

Grid-Connection Approaches for Pico-Hydro Systems

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Abstract— Small hydropower systems are considered an environmentally friendly energy option. They have a huge untapped potential which allow it to make a more significant contribution to future energy demand with many advantages. Grid-connected pico-hydro systems are an emerging solution for application in a huge number of applications such as in household water supply, wastewater treatment facilities and to improve control systems and optimize generation as a part of integrated water management systems. They are also very promising for integration in microgrids in many developing countries. This paper presents and discusses the main three grid-connection approaches for pico-hydro systems: using specifically designed power converters; using standard wind inverters; and using standard photovoltaic inverters. These latest approaches based on conventional inverters are practical solutions able to explore a large amount of feasible sites with low-head and very low-head. Moreover, photovoltaic micro inverters, recently launched in the market, are propose for very low power generators (250-300 W). These approaches improve efficiencies, reduce costs and environmental impacts and improve reliability. Experimental evaluation of the performance in steady-state and in dynamic conditions proves the feasibility of these innovative approaches.

Index Terms—Pico-hydro systems; distributed generation; wind inverters; photovoltaic inverters and micro inverters.

I. INTRODUCTION

There is an active seeking to increase the percentage share of the total electric energy supply from renewable and environmental friendly sources. The integration of distributed generation (DG) into microgrids is an emerging solution for electrification of remote regions and also for self-sustainable systems. But also in developed countries, with well distributed and stable power grids, small-scale hydropower has an enormous untapped potential, which can make a significant contribution to the increasing energy demand, whilst decreasing the carbon footprint [1]. This is important in developed countries but especially important for a huge number of families in many countries [2, 3]. Small-scale hydropower stations are usually run-of-river schemes with no or shallow reservoirs, therefore associated with low impacts on the hydrological regime, on the aquatic or riparian ecosystems and on landscapes [4-6]. In order to enable the widespread exploitation of these systems in a cost effective way, it is

necessary to develop a reliable and cheap conversion system, preferably based in mature technologies.

Pico-hydro power plants are very small-scale infrastructures designed to generate electric power, usually under 5 kW [7] by converting the power available in flowing waters in rivers, canals and streams and they are quite different from classical hydroelectric power plants. They are considered as the most appropriate solution for electrification of rural and isolated communities in hilly and mountainous regions where it is very expensive to implement conventional transmission and distribution power systems [8, 9]. In fact, they have been particularly useful in some countries such as India, Nepal, China, Iran, Peru, Brazil and Kenya [2, 3, 10, 11].

Pico-hydro power plants are frequently used as stand-alone systems, providing electricity for basic needs of a house or a small village, with a turbine driving an AC generator and a design load to regulate the output voltage and frequency [9]. In these systems, since the energy is usually directly used by final consumers, it is essential to provide an effective regulation of the output voltage and frequency to prevent harming their appliances [6]. In some cases this is made by speed regulation using complex and high-inertia mechanical devices which adjusts the flow to the turbine to meet variations in power demand. In alternative, the rotational speed of the turbine is dictated by the available flow and a load management system regulates the power usage in order to balance the power input and output [6, 7]. Some off-grid systems are based on a DC generator and a battery, with or without an off-grid inverter, depending on whether the loads are AC or DC [12, 13]. When connected to a grid, conventional pico-hydro systems are designed to operate at very narrow speed range at different heads in order to approximate the rotational speed as close as possible to the rated speed of the generator [12], to ensure the requirements above mentioned. Most of the times, there will be a trade-off between head and flow rate.

Taking into account variability of heads and the water flow seasonal variation, the efficiency of pico-hydro power plants is greatly improved if they may work at variable speed, enabling increased energy capture [14]. Considering recent advances in low speed generators with off-the-shelf low power solutions for wind systems, e.g., variable speed pico-hydro systems can be applied beyond those conventional structures. If additionally, an inverter-based grid interface is used, other turbine

technologies become viable [15]. However, such dedicated inverters for grid connection, as proposed recently [14, 16-18], would become an expensive solution and are far way to be an off-the-shelf technology available on the market. Conversely, wind and photovoltaic (PV) inverters, in the range of 5 kW, are a mature and reliable technology widely available.

Therefore, and considering the limitations of conventional solutions, the possibility of integrating standard PV inverters in grid-connected variable speed pico-hydro systems becomes an attractive idea [19]. In this non-conventional solution, pico-hydro turbines are designed to behave electrically like PV strings, so that they interact effectively with conventional PV equipment, including grid-connected inverters and charge controllers, as proposed by Smithies Technology Ltd. [20]. However, a complete description and investigation of a general approach was only published recently in [19, 21]. In these works a design procedure to integrate widespread standard PV inverters in grid-connected variable speed pico-hydro systems, previously introduced in [19], was further investigated and optimized. In this context, this work presents and discusses the three main grid-connection approaches for pico-hydro systems: using specifically designed power converters; using standard wind inverters and using standard photovoltaic inverters. This paper is focused on the third approach for grid integration of pico-hydro systems. The integration in small microgrids like the one described in [22, 23] is also very powerful.

Authors believe these innovative solutions have a powerful application domain integrating pico-hydro power systems into microgrids in developing countries and in a huge number of applications in developed ones such as in household water supply [13], wastewater treatment facilities [24] and to improve control systems and optimize generation as a part of integrated water management systems [1, 25].

