ANALELE UNIVERSITĂŢII
"EFTIMIE MURGU" REŞIŢA
ANUL XXI, NR. 3, 2014, ISSN 1453 - 7397

Nicolae Badea, Madalin Costin

Gas Boiler Powered by the Fuel Cell System

The paper presents a new solution for supply of boilers with electrical energy in the order to achieve autonomy from electrical grid. The paper presents the experimental system implemented in the university lab, the components and implementation in Matlab-Simulink for simulation. As a result of numeric simulation performed, the experimental bench has been achieved. The problem of power quality, especially the THD factor, affects the sensitivity of equipment at perturbations. In achieving of these systems, the authors propose that the electrical part of the supply system for building appliances must satisfy the EN 50160 standard, having the main voltage parameters and their permissile deviation ranges at the customer's point of common coupling in public low voltage (LV), under normal operating conditions.

Keywords: PEM fuel cell, renewable source, power quality, hydrogen

1. Introduction

The need to introduce several 'environment friendly' installations (like microturbines, fuel cells, photoelectric installations and other advanced technologies for distributed generation) have determined an increase in the interest for distributed generation, particularly for local ('on-site') generation. Introducing environment friendly installations implies the implementation of two concepts: distributed energy resources (DER) and renewable energy sources (RES). In fact, DER concept encompasses three main aspects, whose focus is set on the electrical standpoint:

- Distributed generation (DG), which is local energy production from various types of sources [1,2]. Distributed generation has emerged as a key option for promoting energy efficiency and use of renewable sources as an alternative to the traditional generation.
- Demand response (DR) that is energy saving brought by the customer participation to specific programmes for reducing the peak power or the energy consumption [3, 4]. Demand response (DR) implies not only satisfying the consumer's electric energy demand, but ensuring any form of energy demanded by the consumer

(heat, air conditioning, etc.) also, at any moment and in the specific quantities necessary to the consumer.

• Distributed storage (DS): local energy storage with different types of devices [5].

In the case of a residence, implementing the DER concept consists of achieving the system for energy production on the basis of the convenient association of three key ideas:

• combined production of heat and power, from the same fuel, in the same system, resulting in a so-called Combined Heat and Power system (CHP system);

• simultaneous use of more sources of energy (fossil fuel, sun, geothermal sources etc) and their integration in a system;

• placing the cogeneration installations as close to the final consumer as possible and dimensioning them so that they may offer the amount of heat and electricity necessary for the consumer, resulting in a local system for producing electric and thermal energy, in the specific quantities necessary to satisfy the useful energy needs of each consumer at any given moment in time.

2. Energy supply solutions for buildings

To satisfy the demand for electric energy of the residence, the following systems may be used:

Centralized energy producing system. In this case, the residence is connected to the electricity grid. The thermal energy demand for heating the residence or for cooling the air in the residence must be ensured with a system which contains equipment installed in the residence. This system includes a conventional condensing boiler (with 90% thermal efficiency) providing heat for space heating and sanitary uses (hot water), and a conventional compressing refrigerator which supplies cold for air conditioning (Error! Reference source not found.).

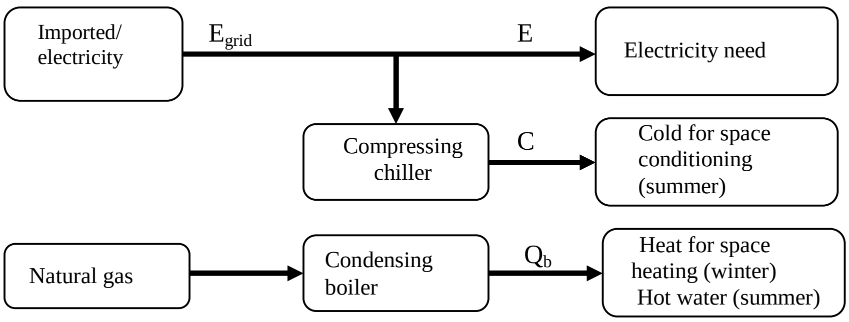


Figure 1. Centralized energy producing system.

Where: Egrid- the quantity of electricity consumed from the grid; Qb- the heat produced by the boiler.

