

Inverter design for four-wire micro-grids

Daniel Heredero-Peris, Marc Pagès-Giménez and Daniel Montesinos-Miracle
 Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC),
 Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya.
 ETS d'Enginyeria Industrial de Barcelona
 Av. Diagonal, 647, Pl. 2.08028 Barcelona, Spain

Abstract-- This paper presents a PQ plane four quadrant three-phase four-wire inverter for micro-grids integration. The inverter is based in two full-bridge IGBT modules connected in a three-phase configuration plus a three-phase parallelized neutral branch. This topology is galvanically isolated through a single-phase transformer bank. The converter operates as a non-ideal voltage-controlled voltage source inverter under AC droop strategy with hot-swap capability based on a dynamic virtual impedance.

Index Terms-- Micro-grid inverter, AC droop, independent PQ control, dynamic virtual resistor.

I. INTRODUCTION

Nowadays, most grid DER (Distributed Energy Resource) connected inverters behave as CC-VSI (Current-Controlled Voltage Sources Inverters) when they are connected to the low voltage distribution grid. Their main objective is to inject as much power as possible to the utility using MPPT (Maximum Power Point Tracking) algorithms. In most countries, the anti-islanding regulations, i.e. VDE0126-1-1 or IEC61727, requires that when the grid is off, the inverter has to be disconnected in a stipulated time, avoiding the creation of electrical islands. However, electrical distribution grids are expected to be smarter. In this direction, new ideas related with efficiency, reliability, robustness, managing and business are gaining strength, such as micro-grids, smart-grids, energy hubs, power routers, virtual power plants, among others.

Referring to the micro-grid concept [1]-[2], the main proposal behind this type of grids is that they can be considered as an evolution of the classical grids. The classical concept is based on a unidirectional distribution model. Otherwise, micro-grids are dynamic active controlled and coordinated bidirectional grids, where production and consumption are almost equal, managing up to few hundreds of kVA. They have to operate as part of a distribution grid (on-grid), also being able to be operated electrically disconnected from the grid (off-grid). A main switch element allows operating the system under both modes. Then, a micro-grid has also to include not only micro-energy generation with sufficient DERs credits, but also monitoring and hierarchical control systems [3]. This hierarchy is handled by distributed LC (Local Controllers) elements and MGCC (Micro-Grid Central Controller) centralized units which requires communications. The requests from the MGCC can come from a DNO (Distribution Network Operator), a MO (Market Operator) or a service provider when on-grid, see Figure 1.

Micro-grids can help to delay investments on new electrical infrastructures becoming a new entity where it is possible to

find new challenges thanks to coordination tasks. Some of these opportunities can be peak shaving capacity, energy optimization, voltage regulation, GHG (Green House Gases) reduction, local market values, aggregation energy exchanges, etc.

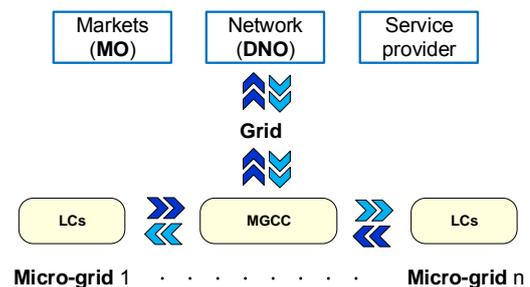


Figure 1. Micro-grid system interaction

One of the possible micro-grid classification depends on the voltage link: DC micro-grids, AC micro-grids or the combination of both, the hybrid micro-grids. An example of a hybrid micro-grid can be observed in Figure 2. Consequently, micro-grids need some elements, the power converters, acting as interfaces between DERs, storage units, the voltage-links or the local loads. One of the most important parts of an urban or industrial AC micro-grid is the inverter because most of usual loads are supplied by AC voltage. This inverter is the physical link between the DC micro-grid and the most usual loads. It must create the voltage and frequency stable enough for a correct operation of connected loads when is off-grid operated.

