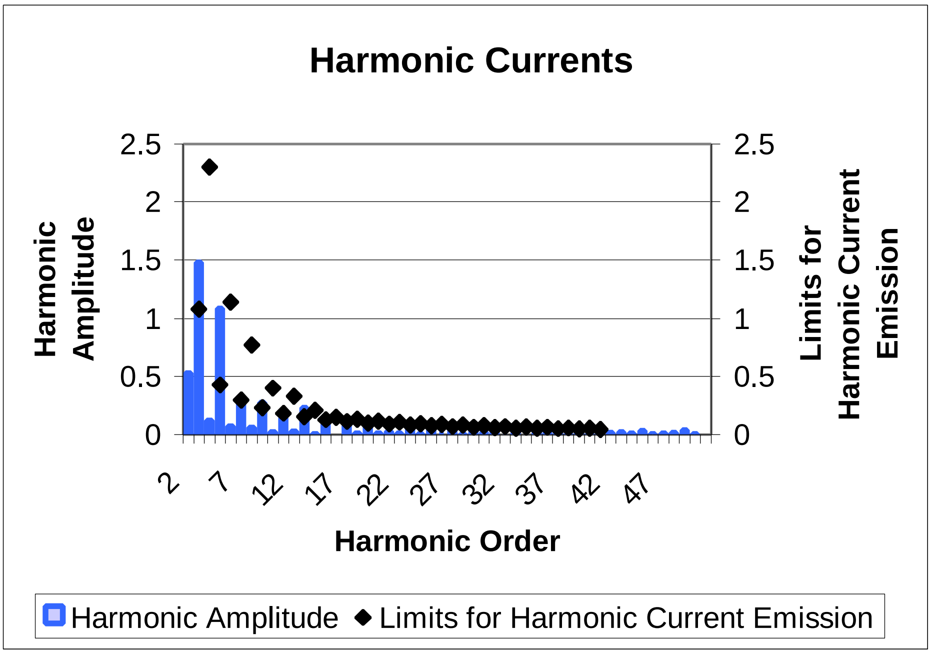


Figure 15- Current Harmonics of the tested grid-connected inverter at Pac=1250 W compared to limits of IEC 1000-3-2.

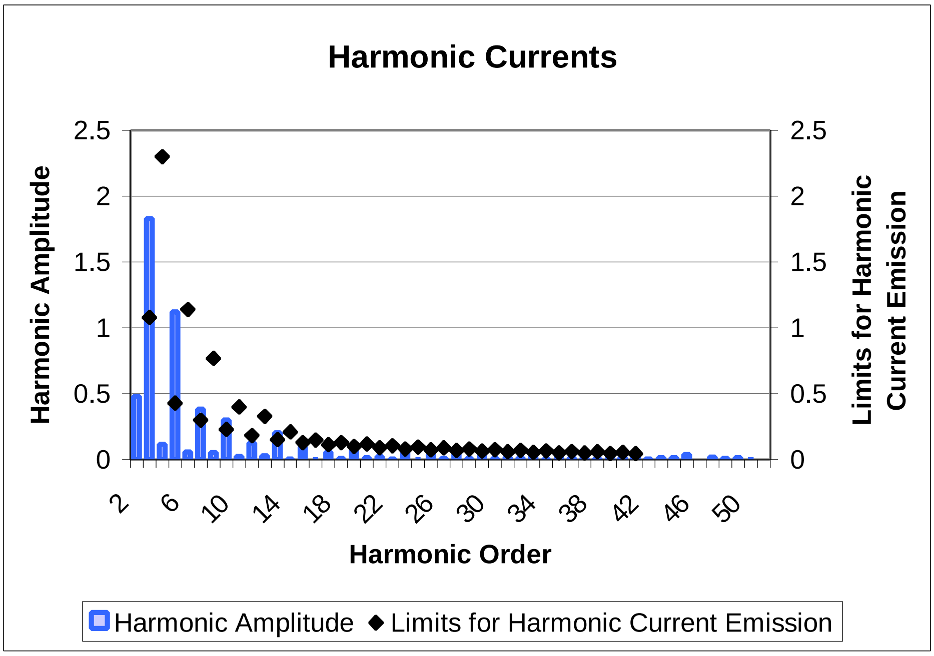


Figure 16- Current Harmonics of the tested grid-connected inverter at Pac=2105 W compared to limits of IEC 1000-3-2.