Decentralized energy producing system. In the case of the decentralized system, two solutions are applied for the supply with electricity: On-grid (or open) system or Of-grid (or "isolated") system. This system (Figure 2) includes also a condensing boiler fueled with hydrogen or natural gas that provides the heat for space heating and sanitary uses (hot water) and where the power supply for boiler operation is ensured by the fuel cell and inverter. The hydrogen production is possible by reforming the natural gas or water electrolysis. The second solution, compared to other applications, consists of hydrogen production by water electrolysis from photovoltaic panels.

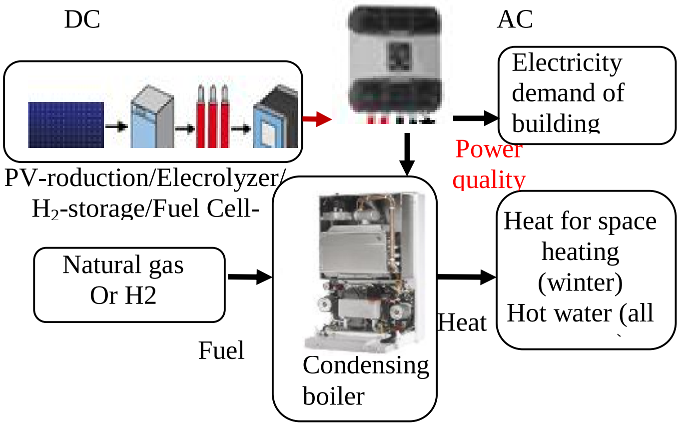


Figure 2. DER solution for the energy supply of boiler

3. New solution of the energy supply of building

The concept of this system is to get the energy supply using fuel cell technology and hydrogen production by renewable sources. The hydrogen production can be made using electrolyses with reversible PEM fuel cell powered by photovoltaic panels. The hydrogen produced by the reversible PEM fuel cell (electrolyser) during summer provides the necessary stock for the cell to function the longest period of time possible, e.g in winter season. Electricity production is achieved with a hydrogen powered fuel cell. To adapt the DC electricity into AC is necessary DC -DC boost converter and inverter(fig.3). The system has two subsystems namely thermal and electrical.

3.1. Thermal subsystem

To achieve the experimental model of the micro-generation system, three modules are used: a thermal condensation boiler for the heating of residential buildings, a fuel cell together with its operation module and a heat converter/exchanger, with its connection/separation elements.

The boiler [6] is a low emission high performance condensing wall boiler using natural gas or LPG that can generate a maximum heat of 24kW for residential space heating and domestic hot water. Hot water for heating is produced using a heat exchanger (aluminum laminated exchanger) that uses efficient water vapor condensation in the flue gas alongside with an advanced electronic control system for a high level efficiency.

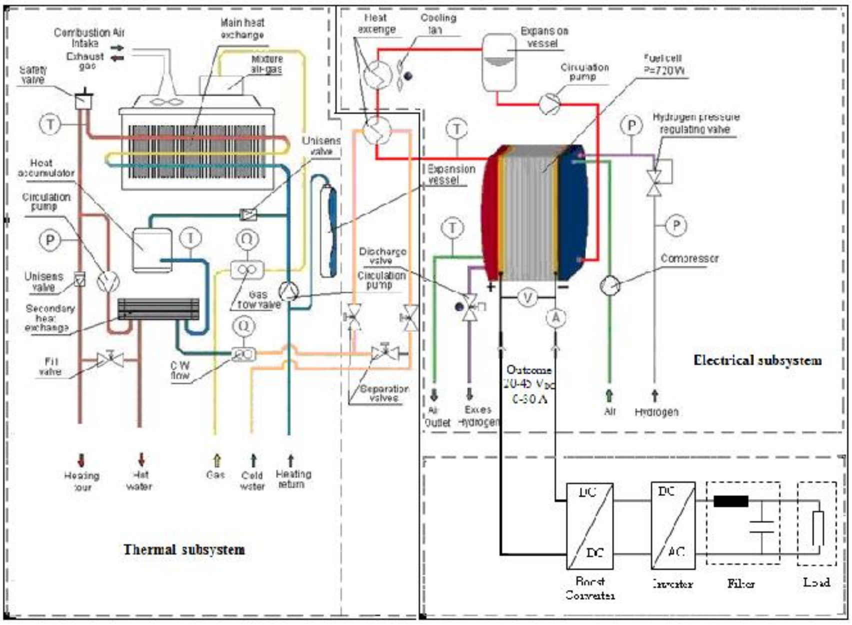


Figure 3 .The electrical and thermal schemes for the experimental energy system.