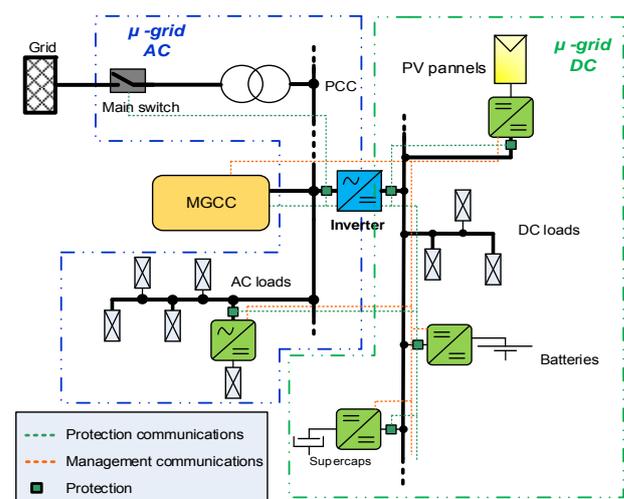


Figure 2. Hybrid micro-grid scheme example

This paper presents the control of an inverter for AC micro-grid integration. The interface with the AC side is done through

a three-phase four-wire inverter which control is developed under the AC droop strategy allowing to be parallelized with other inverters. Thanks to this control alternative it is possible to operate always as a VC-VSI (Voltage-Controlled Voltage Source Inverter). The AC control is performed with hot-swap capability using dynamic virtual resistor. This converter is able to generate a local voltage reference when operates in off-grid, controlling the amplitude and frequency of each phase using adaptive resonant controllers. Also, it manages independently per phase active and reactive targets when on-grid. Thus, the converter operates in the four quadrants per phase in the PQ plane when is exchanging power with the utility.

II. THE AC MICRO-GRIDS

A. AC micro-grid operation

The interconnection between the micro-grid and the grid is carried out downstream of the PCC (Point of Common Coupling), see Figure 2. Thus, the micro-grid can be considered as a single entity by the grid. There exist two operation modes: on-grid connected mode and off-grid mode, but it is also important to highlight transitions issues. Figure 3 shows the operation functionalities of a micro-grid.

- *On-grid mode*: It is the main operation mode. The micro-grid operates in conjunction with the utility grid, exchanging energy in function of the system needs.
- *Off-grid mode*: The micro-grid must be disconnected from the grid in two possible situations: a planned disconnection or a sudden disconnection.

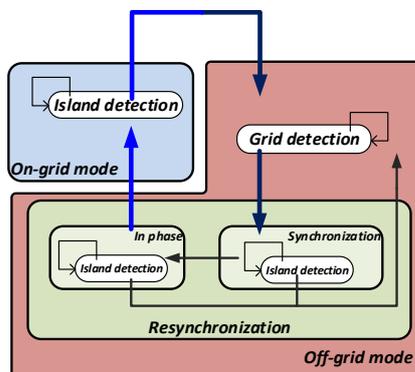


Figure 3. AC micro-grid operation modes

When a fault is detected at the utility grid or any maintenance is needed, the management system has to disconnect the micro-grid from the grid, as fast as possible, and start the off-grid mode. When the main grid is sufficient stable, the MGCC system can decide to start a resynchronization and reconnection procedure. Anti-islanding methods, active and/or passive, has to be considered [4]. In order to determine which voltages disturbances are allowable when a transition occurs, the ITI (old CBEMA) curve [5] could be considered as a reference pattern.

B. Type of micro-grid inverters

In a generic AC micro-grid it is possible to find different type of inverters concerning to control issues [7]:

- *Grid supply inverter*: Are the most common inverters. They operate as unidirectional CC-VSI when on-grid injecting the maximum power available on its connected

DER. When off-grid, they need an external voltage reference with to inject power.

- *Grid constitution inverter*: Basically are VC-VSIs that when on-grid they act as a mirror of the utility. Practically there is no power exchange apart of internal losses. When off-grid, they continue with the last grid connected reference but from this instant it self-generates the voltage reference. It plays the role of the master of the island being the only VC-VSI of the system.
- *Grid support and constitution inverter*: Are non-ideal VC-VSIs. Are based on the AC droop control strategy that handles two degrees of freedom: voltage amplitude and frequency. This allows operating as a parallel source when on-grid, being able to inject or consume requested active or reactive power. When off-grid they continue operating as VC-VSIs self-generating the voltage and frequency with the called secondary control [3].