Comments

- Based on the figures 14, 15, and 16, we can see that harmonic currents injected into grid by the tested inverter are mostly below the limits of IEC 1000-3-2, (equipment input current ≤ 16 A per phase). Sometimes only, at the first harmonic components, there are some cases where the harmonic currents are not below the limits. However, the majority of them are below the limits.
- The systems of electrical energy "filter" the harmonics of current, so, the first harmonic components are the most important components that may affect the result.

Harmonic voltages

Using again the same instrument, namely the digital power meter, –see figure 2, page 21-, we measure the voltage harmonics of the tested Total Energie grid-connected inverter, for power levels of 25 %, 50 % and 84,2 % of the inverter's rating. The extracted results are represented at the next three graphs respectively.

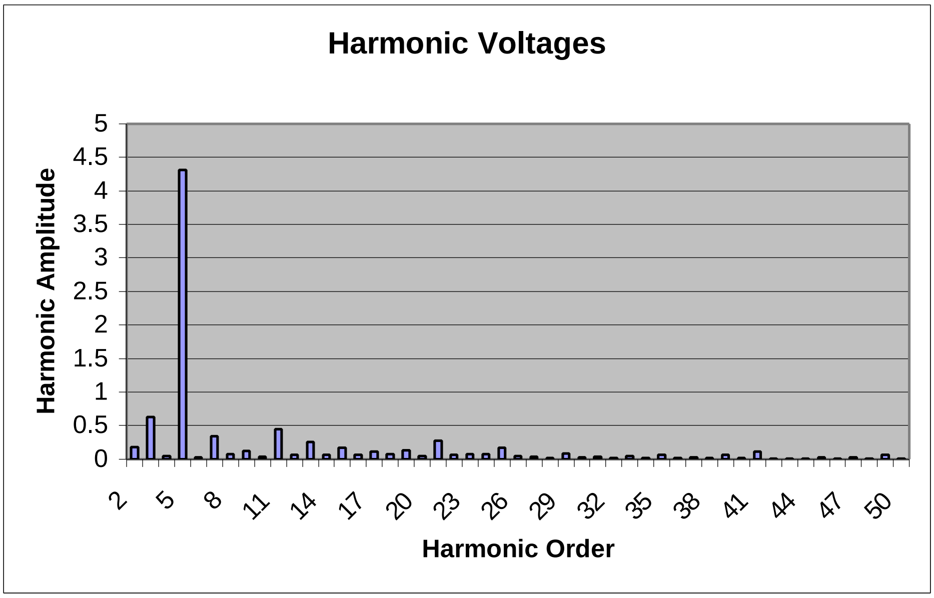


Figure 17- Voltage Harmonics of the tested grid-connected inverter at Pac=625 W

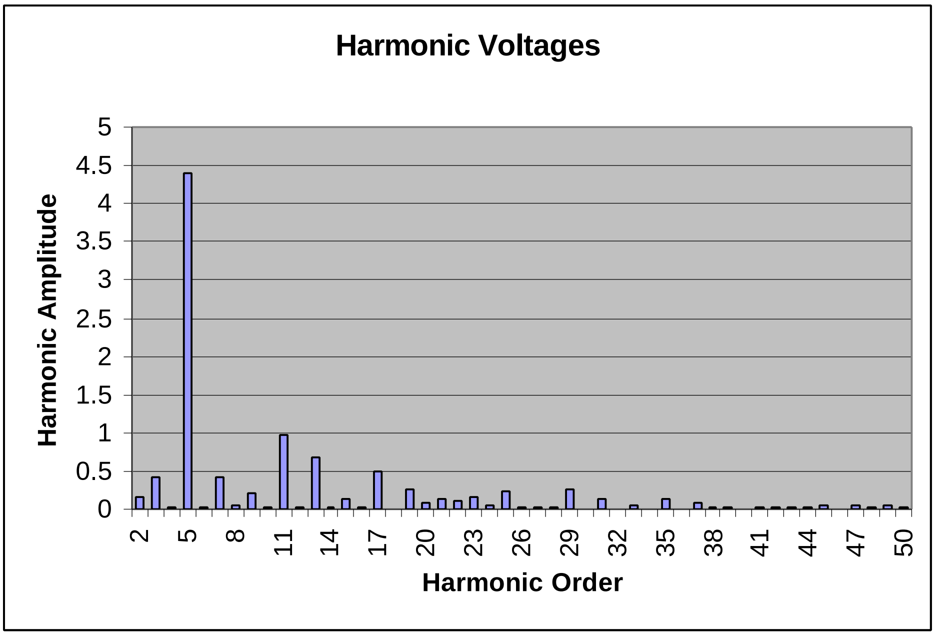


Figure 18- Voltage Harmonics of the tested grid-connected inverter at Pac=1250 W

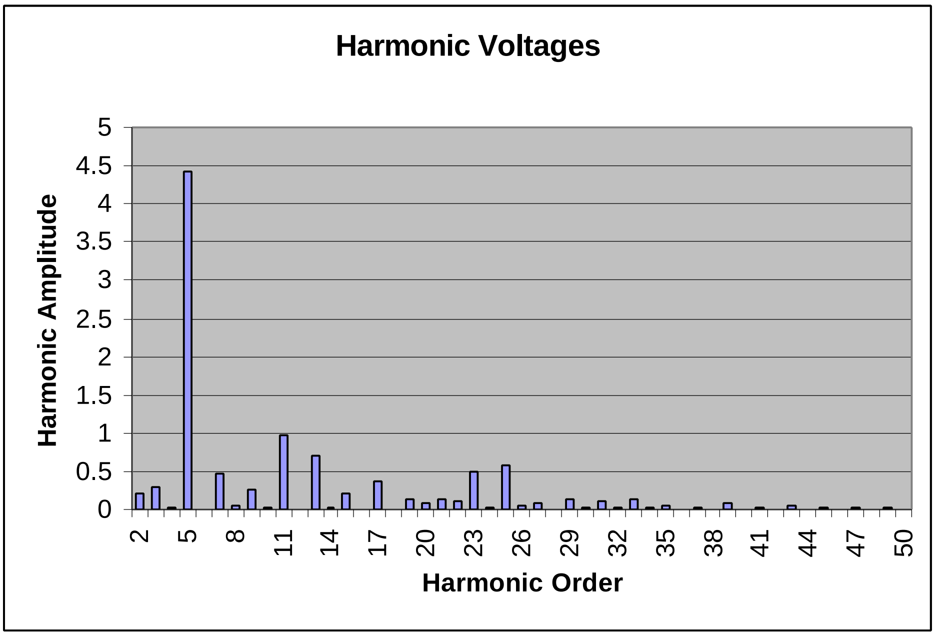


Figure 19- Voltage Harmonics of the tested grid-connected inverter at Pac=2105 W

Comments

- Figures 17, 18 and 19 show that only the first voltage components have high amplitude, which probably could affect the final result. However, We realise again, that the systems of electrical energy “filter” the harmonics of voltage; therefore, the first harmonic components are the most important components that may affect the result.