The boiler is equipped with a modulating gas valve, a fan flue gas exhaust, a variable-speed combustion air intake, an insulated combustion chamber and an igniter device. It is also fitted on its heating circuit with a variable-speed circulating pump, an expansion vessel, a safety valve, pressure and temperature sensors and a safety thermostat. The main characteristics of the gas condensing device are presented in Table 1.

The thermal connection between the fuel cell and the boiler is done by the heat exchanger which aims to recover some of the heat produced during the fuel cell operation. The recovered heat is reflected in the inlet temperature of the DHW boiler, and reduces the thermal load of the boiler. The thermal circuit of the fuel cell is connected on the cold water inlet (CW) of the boiler, through separation valves so that DHW production can be achieved with or without preheating the cold water.

Table 1. Boiler - Technical specifications[6]

Technical specifications	P_{max}	P_{min}
Thermal power, kW	25,2	7,5
Methane gas consumption, N m3/h	2,67	0,79
Methane gas supply pressure, mbar	20	20
Efficiency, %	99,5	97,5
Heating setpoint, ^oC	20-90	
Heating circuit min/max pressure, bar	0,8	3
DHW temperature setpoint, ^oC	40	65
Supply voltage/frequency, V/Hz	220/50	
Max absorption power, W	130	

3.2 Electrical subsystem

Electrical subsystem contains three elements namely as Proton Exchange Membrane (PEM) fuel cell, boost converter and inverter. The design of the electric scheme was achieved starting from the necessity of the micro-generation system to be completely autonomous from the point of view of the electric energy supply.

3.2.1. PEM fuel cell

The experimental cogeneration unit type FC-42 [7], is designed to be supplied with pure hydrogen at the anode and air at the cathode (Figure 3). The unit is cooled with water in a closed circuit and can be used in a temperature range of 50/70 ° C depending on the minimum configuration of the PEM fuel cell.

The characteristics of the PEM fuel cell are shown in the following Table 2

Table 2. Characteristics of the PEM fuel cell [7]

Operating temperature	^oC	<70
Maximum Current	A	30
Open circuit voltage	V	42
Nominal voltage	V	24
Minimum voltage	V	20
Nominal power	W	720

3.2.2 Devices for adapting the voltage at residential use

The main electric scheme of this micro-generation system is presented in Figure 3. A DC / DC converter between the fuel cell and the isolated grid of the residence, a single-phase inverter with output voltage Vout 230V, 50Hz were used in order to convert the DC voltage of the fuel cell to the requirements of residential consumption (boiler supply).

To satisfy the power quality, the electrical systems in this case must meet the requirements of EN 61000 series.

Correct equipment operation requires the level of electromagnetic influence on equipment to be maintained below certain limits. Equipment is influenced by disturbances on the supply and by other equipment in the installation, as well as itself influencing the supply. These problems are summarized in the EN 61000 series of EMC standards, in which limits of conducted disturbances are characterized. Standard IEC 038 [8] distinguishes two different voltages in electrical networks and installations:

- supply voltage, which is the line-to-line or line-to-neutral voltage at the point of common coupling (PCC), i.e. main supplying point of installation
- utility voltage, which is the line-to-line or line-to-neutral voltage at the plug or terminal of the electrical device

On the user's side, it is the quality of power available to the user's equipment that is important. The EMC standards concern the utility voltage, according to IEC 038, while EN 50160 deals with the supply voltage. The differences between these voltages are due to voltage drops in the installation and disturbances (see Table 3) originating from the network and from other equipment supplied from the installation.

