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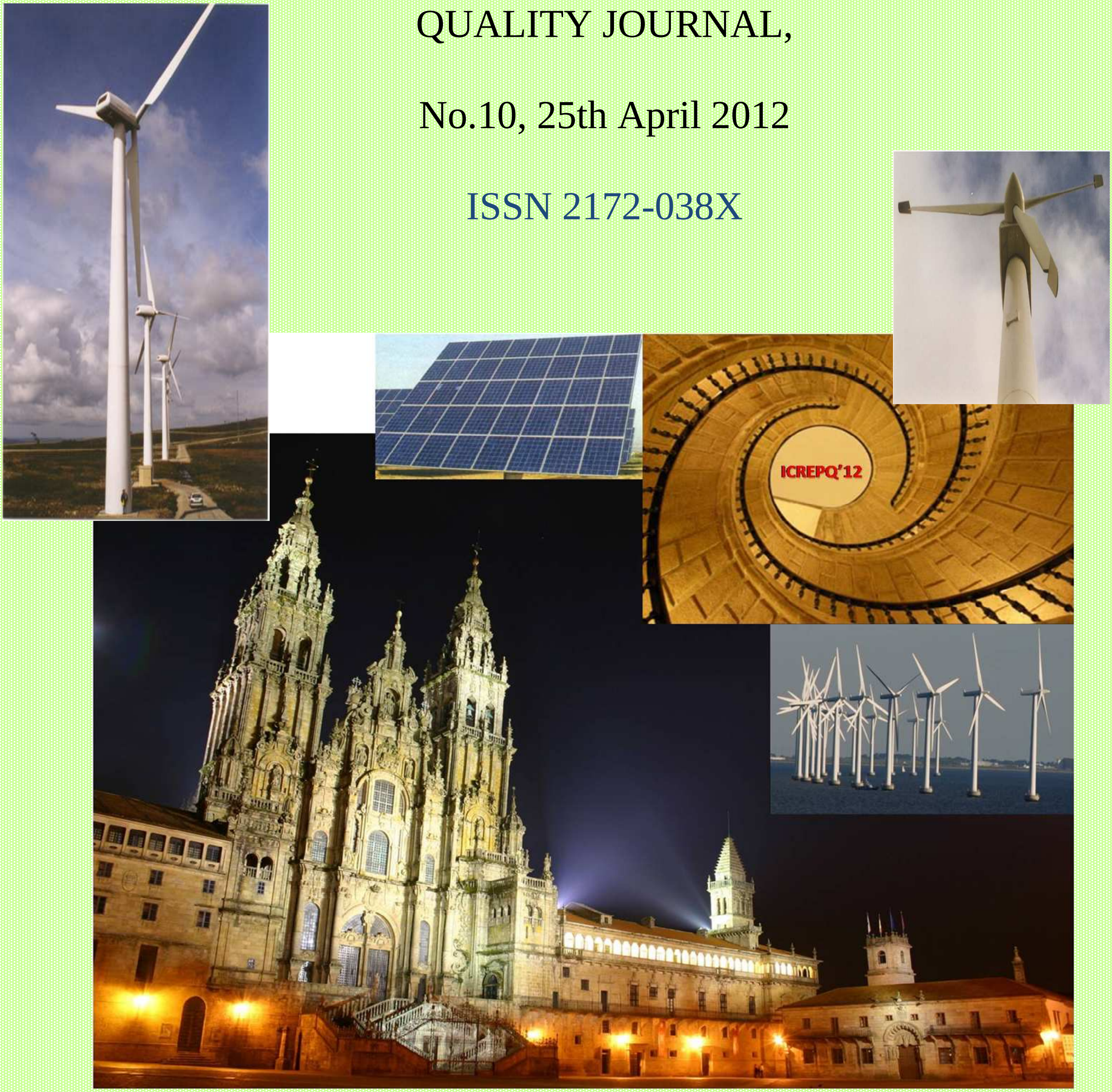