One of the key points of identify which type of inverters are installed in an AC micro-grid it is related on how transference can be faced. If the inverter is a grid-supply device it has to operate by a black-out and re-initialize the system as a VC-VSI or using a flying transference strategy, changing its behaviour from CC-VSI to VC-VSI [6]. This last option implies to use more sophisticated transference strategies if no grid constitution inverter is present in the AC micro-grid. On the other hand, grid support and constitution inverters do not need a change on its operating behaviour in any of both operation modes.

III. THE PROPOSED CONVERTER BASES

The converter must become a flexible device to be integrated in a general AC micro-grid. The AC side must be able to manage both linear and non-linear single or three-phase loads. Thus, the power electronics needs to deal with next specifications.

A. General features of the full converter

The converter must act as a bidirectional interface between the DC micro-grid side and the AC side in order to charge/discharge different storage systems of the DC micro-grid and transfer the energy from/to the grid in any phase combination. It implies that, while on phase can be injecting energy from the DC-side, another one can be consuming from the AC-side. The configuration parameters and references are controlled by the MGCC. The MGCC handles all micro-grid systems, from loads, storage or power converters up to protections or neutral reconfiguration, if necessary.

B. Operation modes and managing strategies

The micro-grid has to operate in the two operating modes aforementioned:

- *On-grid mode*: The micro-grid remains connected to the utility grid. The external utility grid provides the voltage and frequency references to other systems. Active and reactive power values of each phase has to be controlled totally independently of each other. The MGCC sends P and Q requests for each of the phases (either in the direction of charging or discharging).
- *Off-grid mode*: The system will provide voltage and frequency references to other systems, as other grid supply inverters or loads.

During operation there will be transients. These transients can be deliberated or automatic (non-predicted):

- *Deliberated*: The converter accepts an external signal emitted by the MGCC. This implies that the transition occurs instantaneously.
- *Automatic*: The converter should monitor at all-time the grid parameters. When some grid magnitudes are out of a certain range or limits, the converter must manage the transition from on-grid mode to off-grid mode, minimizing the existence and impact of any kind of voltage dip or sag and creates a grid error flag. After the transition, the isolated voltage must follow the voltage waveform at pre-connected values. The ranges limits of the grid conditions governing this transition has to be configurable.

The most problematic transition is the one that goes from on-grid to off-grid, especially when the transient is no-deliberated. The complementary transition is planned. Thus, really smooth transients can be achieved by the proper resynchronization procedure, as using a PLL (Phase Locked Loop) with various operating modes, as can be seen in Figure 4. This PLL has three functional modes; Mode 0: PLL is synchronized with the grid, Mode 1: output angle is self-generated and Mode 2: for reconnection purposes, output voltage angle is self-generated, but synchronized with the grid. U_g is the grid voltage, f_g and θ_g are the frequency and angle of the grid, V_{d-qg} are the direct and quadrature voltage in the synchronous reference, θ_1 is the angle in off-grid when no-grid is present, θ_R is the resynchronized angle and, finally, θ is the operation angle.

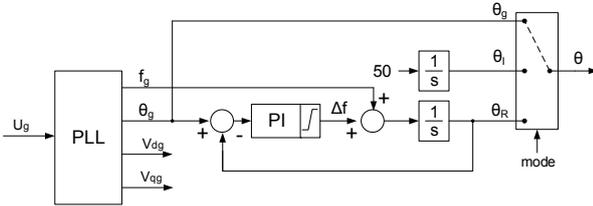


Figure 4. PLL operation modes proposed

The other possible transition is when the grid is again within correct thresholds or the system requires to operate towards the grid. The first step consists in a recovery grid detection algorithm and the transmission of a signal to the MGCC of the micro-grid indicating this situation. Once is received this information, the converter begins the process of synchronization with the external grid. Then, the converter sends a signal to the MGCC when synchronization is done and remains in the off-grid operation mode in synchronization (in phase) with the external grid until it receives a reconnection signal by the MGCC. Finally, the converter switches to on-grid mode, see Figure 3.