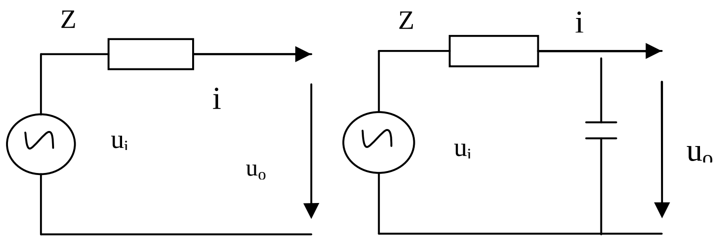
Because of this, in many standards of the EN 61000 series the equipment current is an important parameter, while the load current is not relevant to EN 50160.

Table 3. Requirements for utility and supply low voltage

Supply voltage characteristics according to EN 50160	Requirements for utility low voltage EN 61000 series	
	EN 61000-2-2	EN 61000-2-2
5% 3rd, 6% 5th,5% 7th, 1,5% 9th,3.5% 11th, 3% 13th, 0,5% 15th, 2% 17th . 1,5% 19th 0,5% 21th 1,5% for > 23 th	6%-5 th, 5%-7 th, 3.5%-11 th, 3%-13 th, THDu <8%	6%-5 th, 5%-7 th, 3.5%-11 th, 3%-13 th, THDu <8%

There are two sources of harmonics –one is from the inverter because of the pulse-width-modulation and the switching – and the other is from the load. The majorities of load are non-linear and generate harmonic currents when a purely sinusoidal voltage supply ($u_i = \sqrt{2}U_i \sin(\omega t + \gamma)$) is provided. These harmonic currents can cause harmonic component in the voltage because of the impedance inside the voltage source. The output voltage of the inverter can be modeled as shown in Figure 4a and can be written as:

$$u_o = u_i - Z \cdot i \tag{1}$$



a. without Capacitance b. with filter capacity

Figure 4. Electrical circuit.

Assume the output current have harmonics described by equation $i = \sqrt{2}\sum_{h=1}^{\infty} I_h \sin(h\omega t + \varphi_h)$, then the amplitude of the h-harmonic voltage dropped on the output impedance is: $U_h = \sqrt{2} I_h |Z(jh\omega)|$ and the fundamental component of the output voltage is:

$$u_i = \sqrt{2}U_i \sin(\omega t + \gamma) - \sqrt{2}I_1 |Z(jh\omega)| \sin(\omega t + \varphi_1 + \phi) \tag{2}$$

Where: ω -is the frequency, φ_h -is the initial phase of the harmonic order h

With rms value $U_{1rms} = \sqrt{U_i^2 + I_1^2 |Z(jh\omega)|^2 - 2U_i \cdot I_1 |Z(jh\omega)| \cos(\varphi_1 + \phi + \gamma)} \cdot$

According to the definition of THD of the output voltage on inverter has:

$$THD = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2 \left| Z\left(jh\mu \right) \right|^2}{U_{1rms}}} \cdot 100\% \tag{3}$$

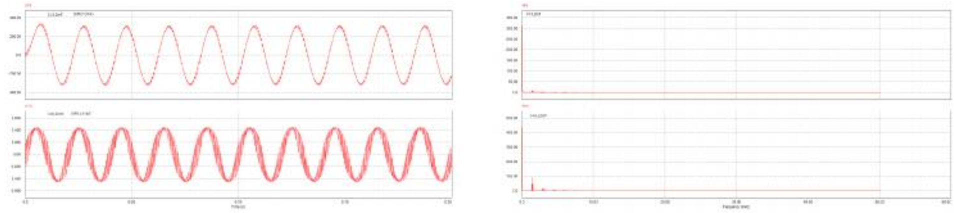
As a result, the THD is mainly affected by the output impedance at the harmonic frequencies. Using simple filter capacity regarded as a part of the inverter, the impact of the filter capacitor on the output inverter (Figure 4b) can be analyzed by the voltage divider equation:

$$u_o = u_i \frac{\frac{1}{jh\omega C}}{\frac{1}{jh\omega C} + Z(jh\omega)} = u_i \frac{1}{1 + jh\omega C \cdot Z(jh\omega)} = u_i \cdot H(jh\omega) \tag{4}$$