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Dealing with the Very Small: First Steps of a Picohydro Demonstration Project in an University Campus

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Abstract. This paper presents the implementation, project and design of a small run-of-river hydropower plant, designed for demonstration purposes, under a Project aimed to be a framework of wide spread dissemination of renewable energies and energy efficiency in an University Campus. The details of the hydroelectric power plant, from the project design until the final use of the produced electric energy, are described. The main requirements of the implementation are presented, with regards to the environmental footprint and topography of the site and the adopted solutions are also described. Considering the demonstration purposes, two different electrical systems were installed in the power house: stand-alone and grid-connected. The latter establishes a case study in the development and application of picohydro power plants as microgeneration units in the context of distributed generation systems. The evaluation of both systems is also presented, based on the experimental results obtained from tests experiments and from monitoring the first months of operation at the site.

Key words

Small-Scale Hydropower Plants, Renewable Energies, Hydro Energy, Distributed Systems.

1. Introduction

The beginning of this century confirmed the need to solve the energy problem at the global level because of the successive oil crises, the emerging climate change issue, as well as continuous social and political instability in many source countries in the oil trade chain [1]. In fact, problems related to and crossing issues as energy, environment and financial/regulatory restrictions in wholesale markets have emerged worldwide in the last decade [2]. On the other hand, the consumption of electrical energy is growing and, at the same time, the number of systems based on electricity will increase in the next decades. It is expect that more than 60 % of all energy consumption will then be converted to and used as electricity [1]. Thus, it is mandatory to find future solutions as more sustainable as possible, changing from conventional to renewable energy sources (RES) and taking advantage of the development of power electronics technology [1]. One possible solution is the so called distributed generation (DG) which consists of generating electricity as near as possible of the consumption location [2]. This concept is emerging as a new paradigm to produce in-site, highly reliable and good quality electrical power [3].

The above-mentioned growth of electricity demand, together with concerns relating to environment, under a climate change scenario, and the suitability of other energy technologies, has renewed the interest in hydropower [4]. In recent years, small-scale hydropower plants (from pico to mini) have been an upward interest in this sector, as a RES based proven technology with a very good performance and feasibility with low investment costs [2], [5] – [8]. The increasing interest in this technology is expected to be continued due to its high potential of application in DG and to the large amount of benefits for the use of RES, including favorable incentives granted in many countries [2]. This is also the case of the Portuguese significant policy initiative called microgeneration, that started in 2007 with a premium feed-in tariff for DG units up to 3.68 kW [9].

Small-scale hydropower stations are usually run-of-river schemes with no or very small dam and reservoir, therefore associated with low impacts on the hydrological regime, on the aquatic or riparian ecosystems and on landscapes [10], [11]. They are one of the most cost-effective and environmentally green energy conversion technologies [5]. Normally, they rely on the mechanical regulation of water flow rate in the turbine to control the active power generation [2].

This paper aims to present a DG implementation case study, consisting on a run-of-river 2 kW hydropower plant, designed and installed with specific demonstration purposes in the framework of VER*Campus* – Live Campus of Renewable Energies. This project integrates a set of technologies, infrastructures, and initiatives carried out in the Campus of the Polytechnic Institute of Bragança (IPB), focused on renewable energies technologies and distributed power generation systems promotion and dissemination [12]. Along with the description of implementation steps and system components, the paper also aims to discuss operational outcomes and foreseen improvements of the plant, under its specific demonstration goals, based on experiments and monitoring actions performed during the first semester of project implementation.

2. Description of the Hydropower Plant

This section describes the most relevant design aspects related to the implementation of the hydropower plant.

A. Requirements and Design

As far as requirements of small hydropower plants are concerned, each project is uniquely tailored according to the site topography from civil works through to turbine design. When looking at several design schemes, this assessment extends to the river basin level [4].
The specific requirements for the IPB hydropower plant design were established as follows:

- Ensure no interference in the riverbed and keep the landscape context untouched;
- Support demonstration purposes, targeted for students, small companies and general community;
- Select safe turbine-generator group location, to account for the significant variation in river water level during floods;
- Promote efficient use of the electric energy produced in stand-alone and grid-connected systems;
- Assume the character of a case study in the context of the microgeneration initiative [9].