II. GRID-CONNECTION APPROACHES FOR PICO-HYDRO SYSTEMS

In conventional systems the generator operates at constant speed in order to approximate the shaft speed as close as possible to the rated speed of the generator. This speed regulation is achieved using complex mechanical mechanisms that adjust the flow to the turbine to meet variations in power [6]. Unlike conventional systems, new approaches for grid-connected pico-hydro systems discussed in this paper are able to operate at variable speed. This is particularly important to improve the efficiency and when water flow variation is expected. In this context, the electricity is produced by means of a permanent magnet synchronous generator (PMSG), directly connected to the water turbine. Basically, there are three main approaches to connect pico-hydro PMSG to the grid:

- Using specifically designed power converters;
- Using standard wind inverters;
- Using standard PV inverters and PV micro inverters.

Additionally, whatever is the approach chosen, an over-voltage protection circuit is needed, as will be described next.

A. Grid-connection using specifically designed power converters

Dedicated power converters, specifically designed for pico-hydro turbines are difficult to find on the market, if there are any. This is due to the need of designing each project specifically according to local topography, from civil works to turbine design [26] and cannot be replicated as a modular system like it happens with photovoltaic systems [6] or thermal solar systems.

A common power topology for a pico-hydro turbine is shown in Fig. 1. It consists of a rectifier bridge and an overvoltage protection circuit connected to the PMSG followed by a DC/DC boost converter and a voltage source inverter (VSI). The over-voltage protection circuit is needed in order to protect the generator against very high speeds, in case of no load conditions, and therefore, it also protects the power converter against voltages higher than its maximum input voltage. A cost effective, reliable and robust over-voltage protection circuit was proposed in [21]. The excess power is diverted to an auxiliary power resistor to reduce the generator speed and thus the over-voltage in the event of surpassing a DC voltage limit.

Specifically designed power converters, or dedicated inverters, for grid connection as the one presented above or others proposed recently [14, 16-18] would turn into an expensive solution and are far way to be an off-the-shelf technology available on the market [19]. To overcome this disadvantage, two effective alternatives are described in the next sections by using wind or photovoltaic inverters and micro inverters widely available on the market.

B. Grid-connection using standard wind inverters

An effective alternative to specifically designed power converters for variable speed pico-hydro systems is illustrated in Fig 2. It consists of a three-phase rectifier bridge and an overvoltage protection circuit connected to the PMSG and a conventional wind inverter which can be easily found on the market. Usually, this type of inverters are parametrized by means of a power curve as a function of the input DC voltage as follows:

$$P_{AC} = a_0 + a_1 V_{DC} + a_2 V_{DC}^2 + a_3 V_{DC}^3 \quad (1)$$

In the above equation P_{AC} is the AC output power of the inverter and V_{DC} is the input DC voltage. The coefficients a_0 to a_3 define the power curve of a wind turbine. Therefore, this

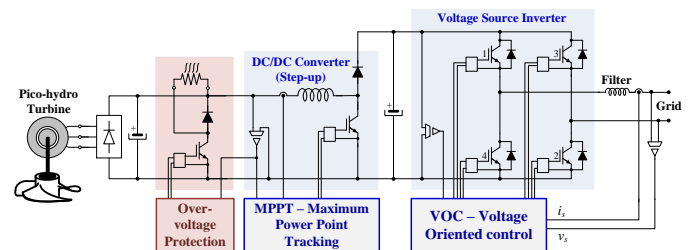


Figure 1. Design topology for grid-connected pico-hydro systems.

approach requires the parametrization of the wind inverter through these coefficients. Additionally, there may need to tune other parameters associated to the dynamic of approximation to the maximum power point such as the proportional and integral gains of the PI controller among other parameters [27].

In pico-hydro systems using PMSG, the no-load output DC voltage of the generator is proportional to the speed. As a consequence, for a given speed, the maximum output DC power is achieved for the maximum allowed (rated) current. Therefore, the maximum output DC power is proportional to the output DC voltage (or speed), provided that the current is kept in its rated value. By this way, eq. (1) will be a straight line with $a_2 = a_3 = 0$ while the remaining parameters are obtained experimentally or given by the manufacturer.

C. Grid-connection using standard photovoltaic inverters

This practical approach, using standard PV inverters, to connect variable speed pico-hydro systems to the grid was proposed in [19] and further analysed in [21]. This approach is illustrated in Fig. 2 but with the wind inverter replaced by a conventional PV inverter. Once again, an overvoltage protection circuit is needed in order to prevent damaging the generator and the inverter, for instance, due to generator runaway if the electric grid fails.

This simple approach has some important advantages such as high performance in terms of component reliability, compliance with the grid connection requirements, broad range of products (up to 5 kW) and technological independence. Furthermore, PV inverters are wide-spread, very cost competitive and their installation is widely disseminated among small and medium enterprises. Nevertheless, the integration of the inverter with the generator must be properly assured, as discussed in [19, 21]. Moreover, it is a plug-and-play solution without need of changing any parameter of the inverter.

In order to be a reliable and safe solution, the integration of the inverter with the selected generator must be properly assured by combining the operating areas of both devices [19, 21]. In fact, the behaviour of the variable speed PMSG is very different from the one of a PV string. However, under certain operating conditions in terms of voltage and power ranges, the solution can be reliable and efficient, benefiting from the advantages previously mentioned.