B6. CONCLUSIONS

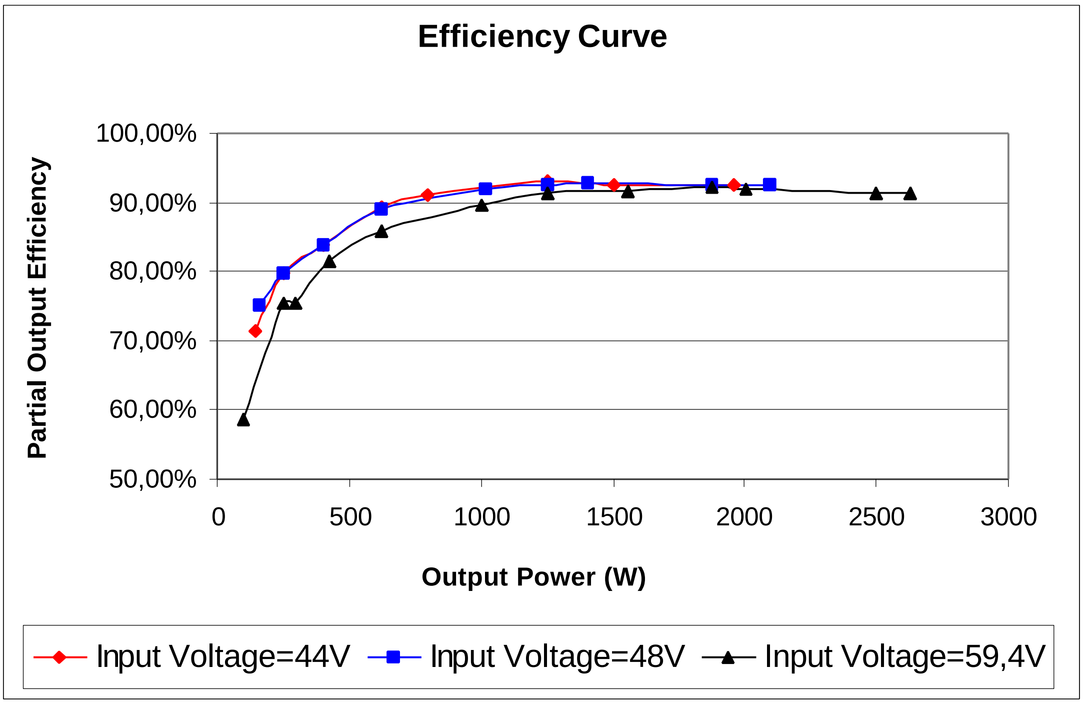


Figure 20- Efficiency curves of the grid-connected inverter at input voltages 44 V, 48 V and 59,4 V

- All the grid-connected inverter's efficiency curves, which are presented at the above figure, are smooth curves, which show that the tested inverter has a very good performance at inverter's input voltage equal to the inverter's minimum rated input voltage, to the inverter's nominal voltage and to 90 % of the inverter's maximum input voltage as well. Actually, the partial efficiency values of the inverter are higher at input voltages equal to the minimum rated input voltage and to the inverter's nominal voltage. At these two input voltages, the efficiency curves are almost the same.
- For all the three above cases of the inverter's efficiency curve, the partial output efficiency remains each time at the same almost values, after power level of 50 % of the inverter's rating. It means that at every one of the three different input voltages of the inverter, its performance remains almost constant.

- In general, based on the results of our experiment, we can say that the performance of the Total Energie grid-connected inverter (Model Onbuleur Joule Prg) is very good. It seems to satisfy the up-to-date requirements of the customers for an inverter, which runs most of the loads, while its design, which is based on the combination of three transformers, -see chapter 2, pages 31 & 32-, seems to be very efficient.

In Conclusion

Many different approaches to inverter design and topology have been attempted. As discussed, all have strong points as well as weaknesses. The “perferct” inverter has yet to be invented, but if it were it would be 100 % efficient with infinite power and a sine wave output. However, since nothing is free in life, we must continue to make due with present technology and move forward, as semiconductors become batter and better.

Acknowledgements

The author gratefully acknowledge all the scientists of the Photovoltaic Department of the Centre for Renewable Energy Sources in Greece for supporting the work presented in this paper.

Namely, sincere thanks to the head of the Photovoltaic Department **Dr. Christos Protogeropoulos** for offering author a place at the Power Electronics Lab of the Photovoltaic Department and providing him all the necessary stuff.

Further, many thanks to **Ioannis Nikoletatos** & **Aristomenis Neris** for providing the necessary theoretical background about inverters different topologies and designs and **George Panagopoulos** for supporting the configuration of the experimental test circuits of the stand-alone and grid-connected inverters.

The present project has finally carried out under the direction of the professor **Dr. Slobodan Jovanovic**. Many thanks to my professor for his advise.

References

[1] International Electrotechnical Commission: IEC 61683.
Photovoltaic systems-Power conditioners-Procedure for measuring efficiency: all parts;
first edition, 1999-11.

[2] International Electrotechnical Commission: IEC 1000-3-2.
EMC: Part 3, Section 2;
Limits for harmonic current emission (equipment input current < 16 A per phase); first edition, 1995-03.

[3] H. Haeberlin, F. Kaeser, Ch. Liebi and Ch. Beutler: "Results of Recent Performance and Reliability Tests of the Most Popular Inverters for Grid Connected PV Systems in Switzerland"
Proc. 13th EU PV Conference, October 1995, Nice, France.

[4] Trace Engineering: " A review of Inverter Design and Topologies";
© Trace Engineering Company, Rev 2/00.

[5] Chapter 5: "Inverters for Photovoltaic Systems"
Course book for the seminar "Photovoltaic Systems";
Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, ©1995.