If

$$Z(jh\omega) = R \text{ results } H(jh\omega) = \frac{1}{1 + jh\omega RC} = \frac{1}{1 + j\frac{h\omega}{\omega_o}} \tag{5}$$

The result is a low-pass filter with a unity gain for a wide range of frequencies. If the $\omega_o = 314 rad/s$ results at fundamental component of the output voltage is $u_o \approx 0.707 \cdot u_i$. If the $\omega_o = 3140 rad/s$ result at fundamental component of the output voltage is $u_o \approx 0.95 \cdot u_i$ .Result of numerical simulations, in PSIM software [9], for a voltage source inverter with sinusoidal PWM and the a low-pass filter influences on the utility voltage are shown in Figure 5a. The harmonic frequencies obtained by FFT for supply and utility voltage are shown in Figure 5b.



a. waveforms b. FFT

Figure 5. The utility voltage

4. Simulation of the whole electrical sub-system

4.1 Description of the models simulation

To simulate the whole electrical sub-system were created the Matlab-Simulink blocks for all involved equipment (Figure6) . The simulation model of the fuel cell [10] was adapted to the technical characteristics of FC-42/HLC. The DC output voltage of the fuel cell was increased with the help of a boost converter. This voltage was increased in the order to adapt to the input level of inverter. The AC output voltage of the inverter must be 220V, 50Hz.

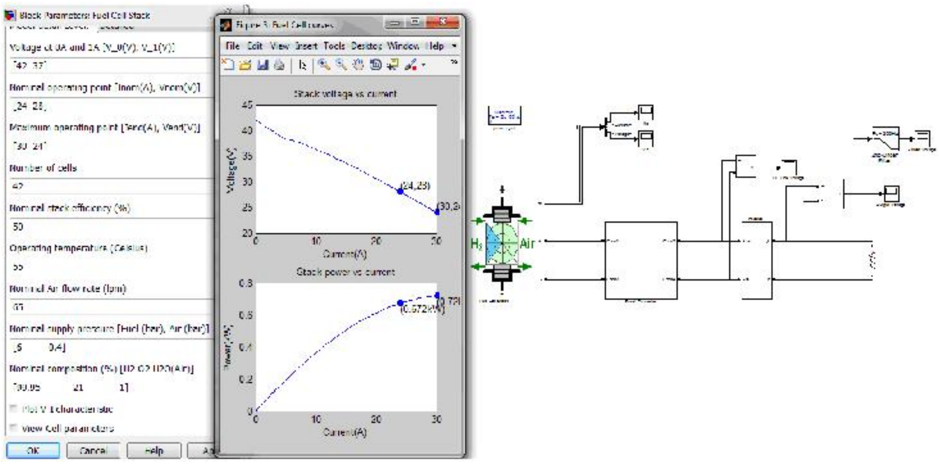


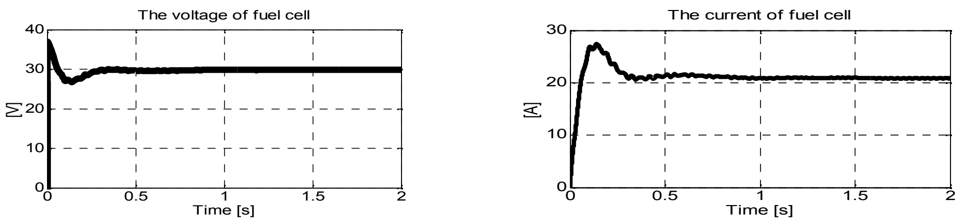
Figure 6. The voltage-current and power characteristics of fuel cell and Simulink implementation

In modeling the electrical subsystem components we followed:

- to implement and obtain voltage-current and power characteristics of fuel cell type FC-42 / HLC (Figure 6) ;
- sizing the boost converter for raising DC output voltage of the boost converter;
- Conversion of constant DC power to oscillating AC power;
- Frequency of the AC cycles -- should be 50 cycles per second;
- Quality of the AC sine curve -- whether the shape of the AC wave is jagged or smooth.