The integration of the PV inverter with the generator is determined by the superposition of the operating areas of the inverter and the generator, as proposed in [19, 21], and is illustrated in Fig. 3.

Regarding the PV inverter, the input voltage range is defined by $V_{DC\ min}$ and $V_{DC\ max}$; the range within it is able to track the maximum power point (MPP) is frequently defined by $V_{MPP\ min} \geq V_{DC\ min}$ and $V_{MPP\ max} < V_{DC\ max}$; the maximum input current and power of the inverter, $I_{DC\ max}$ and $P_{DC\ max}$ respectively, establish the remaining limits of its safe operating area (SOA). An additional key characteristic of the inverter is the initial minimum input voltage needed for the inverter start working, $V_{PV\ start}$.

If a generator is to be connected to a conventional PV inverter, the operating point of the generator given by the output DC voltage and current, after rectification, i.e., the I-V characteristics for the desired speed range should be inside the SOA of the inverter, as illustrated in Fig. 3 by straight lines. For a given speed, the I-V characteristic is defined by the no load rectified output voltage, V_{GDC0} , and the slope given by the voltage drop in the internal impedance of the generator. The integration of the PMSG and the PV inverter as described here is straightforward, provided that a set of conditions is guaranteed [19].

Usually, it is possible to change some parameters of conventional PV inverters such as the maximum output power and the minimum input voltage. These features may improve the robustness of this approach, by performing adjustments to a specific practical application, without losing its main benefit of the outlined plug-and-play procedure, as desired.

Taking into consideration the conditions described in [19, 21], a possible route of the operating point of the generator, set by the MPP tracking algorithm of the inverter, is shown in Fig. 3 (black dots). For an initial speed higher than the corresponding to the initial minimum input voltage, “speed 5” e.g., the MPP algorithm will start from point 1 and increases the current up to its maximum (point 2). From this point, if the available power increases, the operating point will be set eventually in point 3, provided that the corresponding voltage is lower than the maximum voltage allowed by the over-voltage protection. On the other hand, from point 2, if the power decreases the operating point will be set in point 4. It must be noticed that the maximum admissible current may be set by $I_{DC\ max}$ of the inverter, or through the internal impedance of the generator, from which the voltage drop superimposes an

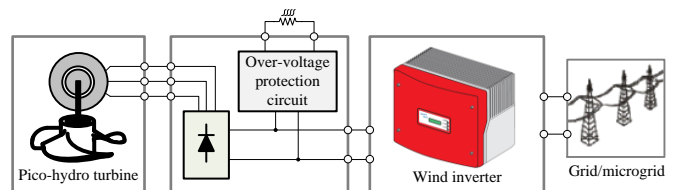


Figure 2. Grid-connected pico-hydro systems using conventional wind inverters.

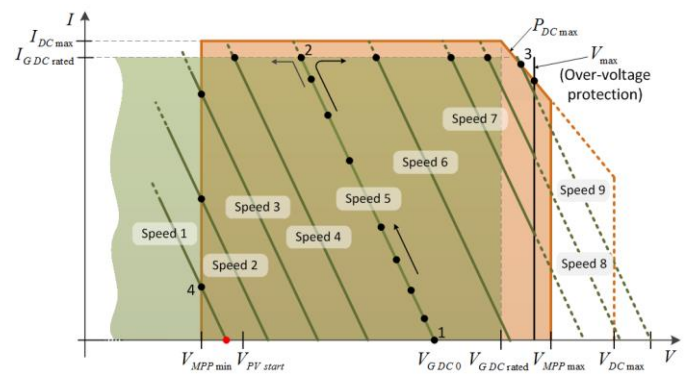


Figure 3. Overlapping of the operating areas of PV inverter and PMSG.

incremental current variation in finding the MPP. Usually, this situation occurs near the generator rated current, preventing critical overloads.

Photovoltaic micro inverters, for output power levels of the order of magnitude of 200 to 250 W, have recently been brought to the market. They can also be explored with very small wind generators in pico-hydro systems, which have been unexplored till now. The energy production can be much higher than the one produced with a PV module, depending on the solar potential of the site, since it works 24 hours a day.

III. EXPERIMENTAL RESULTS

This section presents some experimental results for the three approaches described above to connect PMSG-based pico-hydro systems to the grid.

A pico-hydro turbine emulator was implemented in the laboratory by means of an inverter controlled squirrel cage induction motor of 3 kW rated power [21]. Typically, hydro turbines present low dynamics speed variations due to high damping factor and inertia. Therefore, it is possible to consider the speed control of the electrical drive, as previously performed in [19]. Nevertheless, to emulate flow variations or various head and flow combinations, it was adopted the power control of the drive which results in a variable speed operation, being the inverter connected to the grid responsible for the efficiency and power management of the overall system [21]. It was used the over-voltage protection circuit described in [21]. The steady-state and dynamic operation of the three proposed approaches have been tested with: a) the specifically designed power converter shown in Fig. 1, b) a standard wind inverter and c) two standard PV inverters. For this purpose, extensive steady-state and dynamic experimental tests have also been performed. Two different PMSG were used with the technical data presented in Table I. Table II introduces the main characteristics of the standard wind and PV inverters.