IV. HARDWARE AND CONTROL IMPLEMENTATION

Real electrical systems are usually integrated by non-balanced and non-linear local loads. To control absolutely a non-balanced system it is necessary to consider a structure that allows managing the direct, inverse and homopolar components. Due to this challenge, it is necessary to take into account some hardware and control considerations.

A. Hardware considerations

A typical three-branch three-wire inverter topology must be avoided in order to use a three-phase four-wire structure if it is desired to operate/create a complete controllable non-balanced system. This can be implemented, mainly, using a three-phase split-capacitor with the mid-point connected to the neutral or a four-branch structure. In this paper, four-branch inverter has been chosen using two three-phase full-bridge modules, as can be seen in the complete schematic of Figure 5, due to AC side must be able to manage either single or three-phase loads with any phase combination. This implies that the three active phases can be operated without any shift between them on the inverter side. Thus, the current though the neutral wire can achieve three-times the current that is circulating per each phase.

If galvanic isolation is required, a free-flux transformer has to be used. Ironclad transformer, three single-phase banks or five columns transformer are free-flux options. In this case, the three single-phase bank alternative has been chosen, as is shown in Figure 5.

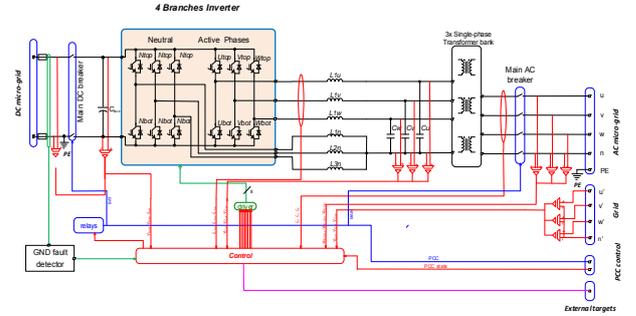


Figure 5. Scheme of the full DC/DC and DC/AC converter proposed

B. Control algorithms considerations

The inverter is controlled by means of an internal LCL filter inductor current controller, and for operating as a non-ideal VC-VSI, the voltage at the LCL filter capacitor is controlled in cascade with a more external loop based on AC droop [3],[7]-[8].

The droop control operation principles are deduced from the equations that describe the power flow through a resistive-inductive line. In function of the power balance between generation and consumption, it is possible to adapt the output inverter voltage frequency and amplitude to adjust the injection of active and reactive power So, considering a grid with two nodes, A-B, and with a line impedance where $X_L \gg R$, active power can be obtained from

$$\delta \approx \frac{X}{U_A \cdot U_B} \cdot P \quad (1)$$

where U_A and U_B are voltages at nodes A and B respectively, X is the grid impedance, δ the angle difference between voltages at nodes A and B, and P is the active power. And reactive power can be computed from

$$U_A - U_B \approx \frac{X}{U_A} \cdot Q \quad (2)$$

where Q is the reactive power. In function of the power balance between generation and consumption, it is possible to adapt the output inverter voltage frequency and amplitude to adjust the injection of active and reactive power as

$$\omega - \omega_0 = -m \cdot (P - P_0) \quad (3)$$

$$U - U_0 = -n \cdot (Q - Q_0) \quad (4)$$

where U_0 and ω_0 are the nominal voltage and angular frequency of the grid, respectively, while U and ω are the current values. It is possible to deduce a direct linear relationship between the power angle and active power, whereas the voltage difference depends on reactive power. However, in a general case, the impedance of a micro-grid will not be purely inductive. New relation for P and Q can be obtained using the rotation matrix that takes into account the grid. The virtual impedance concept [3],[7] it is also used. Figure 6 shows the implemented droop algorithm per each phase of the inverter.