4.2. Result simulation

The result of numerical simulation the evolution of the output voltage and current of the fuel cell are shown in Figure 7.



a) Voltage characteristic　　b) Current characteristic

Figure 7. The output voltage and current of fuel cell.

Voltage of the fuel cell was increased in three stages with boost converter and the value obtained to output is shown in Figure 8.

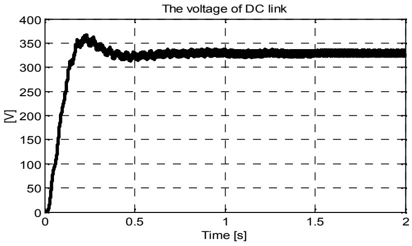
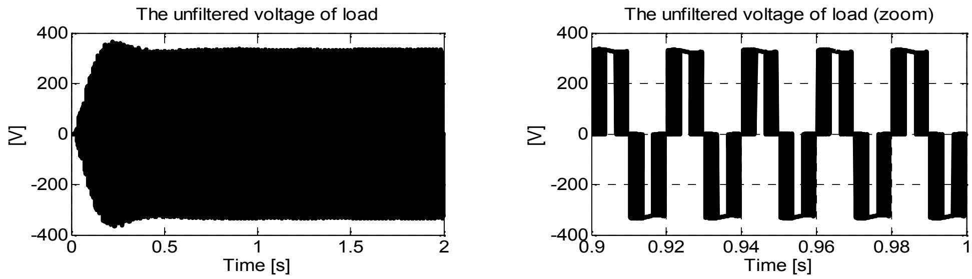


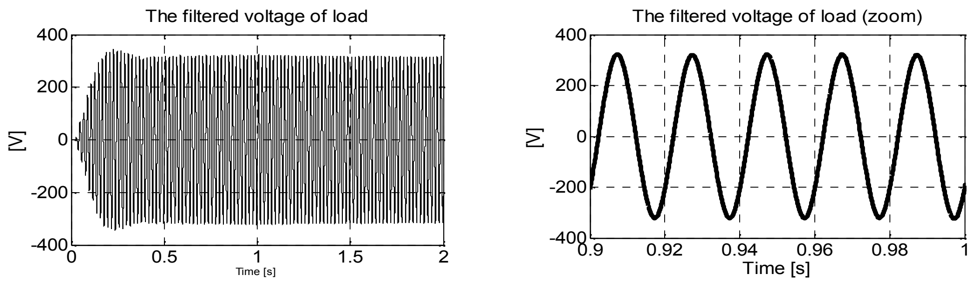
Figure 8. The voltage of DC link

The unfiltered and filtered voltage on the inverter output is shown in Figure 9 and 10.



a) Whole range b) Zoom details

Figure 9. The unfiltered voltage on the inverter output.



a) Whole range b) Zoom details

Figure 10. The filtered voltage on the inverter output.

5. Experimental system testing

A picture of the experimental system implemented in Dunarea de Jos University laboratory is shown in Figure 11b.The first step in testing the system was priming the fuel cell with hydrogen at a constant pressure (314 mbar) and electricity from inverter with rectangular wave. The power, voltage and current of the fuel cell is shown in Figure 11b.