A. Grid-connection using a specifically designed power converter

To demonstrate this approach, a power topology emulating a typical power inverter used in wind and PV applications was used and is illustrated in Fig. 1. The experimental set-up is based on MATLAB with Simulink and dSPACE ACE kit based on the 1103 controller board. The boost converter and the voltage source inverter (VSI) are implemented with the intelligent power module (IPM) PM75RLA120 from Powerex by suitable control of the seven IGBTs of this IPM. The boost converter is current controlled by means of a PI controller, providing MPP tracking by using the so-called Perturb & Observe algorithm. The VSI controls the DC-Link voltage as well as the active and reactive power injected into the grid. The control scheme of the VSI is based on Voltage Oriented Control as described in [28, 29].

Fig. 4 presents the I-V plots corresponding to the output DC current as a function of the output DC voltage of the generators as illustrated in Fig. 3. Fig. 5 shows additional tests in order to evaluate the effect of the generator (hydro system) dynamics. Tests with the generator 1 (left) consist of three runs from 1600 rpm to 900 rpm with different deceleration times.

TABLE I
TECHNICAL DATA OF THE PMSG

Gen.	Speed (rpm)	V_{DC0} (V)	V_{DC} (V)	I_{DC} (A)	P_{DC} (W)
1	1500	219	150	8.6	1297
2	1500	381	266	4.9	1300
3	300	45	28	10.71	300

TABLE II
TECHNICAL DATA OF THE INVERTERS

	Wind Inverter	PV Inverters		PV Micro Inverter ⁽¹⁾
	WB 1200	SB 1500	SB 2100TL	SB 240-10
$P_{DC\ max}$ (W)	1320	1600	2200	245
$I_{DC\ max}$ (A)	12.6	10	11	8.5
$V_{DC\ min}$ (V)	100	50	125	23
$V_{DC\ max}$ (V)	400	600	600	45
$V_{MPP\ range}$ (V)	100-320	160-500	125-480	23-32

⁽¹⁾ With Sunny Multigate, from SMA.

Tests with the generator 2 (right) consist of two runs 500-1600-500 rpm, with different acceleration / deceleration times.

The steady-state operation of the system with Generator 1 is reported in Fig. 6 by the DC current and power versus DC voltage at various speeds. The inverter efficiency, injecting power to the grid, varies from 68% to 89%. $I_{DC\ max}$ is set by the inverter in the rated value of the generator.

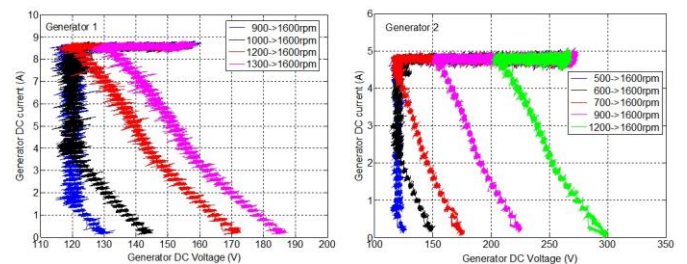


Figure 4. I-V plots with the Generator 1 (left) and Generator 2 (right) starting from different speeds up to 1600 rpm.

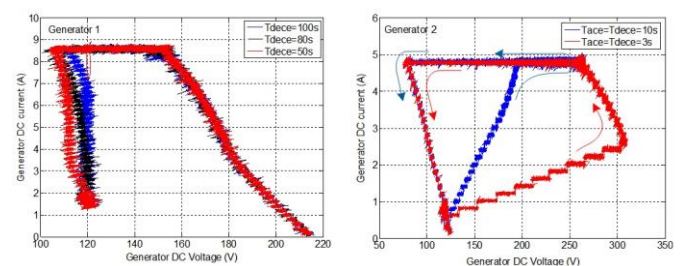


Figure 5. Evaluation of the generator (hydro system) dynamics: decelerations from 1600 rpm to 900 rpm with Generator 1 (left) and two runs 500-1600-500 rpm with Generator 2 (right).

B. Grid-connection using a standard wind inverter

To evaluate the feasibility of this approach it was used the wind inverter WB1200 from SMA with Generator 2, whose main characteristics were previously introduced. The wind inverter has two modes of operation [30]: Turbine and Maximum Power Point (MPP). A third operating mode is also available - Constant voltage mode (V-Const) which can be used if a power converter is used between the generator and the WB 1200, e.g. the boost converter of the power topology shown in Fig. 1. This power converter can be avoided if the turbine operates at constant speed and, therefore, constant voltage, but this is not the context of the applications of this work.

To explore the Turbine operating mode, the first step was the definition of the maximum power curve given by (1) from experimental data with the selected generator. The parametrization of the inverter power curve, obtained experimentally from tests with Generator 2, loaded with its rated DC current for different speeds, is given by

$$P_{AC} = -6.6738 + 4.3702V_{DC} \quad (1)$$

The other parameters were set as follows: grid connection voltage, $V_{pv-Start} = 150$ V; starting point of the output characteristic, $V_{dcWindStart} = 90$ V; maximum AC output power of the inverter, $P_{max} = 1200$ W; proportional factor of the power control, $K_{PWind-Reg} = 0.25$; integral factor of the power control $K_{IWind-Reg} = 0.002$, and finally the configuration of the controlled startup of the system, $P_{Wind-Ramp} = 10$ W/step.

Fig. 7(a) and (b) show the steady-state performance of the system, with Generator 2 connected to the WB 1200 in Turbine and MPP operation modes, respectively.