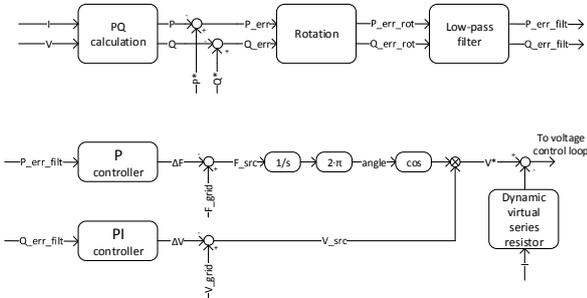


Figure 6. Scheme of the P/Q error calculation and rotation

With the voltage and current at the grid side, P/Q and P/Q error can be calculated. With a rotation of these two components, a new error is obtained. The angle of this rotation depends on the resistive/inductive relation of the impedance in a way that the rotated components have a P/Q to V/f relationship as if the impedance was purely inductive. Then, a low-pass filter is used to suppress noise and harmonic effects in the system and at the same time it provides a virtual inertia like in a synchronous generator. The resulted P and Q error are introduced into the droop controllers which effort is related to the amplitude and frequency of the referenced voltage.

Since the real impedance of the system is formed by the addition of the output transformer and the Thévenin impedance of the grid, it is assumed to be relatively low. A low impedance value may cause high gain in the plant of the system, i.e. high power flow variations would be caused by low voltage and frequency variations in the converter. On the other hand, the impedance can vary depending on the converter allocation, due to the differences in the short-circuit ratio of the grid. In order to avoid all these issues regarding stability of the system, a dynamic virtual impedance is proposed. This impedance consists in a voltage drop in the reference as a result of a virtual resistor value and the current delivered to the grid. The value of the resistor is assumed to be one order of magnitude higher than the output transformer impedance. The rotation and controller gain must be recalculated taking in account the new equivalent impedance.

A hot-swap method is used to have a successful initialization of the whole system in the grid connected mode. This method consists in a dynamic value of the virtual series resistance. The system operation is started with a one order of magnitude higher value and it is reduced to the normal operating value with a time-ramp. The initial output angle must also be initialized to the grid value at the starting time.

On the other hand, inner loops are crucial to achieve independent references and to affront non-linear load issues. For the inner loops, PR (Proportional-Resonant) with HC (Harmonic Compensation) controllers are a good candidate for tracking sinusoidal references using SOGI (Second Order Generalized Structure) structures, as can be observed in Figure 7. In this case, are based on dynamic resonant controllers developed from the current PR approach presented in [9]. It is based on find a simplification of the obtained close-loop transmittances to get an expression that can be treated as a second order system.

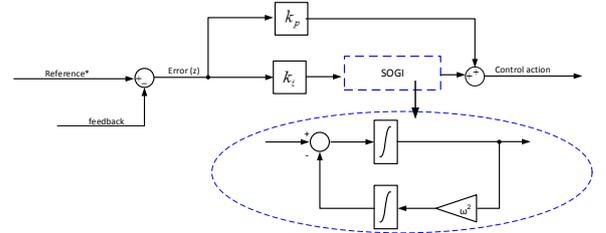


Figure 7. Scheme of a PR controller

Thus, following the same rules exposed in [9] and assuming that the current close-loop cut-off frequency is at least one decade higher than the AC voltage loop, the time response of current loop is faster and a unity gain it is possible to find the controller gains for the fundamental frequency of the AC voltage loop per phase as

$$\begin{aligned} k_{p,v} &= Ak_v \\ k_{i,v} &= \frac{k_v - k_{p,v}}{\omega_0 T_s} \end{aligned} \quad (5)$$

where

$$\begin{cases} k_v = \frac{2 - 2\rho \cos(\theta)}{D} \\ A = \frac{1 - \rho^2}{k_v D} \end{cases} \quad (6)$$

with $D = \frac{T_s}{C}$, being T_s the switching time in seconds, C the capacitance in F of the LCL capacitor and ω_0 the desired pulsation in rad/s to control. In this way, ρ and θ can be defined as parameters that depends of the damping factor ξ , the natural pulsation ω_n and the set time t_s as

$$\begin{cases} \rho = e^{-\xi \omega_n t_s} \\ \theta = \omega_n t_s \sqrt{1 - \xi^2} \end{cases} \quad (7)$$

It can be observed in (6) that only re-scaling k_{i_v} with a ω_0/ω_0' factor, being ω_0' the new desired pulsation, the controller can be dynamically adjusted to obtain zero permanent error if the tuning specification does not change.