Considering the above requirements and local topography in the IPB *Campus*, a run-of-river plant was designed with no dam or water storage. This solution has low environmental footprint when compared to traditional reservoir hydro projects. Furthermore, in order to not interfere in the riverbed and maintain the landscape context untouched, the water is conveyed in a former irrigation canal, the actual feeder. Upstream, the water is taken from the Fervença river, which crosses the IPB *Campus*, through a small weir as shown in Fig. 1.

Fig. 1. Irrigation canal in the IPB *Campus* (left), small intake weir in Fervença river (centre) and the end of feeder canal (right).

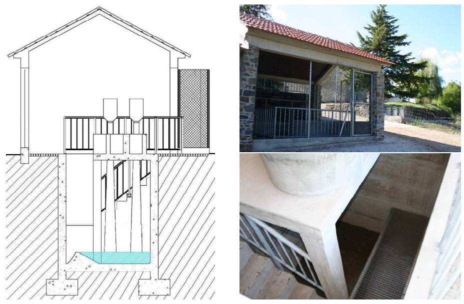

Fig. 2. Cross-section and perspective photos of the picohydro power house.

Fig. 3. Feeder canals (left), discharge divisor and spillway (centre) and turbine supporting structures (right).

Aimed to be an open platform for dissemination and demonstration of hydro energy, both for regular guided visits as for people that are passing by, the picohydro power plant was built in a place of passage of students and people in general since the IPB has an open *Campus*. Also a small power house, shown in Fig. 2, was designed and built for two specific turbines and with the purpose of being an experimental platform for studies and visits. This minihydroelectric power house has metal grid stairs and a platform that allow visiting the gallery and an insight on the draft tube, the discharge basin and the spillway to tailrace pipe that drains water again to the river.
In the place where the power house was built, the Fervença river level varies significantly throughout the year, rising sharply during floods in the rainy season. To prevent damage due to the rise of the river level (more than 2 m in peak discharge), that could flood the generator and other electrical equipment, a specific solution was designed according to local topography. Thus, the two hydro turbines were mounted upstream of a draft tube instead of downstream a penstock.
Besides the power house, an entirely new structure well-fitted to local existing farm-type buildings, either in size and in style, additional civil work performed simply comprised (Fig. 3): (i) concrete lining of the final 160 m of the earthen irrigation canal, ended with a leveled sediment load settling segment; (ii) a discharge divisor to split flow between turbines, spilling excess water back to the irrigation canal; (iii) the turbine spiral-shaped support structures.
Given that the hydropower house should have demonstration purposes, it was sought to diversify ways of using the energy produced. To this end, two propeller hydro-turbines were installed with different generators. One of these turbines was integrated with suitable equipment (described in the next section) to build a grid-connected system as a hydroelectric distributed generation system. The other turbine is used in a very simple stand-alone system where the energy produced by the generator is directly used by the loads. In this case the load is a power resister of a hot water heating system with a high thermal inertia in order to absorb the produced energy during 24 hours per day. Thus, a pair of small propeller hydro-turbines was installed, but with different generators, operating at 2.5 m head, a solution suited for low discharge and low head conditions. The discharge divisor (Fig. 3) controls water conveyance to one or both turbines, the former case occurring at high water flow. For similar total power installed, the two turbine solution allows a longer operation period under a wider range of discharge. Anyhow, this picohydro is not expected to operate in the dry summer months. So, the turbine of the system connected to the grid was installed in the canal that has water during more time (right), while the turbine of the stand-alone system was installed in the canal that only has water during the months with more

water available, which coincides with the period of greatest need hot water.