To evaluate the performance of the approach based on the WB 1200 in dynamic conditions, both in Turbine mode and in MPP mode, several experimental tests were carried out with the protection circuit. Fig. 8 reports a grid failure for the power conversion structure in analysis, in Turbine and MPP operating modes. The maximum voltage allowed in the DC bus, set by the over-voltage protection circuit, was set in 335 V with a hysteresis band of about 20 V. The experimental data acquisition set-up was based on the MATLAB with Simulink and the dSPACE 1103 controller board.

C. Grid-connection using photovoltaic inverters

C1. Grid-connection using standard PV inverters

The experimental feasibility of this approach is demonstrated with two PV inverters - SB1500 and SB20100TL from SMA (Table II). The results obtained in steady-state operation are reported in Fig. 9 and 10 with Generator 1 and Generator 2, respectively.

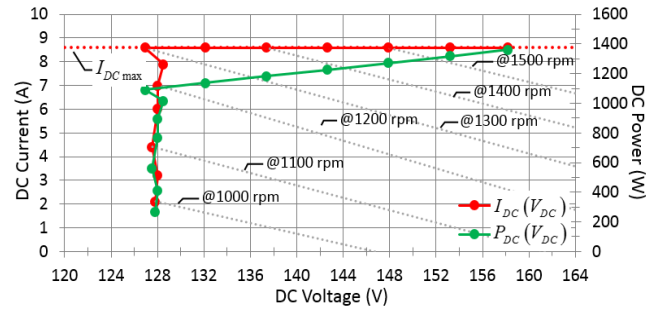


Figure 6. Steady-state operation of Generator 1 with the power converter of Fig. 1.

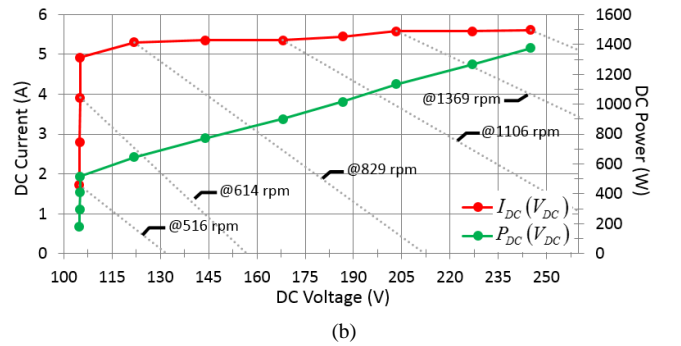
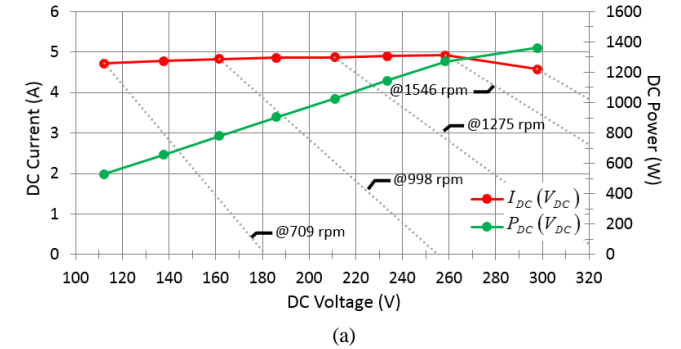
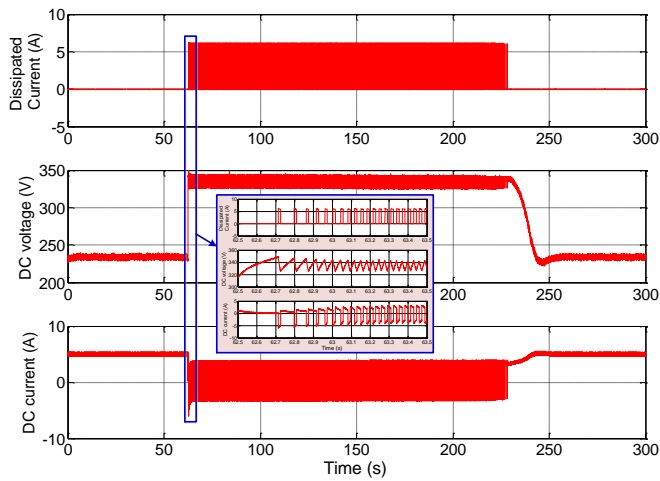


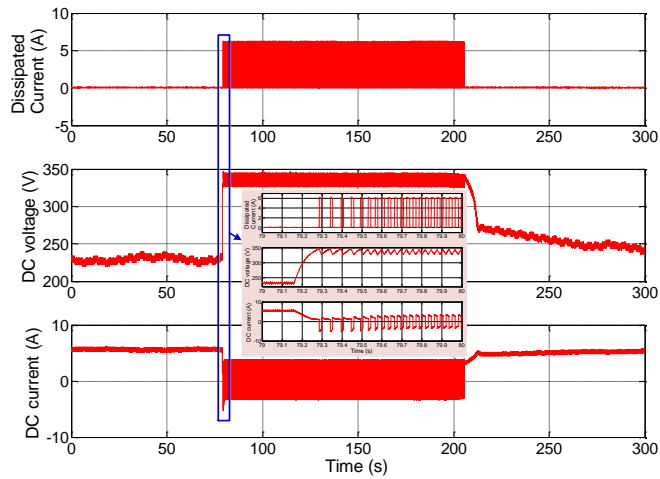
Figure 7. Steady-state operation of Generator 2 with the WB1200 in (a) Turbine operation mode and (b) in MPP operation mode.