V. EXPERIMENTAL PLATFORM AND RESULTS

The experimental micro-grid inverter proposed is sized to manage up to 135 kVA of rated power and is presented in Figure 8. All IGBT stacks used are Semikron IGD_2_424 interfaced by optic fiber with the control boards. The AC coupling filters elements are summarised in Table 1. The chosen switching frequency is 8 kHz. The selected input voltage range of the converter in the DC micro-grid is 700 V_{DC}. The interaction between AC output side of the converter and the micro-grid is at 400 V_{AC} and 50 Hz micro-grid with TT or TN-S ground connection scheme with galvanic isolation.

TABLE I

BATTERY CELLS PARAMETERS

| ELEMENT | SUB-ELEMENT | VALUE | UNIT |
|---------------|--------------------------------|-------|---------------|
| AC LCL filter | Output phase inductance | 250 | μH |
| | Output neutral inductance | 750 | μH |
| | Transformer leakage inductance | 70 | μH |
| | AC Capacitor | 350 | μF |

There exists several test that can be applied to the micro-grid inverter. In this paper it is proposed to show the behaviour of the device using four significant procedures.



Figure 8. Proposed up to 135 kVA micro-grid converter

- *Transition from on-grid to off-grid at maximum power without connected load:* Phase U is injecting 45 kW while the other two are with null P/Q requests. Then, a forced disconnection to start operating in off-grid is done. Figure 9 shows the proper behaviour of the voltage, creating a short-duration dip that meets ITI curve. Figure 9.a are the simulated simple voltage and current of the phase U. Figure 9.b presents an oscilloscope capture of the same test with bottom zoom image.
- *Transition from off-grid to on-grid with load:* the system is working in off-grid with a local single-phase load of about 2Ω connected to phase U. Then a reconnection procedure is forced with null P/Q requests in all phases. Figure 10 shows the proper behaviour of the voltage, creating a short-duration dip that meets ITI curve. It is possible to observe that after reconnection, almost no current is flowing to the grid. Figure 10.a are the simulated simple voltage and current of the phase U. Figure 10.b presents an oscilloscope capture of the same test with bottom zoom image.

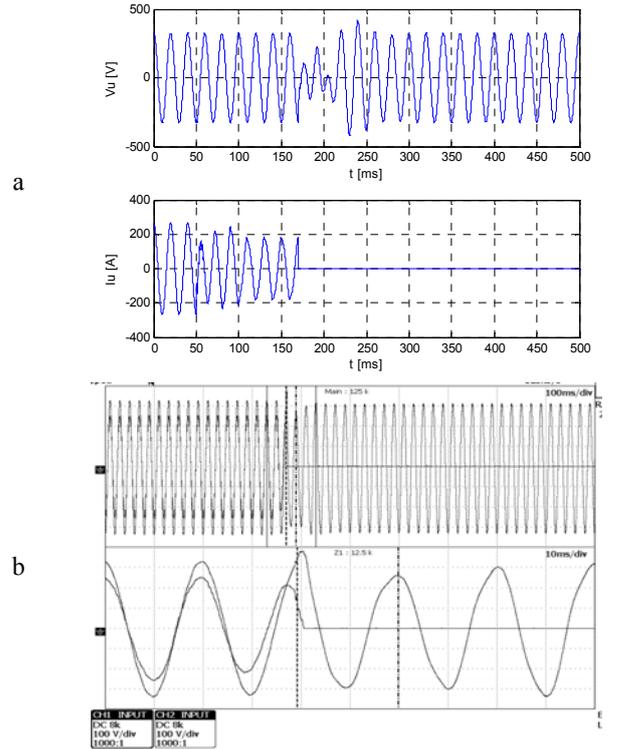


Figure 9. Voltage and current behaviour when on-grid to off-grid transference without load