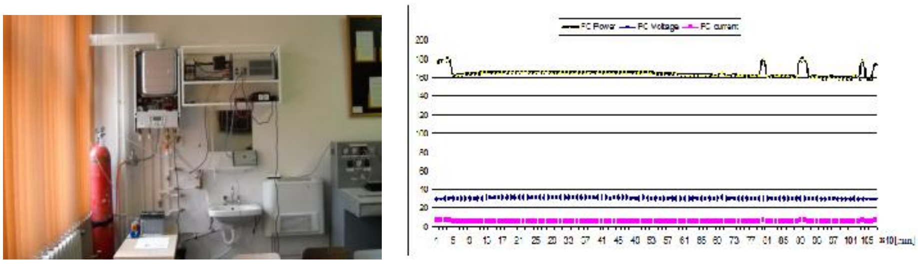
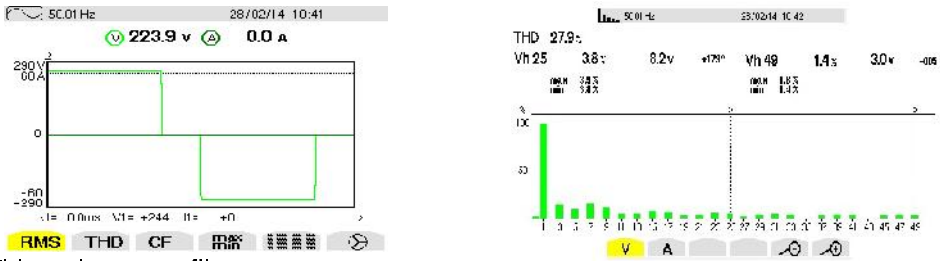
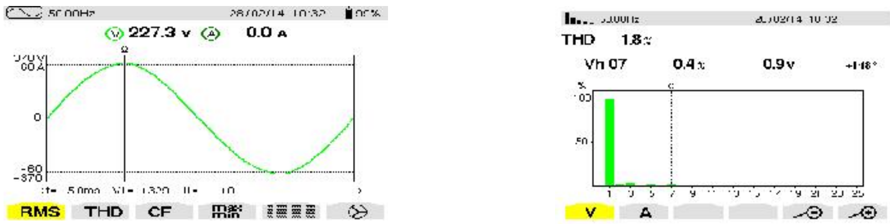


Figure 11. Test bench, power, voltage and current of fuel cell to boiler only

Experimental power quality of rectangular wave inverter with or without filter to boiler supply is shown in Figure 12.



a Without low-pass filter



b With low-pass filter

Voltage shape Voltage harmonics

Figure 12. Rectangular wave testing

Without low-pass filter for rectangular wave inverter, the boiler worked with interruptions, requiring restart. Add low-pass filter to the boiler is working well.

6. Conclusions

The output impedance of an inverter plays an important role on the THD output voltage. The fact that the output impedance of an inverter plays an important role on the THD of the output voltage offers an alternative to improve the quality of output voltage of an inverter. As a result, it is feasible to optimize the design of the output impedance at high frequencies to minimize the THD of the output voltage, without affecting the impedance at the fundamental frequency. The design of the output impedance can be decoupled to meet two different requirements in the frequency domain such, the output impedance at the fundamental frequency can be designed to meet the requirements of the droop controller for proportional load sharing and the output impedance at the harmonic frequencies can be designed to reduce the THD of the voltage. In conclusion, the electrical part of the supply system for building appliances must satisfy the EN 50160 standard, having the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling in public low voltage (LV), under normal operating conditions.

The electrical equipments, especially the inverter, must satisfy EN 61000 series of EMC standards having the main voltage parameters and their permissible deviation ranges. Correct equipment operation (equipment with microprocessor) requires the level of electromagnetic influence on equipment to be maintained below certain limits given in particular by harmonic voltage.

References

[1] Pepermans G, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W, Distributed generation: definition, benefits and issues. Energy Policy; 33(6): 787-98, 2007.

[2] Alanne K., Saari A., Distributed energy generation and sustainable development, Renew Sustain Energy Rev; 10: 539-58, 2006.

[3] Kirschen D.S., Demand-side view of electricity markets, IEEE Trans Power Syst; 18(2): 520-7, 2003.

[4] Levy R., A vision of demand response – 2016, Electr J; 19(8): 12-23, 2006.

[5] Clark W, Isherwood W., Distributed generation: remote power systems with advanced storage technologies. Energy Policy; 32(14): 1573-89, 2004.

[6] www. Ferroli.ro

[7] www. Heliocentris.com

[8] IEC 038, IEC standard voltages, 1999

[9] www.powersimtech.com

[10] www.mathworks.com

Addresses:

- Prof. Dr. Eng. Nicolae Badea "Dunărea de Jos" University of Galaţi, Domnească, nr. 47, 800008, Galaţi, România, Nicolae.Badea@ugal.ro
- Dr. Eng. Mădălin Costin, "Dunărea de Jos" University of Galaţi, Domnească, nr. 47, 800008, Galaţi, România,, Madalin.Costin@ugal.ro