Dynamic tests, with the experimental data acquisition set-up previously introduced, were also carried out with the proposed topology using SB 1500 and SB 2100TL inverters and Generators 1 and 2. The threshold of the maximum voltage allowed in the DC bus, set by the over-voltage protection circuit, was 180 V for the topology using Generator 1 and 250 V when using Generator 2.

Fig. 11 presents the synchronization with the grid and Fig. 12 reports a grid failure test. The power flow is diverted from the generator to the auxiliary power resistor by the over-voltage protection circuit, respectively, before the inverter start injecting the power into the grid and during the grid failure.



(a)



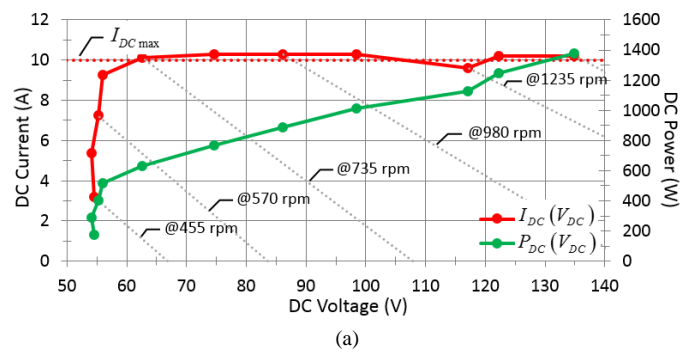
(b)

Figure 8. Steady-state operation of Generator 2 with the WB1200 during the grid failure: (a) In turbine operation mode and (b) in MPP operation mode.

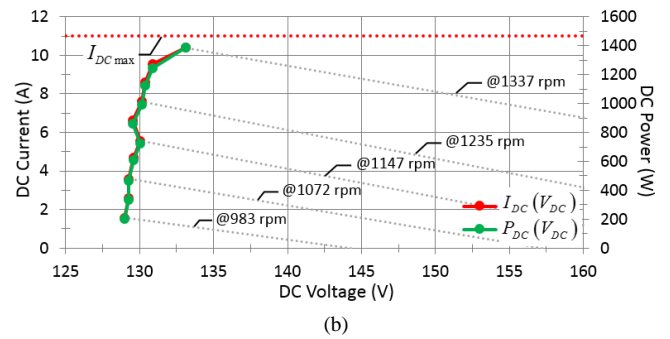
C2. Grid-connection using PV micro inverters

The experimental feasibility of using PV micro inverters with very low power PMSG in hydro systems is also demonstrated. For this purpose it was used the micro inverter SB240-10 (with Sunny Multigate) from SMA (Table II) and the generator 3 (Table I) AFPMG260-0.3kW/300RPM. The results obtained in steady-state operation are presented in Fig. 13.

Several dynamic tests were also carried out and the obtained results are similar to those presented in the previous section, with standard PV inverters and generators 1 and 2. Fig. 14 shows the DC current, the DC voltage and the dissipated current before, during and after a grid failure.

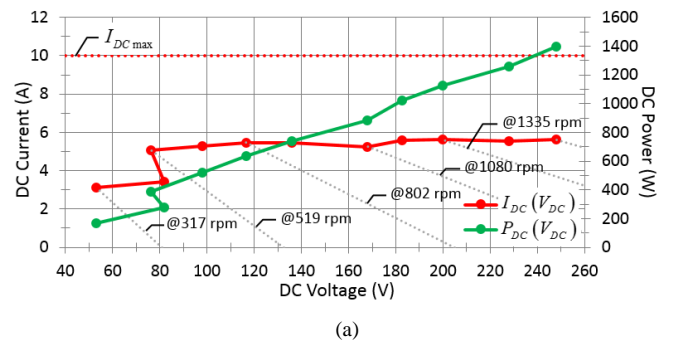


(a)

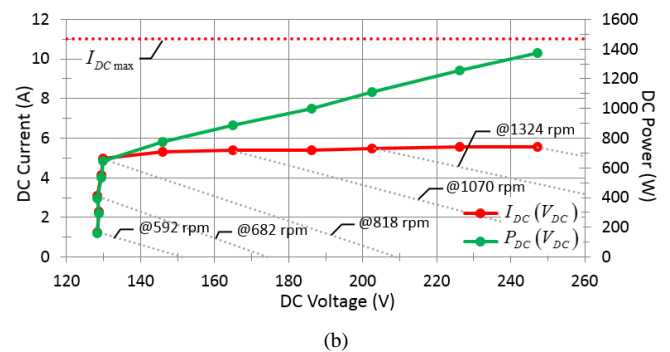


(b)

Figure 9. Steady-state operation of Generator 1 with (a) SB1500 and (b) SB2100TL.



(a)



(b)

Figure 10. Steady-state operation of Generator 2 with (a) SB1500 and (b) SB2100TL.