- a) Simulation results
b) Experimental results

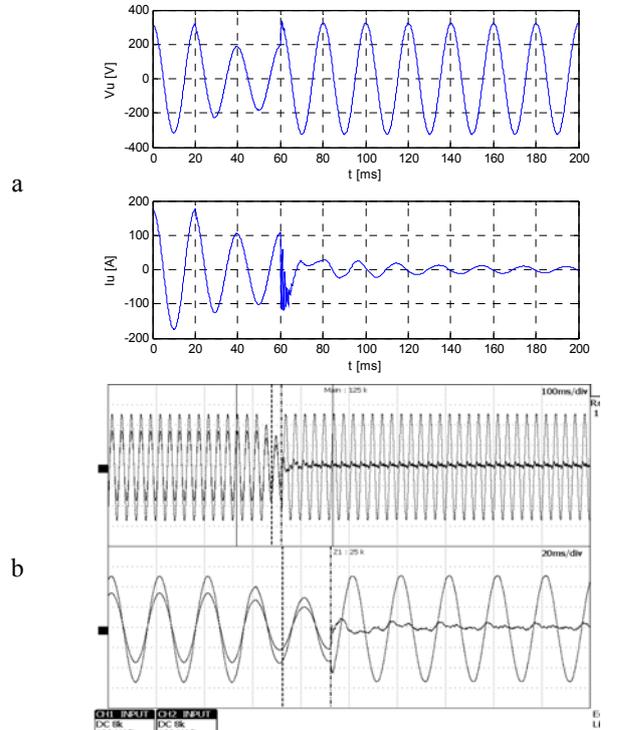


Figure 10. Voltage and current behaviour when off-grid to on-grid transference with load

- a) Simulation results
b) Experimental results

- *Inverter operating in on-grid with unbalanced P requests:* the system is operating in on-grid with MGCC PQ requests being $P_U = 30$ kW, $P_V = -30$ kW, $P_W = 30$ kW and Q_s all nulls. Figure 11 shows that the inverter is capable to synthesize non balanced currents from non-balanced targets.
- *Inverter operating in off-grid load transient:* the system is operating in off-grid with MGCC V/f requests being V_U 400 and 50 Hz without any connected load. Then, a local single-phase load of about 2Ω is connected to phase U. Figure 12 shows the current and simple voltage waveforms during the connection of the local load. Again, appears short-duration dip that also meets ITI curve

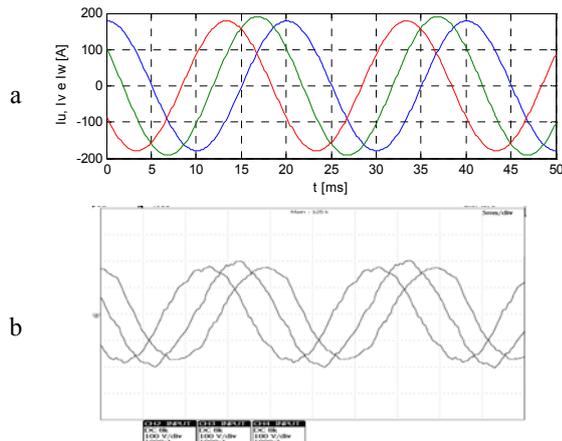


Figure 11. Current wave-forms on the inverter side when unbalance P
 a) Simulation results
 b) Experimental results