As mentioned above, the picohydro power plant is assumed as a case study of hydroelectric distributed generation system in the context of the microgeneration [9], which is a Portuguese policy initiative started in Portugal in 2007 and was revised in 2010 (Decree-Law 118-A/2010, revised Decree-Law 363/2007). Under the microgeneration initiative the maximum capacity per system for the premium tariff is 3.68 kW (or 11.04 kW in condominiums) and at least 2 m^2 of solar water heating system (or equivalent biomass boiler) must be installed. The starting premium tariff has a reference value of 0.40 €/kWh and is revised down 0.02 € every year. This premium tariff depends on the renewable source and is determined by applying the following percentages:

a) Solar - 100%;
b) Wind - 80%;
c) Water - 40%;
d) Biomass co-generation - 70%;
e) Fuel cells based on hydrogen from the renewable sources a), b), c) and d) - the corresponding specified percentages;
f) Co-generation non-renewable - 40%.

Until 30 June 2011, about 12140 systems with 3.54 kW average unit capacity had been installed and were operating with the following share [9]:

- PV: 11956 units (98.52%);
- Wind: 145 units (1.15%);
- Hybrid (PV+Wind): 34 units (0.29%);
- Hydro: 5 units (0.05%);

A reason for such reduced number of hydro systems is that most of the companies working on the microgeneration initiative are very small companies without any experience in small hydro systems. Even the biggest ones do not have experience with pico and microhydro systems. Furthermore, to get experience is not easy since each project is specifically designed according to local topography, from civil works to turbine design [4] and cannot be replicated as a modular system like it happens with PV systems.

This was an important fact that motivated the development of the hydropower plant described in this paper under the context of the VER*Campus* Project which integrates a set of technologies, infrastructures, and initiatives carried out in the Campus IPB regarding the promotion and dissemination of renewable energies technologies and distributed power generation systems [12].

B. The Power House Hydro Systems

As described in the previous section, two propeller turbines, connected to different systems in view of demonstration purposes, were mounted in their respective support structures. These have a spiral-shape design to ensure efficient conversion of tangential inflow in axial outflow towards the draft tube, meaning to minimize flow residual angular momentum [5]. In this case, fixed vanes guide water to the turbine propeller, rotation inducing shaft power and producing electricity by means of a permanent magnet synchronous generator, directly connected to propeller.

The next sections describe the above-mentioned stand-alone and grid-connected hydroelectric systems installed in the power house.

B1. The Stand-Alone System

In stand-alone systems, as the energy is directly used by the loads, an effective regulation of the output voltage and frequency is important for the electrical loads in order to ensure a stable voltage and frequency, equal to 230 V and 50 Hz respectively. In some cases this is made by speed regulation using complex mechanical mechanisms that adjusts the flow to the turbine to meet variations in power demand. In other cases the turbine always runs at rated power and the speed is controlled by adjusting the electrical power output instead of the water power input. In these cases the excess of electrical power is switched in and out of a ballast load by an Electronic Load Controller [5]. In the case of the turbine used in the IPB hydropower plant, the regulation is achieved by means of a resistor that dissipates the excess of power. This is usually done using an electronic circuit based on a triac through the control of its firing angle [13]. Nevertheless, since in this case study the electrical load is a resistor used to produce heat, there are no special requirements regarding the power quality.

In order to use efficiently all the energy produced and considering the performance of the generator, which is described in the next section, it was directly connected to a resistor of a water heating system with a high thermal inertia. Thus, all the produced energy (24 hours a day) is used since it did coincide the electrical energy production cycle with the one of the hot water consumption. This is an interesting and efficient way to use the electric energy generated, in a stand-alone application, with the context described previously.

B2. The Grid-Connected System

For the grid-connected system, a three-phase generator was assembled with the same propeller turbine, which will operate in the power house from the next winter. This new permanent magnet disc generator is connected to a three-phase rectifier, with a power resistor for excessive power dissipation, which in turns is connected to a single-phase inverter, as a typical wind microgeneration system. This is an innovative integration of a water turbine with a widely used wind inverter resulting in a grid-connected hydro system which operates in similar way. The simplified power conversion system of the wind (hydroelectric, in this work) turbine is illustrated in Fig. 4.