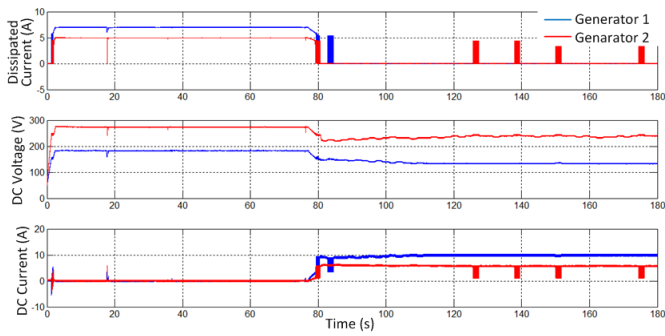
IV. DISCUSSION

A. Grid-connection using dedicated power converters

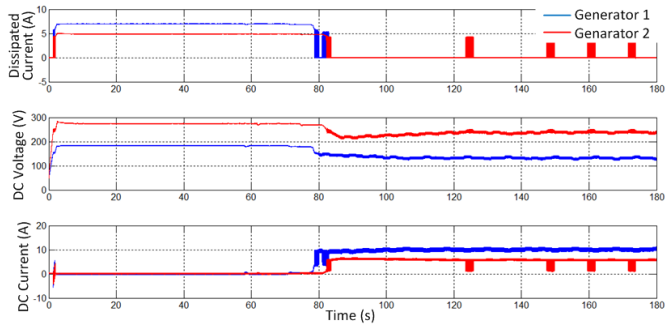
The most flexible and perhaps the most efficient approach for grid-connection pico-hydro systems is one based on dedicated power converters. In this case, the MPP tracking algorithm can be specifically designed and tuned for a specific application/site. Furthermore, other MPP tracking strategies can be applied for convenience such as tracking a power curve and the over-voltage protection circuit can also be integrated. However, this kind of approach for grid connection like the one presented in Fig. 1, or other ones described in literature [14, 16-18], are much more expensive and far way to be an off-the-shelf technology easily available on the market [19]. The results shown in previous section demonstrate that it is possible to overcome this disadvantage, with effective and efficient alternatives by using wind or PV inverters widely available on the market with costs increasingly affordable.

B. Grid-connection using dedicated power converters

Conventional wind inverters are a suitable and efficient approach for grid-connected pico-hydro systems. There is an interesting range of products on the market for small wind turbines that can also be applied in pico-hydro applications. However, it is necessary to obtain the maximum power curve

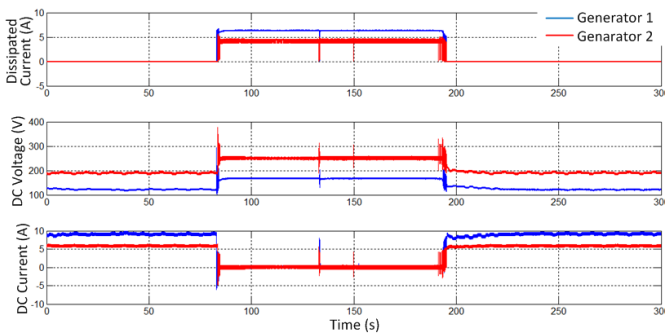


(a)

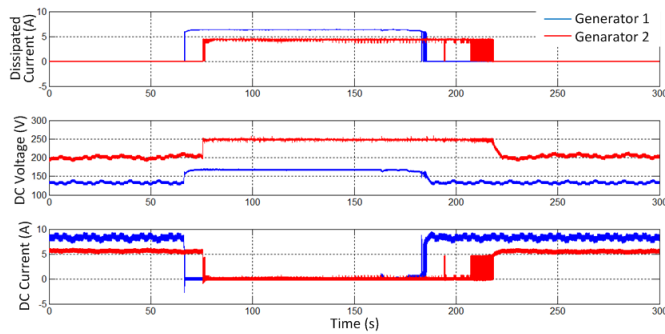


(b)

Figure 11. Synchronization with the grid with (a) SB 1500 and (b) SB 2100TL inverters.



(a)



(b)

Figure 12. Grid failure with (a) SB 1500 and (b) SB 2100TL inverters.

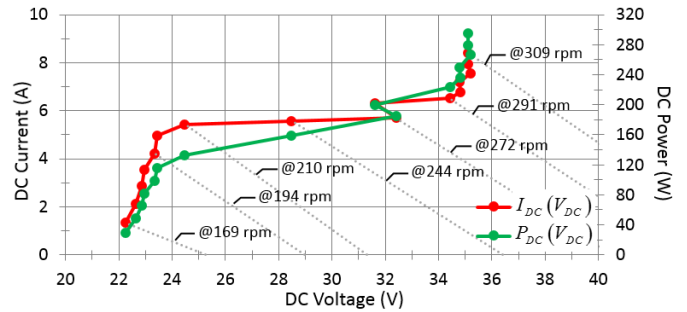


Figure 13. Steady-state operation of Generator 3 with the micro inverter.