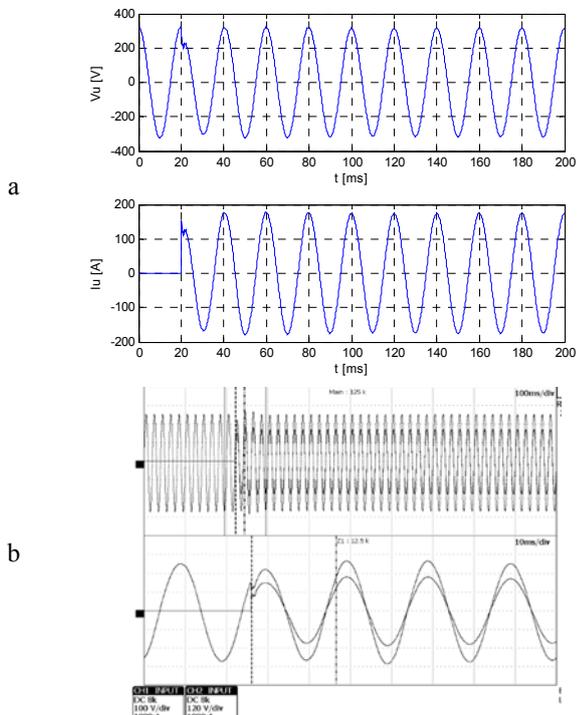


Figure 12. Voltage and current behaviour when off-grid load transient
 a) Simulation results
 b) Experimental results

VI. CONCLUSIONS

This paper has exposed the problematic of current grid supply inverters and proposes a converter to be integrated in a AC micro-grid as an alternative to enhance the current distribution grid. It has been also briefly defined which kind of elements are necessary and which functional modes and strategies can be adopted to satisfy a three-phase system with any kind of local load connected.

It has been designed, simulated, constructed and tested a 135 kVA converter with a four-wire AC output and low-frequency galvanic isolation that can be configured to operate connected to the grid and/or islanded from it. The control strategy used is based on AC droop control complementing it with hot-swap capability thanks to variable virtual resistor implementation. For all test proposed, simulated behaviour matches with experimental results without dangerous over/under voltages for local load supply. The proper validation of the results has been done considering as a pattern the ITI curve extrapolated to 230V-50 Hz.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union seventh framework program FP7-ICT-2013-11 under grant agreement 619610 (Smart Rural Grid).

REFERENCES

- [1] N. Hatzigiorgiou, "Architectures and Control", John Wiley and Sons Ltd, Chichester, Wiley - IEEE, 2014
- [2] Kroposki, R. Lasseter, T. Ise, and et al., "Making microgrids work," Power and Energy Magazine, IEEE, vol. 6, no. 3, pp. 40–53, May-June 2008.
- [3] J. Guerrero, J. Vasquez, J. Matas, L. de Vicua, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids," Industrial Electronics, IEEE Transactions on, vol. 58, no. 1, pp. 158–172, Jan.2011.
- [4] Kunte, R.S.; Wenzhong Gao, "Comparison and review of islanding detection techniques for distributed energy resources," Power Symposium, 2008. NAPS '08. 40th North American , vol., no., pp.1,8, 28-30 Sept. 2008
- [5] ITI (CBEMA) Curve application note, Information Technology Industry Council. Revision on 2000. Std.
- [6] Heredero-Peris, D.; Chillón-Anton, and et al., "Implementation of grid-connected to/from off-grid transference for micro-grid inverters," Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE , vol., no., pp.840,845, 10-13 Nov. 2013
- [7] K. D. Brabandere, "Voltage and frequency droop control in low-voltage grids by distributed generators with inverter front-end," Ph.D. dissertation, Katholieke Universiteit Leuven, 2006.
- [8] E. Alves Coelho, P. Cortizo, and P. Garcia, "Small signal stability for single phase inverter connected to stiff ac system," in Industry Applications Conference, 1999. 34th IAS Annual Meeting, vol. 4, 1999, pp. 2180–2187 vol.4.
- [9] Rodríguez, F.J.; Bueno, E.; Aredes, M.; Rolim, L. G B; Neves, F.A.S.; Cavalcanti, M. C., "Discrete-time implementation of second order generalized integrators for grid converters," Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE , vol., no., pp.176,181, 10-13 Nov. 2008
- [10] Kanakasabapathy, P.; Vishnu Vardhan Rao I., "Control strategy for inverter based micro-grid," Power and Energy Systems Conference: Towards Sustainable Energy, 2014 , vol., no., pp.1,6, 13-15 March 2014