A protection box, with a rectifier and an overvoltage protection circuit, converts the variable-speed voltage of the hydro generator into DC voltage and protects the inverter from high input voltage at the same time. An external resistor dissipates the excessive power due to possible surges and overvoltages and protects the generator from high speeds when the grid is down. Then, the inverter converts the DC voltage to grid-compliant voltage.

It should be noticed that, in this case and unlike the stand-alone system described above, there is no need of

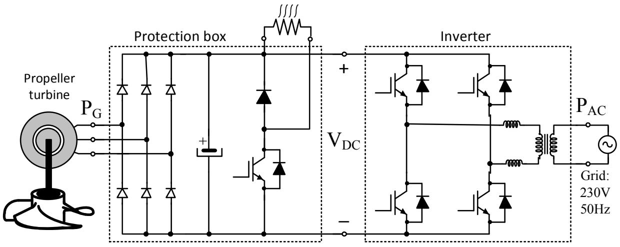

Fig. 4. Simplified power conversion system for the hydroelectric turbine connected to the grid.

any regulation system for the output voltage and frequency of the generator. In fact, it can operate with a wide range of speed and, therefore, a wide range of frequency.

3. Evaluation and Results

This section describes the evaluation of the hydropower plant operational conditions and performance in the first semester after installation, reporting and discussing some important outcomes of this on-going case study.

A. Hydrological Evaluation

According to design criteria adopted, which follow the above stated requirements for IPB picohydro power plant, river flow diverted to the hydraulic circuit is much lower than the available discharge in order to approach reserve flow as much as possible to that of pristine conditions.

Fervença river discharge data was estimated from data collected in the river, at the Campus gauging station, during a two-year period, after which it was deactivated [14]. Matching these data with those of several recording stations in the area, provided by the National Water Resources Information Service [15], allowed deriving the average flow duration curve for Fervença river at IPB Campus (Fig. 5). Daily discharge reaches a maximum of 12 m^3/s, the median being 0.23 m^3/s. Discharge values exceeded in 10 days (Q10) and in 355 days (Q355) out of the whole year are 4.42 and 0.005 m^3/s, respectively, while the average computed (0.63 m^3/s) is exceeded in 87 days (Fig. 5).

As shown above, rated discharge for each turbine is 0.05 m^3/s. Local depth-discharge curve [14], crossed with long-term empirical observations of river flow regime, suggests keeping 0.07 m^3/s reserve flow from intake to tailrace. As so, in average conditions, discharge for power generation is not available for 104 days (the dry summer season), and it is fully available at rated discharge during 230 days out of the whole year. However, the operation period has to be not longer than 8 months, either because of water and head losses along the feeder, upstream its lined segment, where it keeps the earthen bed of the original irrigation ditch, or due to the too low global plant performance achieved for low discharge.

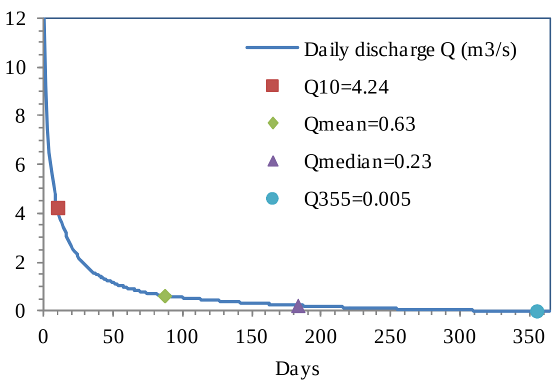

Fig.5. Average daily flow duration curve estimated for Fervença river at IPB *Campus* and characteristic discharge values.

During the observation period being reported in this paper, flow velocity along the hydraulic circuit was measured twice, accounting for, roughly, mid spring and late spring flow conditions. Measurements performed with a digital propeller device, and applying the section-velocity method for discharge computations [16], gave a well-grounded insight on flow conditions in the feeder canal. As well, global turbine-generator group performance in late spring was computed with actual discharge and gross head as input, and electrical power output in the generator.