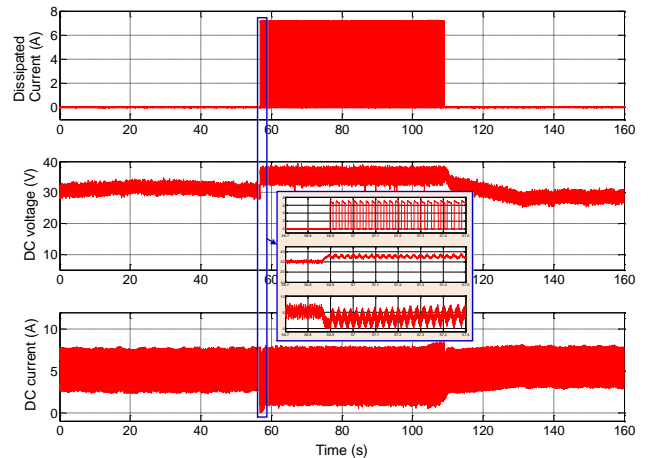


Figure 14. Grid failure with SB 240-10 and Generator 3.

given by (1) from experimental data because the most likely, in the case of pico-hydro turbines, it is not available. Furthermore, other parameters must be adjusted. For example, in the case of power converter structure under analysis (Generator 1 and inverter WB 1200) the parameter $K_{P_{Wind-Reg}}$ was changed from 0.001 to 0.25 in order to improve stability in a wide range of speeds.

Remarkably, in the case of the WB 1200, is the fact that the MPP operating mode used for PV systems, be also available. Experimental results presented above show that it is possible to use this mode of operation provided that a suitable design procedure is used to integrate the PMSG with the inverter.

C. Grid-connection using photovoltaic inverters

C1. Grid-connection using standard PV inverters

From the obtained results for steady-state performance and the analysis of the dynamic behaviour in specific conditions, it can be seen that the integration procedure of PV inverters with selected generators preconizes a stable and reliable configuration for grid-connected pico-hydro systems.

Regarding the steady-state analysis, it can be seen that operating points of the generators are within the SOA of the inverters without surpassing their rated quantities in a critical extent, provided that the reference mechanical power is kept in the power range of the generators and the compatibility conditions are verified. For each tested generator, both inverters are able to process the available mechanical power, though with different I-V characteristics for each generator. Generators work within the MPP range with SB 2100TL inverter (Fig. 9 (b) and 10 (b)), but when using SB 1500 inverter, the locus of the operating point is, in a large extent, out of its MPP range due to the deviation between its minimum input voltage (50 V) and minimum MPP voltage (Fig. 9 (a) and 10 (a)).

It can be seen that for a given mechanical power reference, the inverter imposes an increasing current while keeping the voltage around its minimum input voltage till reaching its maximum DC input current or while the ratio between the processed power and the minimum input DC voltage is lower than the rated current of the generator. For instance, Generators 1 and 2 have rated currents of 8.6 A and 4.9 A, respectively. While $P_{DC}/V_{DC_{min}}$ is lower than those quantities, for an increasing input power both inverters increase the current till this increment is overlapped by the voltage drop in the internal impedance of the generators for a given power to be processed. From this point forward, inverters increase the voltage, while keeping the current, approximately, in its previous maximum. Eventually, inverters may increase a little further the current (e.g., Fig. 9 (a) and 10 (a)) overloading the generators in an acceptable extent.

From the reported results in the dynamic analysis it can be seen that the time delay for the inverter synchronization with the grid is 80 seconds for both inverters (Fig. 11), being a parametrized value by manufacturers. After the synchronization, it can be seen that the topology using Generator 2 is operating with a DC voltage near the threshold of the maximum DC voltage allowed by the protection circuit

which leads to current divert to the auxiliary power resistor for short time intervals, restoring the DC voltage below its maximum allowed. Fig. 13 validates the instantaneous limitation of the DC voltage, when the grid fails, with the proposed topology using both inverters.

C2. Grid-connection using PV micro inverters

From the obtained results in steady-state operation, which are presented in Fig. 13, the micro inverter starts feeding power into the grid when the DC voltage of the generator is higher than 23 V ($V_{DC_{min}}$). After that, while the power is increasing, it keeps the operating point of the generator inside the MPP range while it is able to do that, according to the power generated by the turbine emulator. Around 32-33 V, the micro inverter tries to keep the operating point within the MPP range, as can be seen in Fig. 13. However, as the power continues increasing, the voltage also increases and the operating point goes out of that range. When the AC output power achieves 230 W, the excess of power is diverted to the auxiliary power resistor by means of the over-voltage protection circuit. From then on, the maximum DC voltage is limited to 35 V.

The extensive tests carried out in steady-state and dynamic operation demonstrate the feasibility of using PV micro inverters with PMSG in very low power hydro systems.

V. CONCLUSIONS

This paper discussed three practical approaches for grid-connected pico-hydro systems: 1) using dedicated power converters; 2) using conventional wind inverters, and 3) using photovoltaic inverters, including micro inverters recently launched in the market. All the presented approaches are suitable for grid-connected systems and they are powerful for integration in microgrids such as the one presented in [22, 23]. Integration approaches of pico-hydro systems based on conventional inverters are very interesting, preconizing a cost effective solution with off-the-shelf technology. The use of conventional PV inverters and micro inverters is especially interesting since it is a plug-and-play solution. This topology allows a variable speed operation mode whereas a maximum power efficiency operation tracking is provided by the PV inverter. However, like in small wind systems, an over-voltage protection circuit is required in order to protect both the generator and the inverter against special states, such as sudden relieving of the inverter due to grid failure. Steady-state and dynamic performances of the approaches based on conventional inverters have been experimentally tested under power control by using a turbine emulation system. The obtained results allow the validation of the proposed approaches for pico-hydro systems, particularly in applications with a wide speed range.

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