Slope of the energy line along the steady state feeder canal segment, with trapezoidal cross-section, estimated by regression with data collected (Table I), was very low (equal to 0.0003 m/m in both mid and late spring). This means flow velocity may show important fluctuations according to disturbance in the feeder canal, calling the attention to the need of a regular maintenance programme.

In mid-spring, flow was fast, near 1 m/s at inlet, and discharge ensure one group operation using full available water resources (Table I). For the higher discharges that occur in winter and late autumn, two group operation is possible. Performance was not assessed in this period but it should reach a much higher value than that of late spring, the period when plant operation ceases at the beginning of the dry season. Under these specific conditions, at inlet velocity drops 60%, flow depth is halved and discharge is less than one third of the values found in mid-spring (actually, about a month earlier). At this time of the year, performance estimated is not acceptable for a production-oriented plant (16 %).

B. Evaluation of the Stand-Alone System

The turbine-generator group chosen for the stand alone system was the so called Micro-Hydro-Power-Propeller-Turbine-Arial ZD2.5-1.0DCT4-Z [17], with announced main characteristics according to Table II.

Laboratorial tests were first carried out to ascertain the

Table I. – Flow hydraulic conditions in the feeder canal and turbine-generator group performance in mid (MS) and late-Spring (LS) 2011.

Flow parameter/ performance	Steady state segment*		Turbine inlet	
	MS	LS	MS	LS
Depth (m)	0.282	0.158	0.250	0.120
Velocity (m/s)	0.241	0.206	0.955	0.593
Discharge (m^3/s)	0.083	0.024	0.086	0.026
Global effic. (%)	-	-	na	16

*Means of 5 measurement section data along 80 m; na – not assessed.

performance of the generator, using the test bench shown in Fig. 6. Resistive load tests of the generator, prime moved by an induction motor with rated power of 1.5 kW, driven by a speed controller, are presented in Fig 7. From the obtained results it is obvious that the generator is far behind the expected performance, with a maximum electrical power of 570 W at rated speed 1500 rpm, which corresponds a resistive load of 30 Ω. Both manufacturer and supplier will be confronted with the test results in order to be aware of those discrepancies.

Table II. – Arial ZD2.5-1.0DCT4-Z turbine-generator group main rated characteristics [17].

Single-phase generator		Turbine	
Type	Permanent magnet synchronous	Type	Axial flow propeller
Active power	1000 W	Head	2.5 m
Voltage Current Frequency	230 V 4.34 A 50 Hz	Flow	50 l/s
Speed	1500 rpm	Power	1000 W
Poles	4	Efficiency	60 %

Fig. 6.Test bench used to obtain the experimental tests.

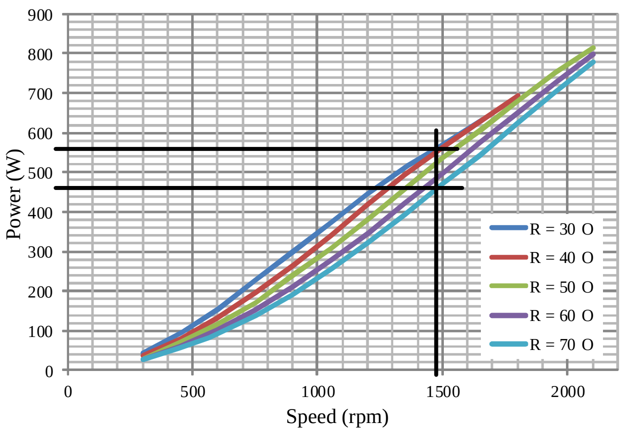

Fig. 7. Resistive load tests of the single-phase generator at variable speed.

Despite of this setback, the group has been used in the stand-alone system previously described, since February of the present year. The practical load in situ was obtained with the parallel of two 60 Ω resistances, which were already part of the heating system.

C. Evaluation of the Grid-Connected System

In a similar way as described for the stand-alone system, the test bench shown in Fig. 6 has been used to verify and evaluate the performance of the three-phase permanent magnet synchronous generator, as well as the electric conversion system shown in Fig. 4. The technical characteristics of the chosen generator [18] and also the rectifier and overvoltage protection box [19] are shown in Table III. Table IV shows the technical characteristics of the Windy Boy WB 1200 inverter [19].

Equipment integration from different manufacturers is not a straightforward task. Notwithstanding the fact that the adopted solution includes the same equipment the

Table III. –Rated/technical characteristics of three-phase generator PGS100R-WB488 [18] and rectifier and overvoltage Windy Boy protection box [19].

Three-phase generator		Rectifier/Protection box	
Type	Permanent magnet synchronous	Type	WB Protection Box 400
Active power	800 W	Input voltage	0 – 500 V
Voltage Current Frequency	385 V 1.25 A 100 Hz	Input current	0 – 11.5 A
Speed	1500 rpm	Frequency	0 – 400 Hz
Poles	8	Maximum DC voltage	400 V

Table IV. –Rated/technical characteristics of the inverter WB 1200 [19].

Input (DC)		Output (1~AC)	
Maximum Power	1320 W	Active power	1200 W
Maximum voltage	400 V	Maximum current	6.1 A
Voltage range	100-400 V	Voltage	230 V
Maximum current	12.6 A	Frequency	50 ± 4.5 Hz
		Power factor	1
European efficiency: 90.9%			

Table V. – Output voltage, current, and power with the turbine-generator group connected to a variable resistive load at 100 Hz.

$R_{Load}(\Omega)$	V_G(V)	I_G(A)	P_G(W)
170	371.6	1.3	837
180	374.2	1.25	810
190	378.3	1.18	773
200	381.3	1.13	746
210	384.0	1.08	718
220	386.1	1.03	689
230	388.0	0.99	665
240	390.5	0.96	649
250	392.2	0.92	625
260	394.1	0.89	608

wind energy conversion systems use, the hydropower energy resource imposes a different operating scheme, which is reflected in the integration procedure.

Procedures for equipment integration and evaluation of the above-described solution are under progress. The rated performance of the generator was verified from various resistive load tests. Table V shows test results at a fixed frequency of 100 Hz (rated frequency).

As it was expected, preliminary tests of the equipment integration and grid connection, brought into view the need to adequate the inverter power curve ($P(V_{DC})$), which is set by default for a wind energy system, to the current application, characterized by a different behavior of the prime energy resource. The actual power curve of the inverter (3^{th} degree polynomial function) overloads the generator for a frequency below the rated one (100 Hz), without extract the generator rated power. This work is ongoing and will be subjected to further developments.

4. Conclusion

This paper has presented a run-of-river hydropower plant, designed for specific demonstration purposes, under the Project VER*Campus* – Live *Campus* of Renewable Energies, which is aimed to be a framework of wide spread dissemination of renewable energies and energy efficiency in an University *Campus*. The adopted solution has an environmental footprint very low when compared to traditional reservoir hydro projects and maintains the landscape context untouched, since a former irrigation canal was used. Considering the demonstration purposes, a small power house was built, at a site and with features allowing regular visits. Two picohydro propeller turbines were integrated with different electrical systems for each one. The first, already in situ, is a stand-alone system in which the electrical energy produced has been used for water heating. The second one is a grid-connected system, which establishes an innovative case study of a microgeration unit based on a picohydro power plant in the context of DG systems. The grid-connected system uses standardized equipment, whose integration is not straightforward and is towards completion. Hydrological evaluation during the first months of operation and laboratorial tests to ascertain the performance of the two picohydro units has been reported.

Despite the low power of the two turbines, they should not be neglected since they are expected to operate 230 days per year, producing an equal amount of energy of a 3 kW photovoltaic system mounted on a roof in the same region.

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