Integrated control strategy for islanded operation in smart grids: virtual inertia and ancillary services

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Abstract— **Distributed Generation has become a consolidated phenomenon in distribution grids in the last few years. Even though the matter is very articulated and complex, islanding operation of distribution grid is being considered as a possible measure to improve service continuity. In this paper a novel static converter control strategy to obtain frequency and voltage regulation in islanded distribution grid is proposed. Two situations are investigated: in the former one electronic converter and one synchronous generator are present, while in the latter only static generation is available. In both cases, converters are supposed to be powered by DC micro-grids comprising of generation and storage devices. In the first case converter control will realize virtual inertia and efficient frequency regulation by mean of PID regulator; this approach allows to emulate a very high equivalent inertia and to obtain fast frequency regulation, which could not be possible with traditional regulators. In the second situation a Master-Slave approach will be adopted to maximize frequency and voltage stability. Simulation results confirm that the proposed control allows islanded operation with high frequency and voltage stability under heavy load variations.**

Keywords— Ancillary services; virtual inertia; smart grid; islanded grid operation;

I. INTRODUCTION

Distributed Generation has been having a growing impact on distribution grids in the last few years. More and more active users are hence involved in grid dynamics, but, because of normative and technical issues, they are not involved in grid management.

In order to improve service continuity, active users and generators should be involved in an integrated grid management strategy [1][2][3]; this approach, with particular attention to islanded operation, can be a key to evolve from traditional grids to smart grids. Transition to islanded operation in public distribution grids is strictly regulated and substantially not realized, but it should be considered as a possible strategy to improve service quality, with significant advantages both for users and Distribution System Operators. Moreover, active users are not highly involved in frequency regulation - only active power modulation during frequency transients is foreseen [4][5][6].

Among many available studies, two main approaches are recognizable: some of them [7][8][9][10][11][12] aimed to control static converters in order to emulate synchronous generators behaviour. This approach allows easier integration in the existing grid and mitigates Diffused Generation impact. Other studies [13][14] aimed to realize efficient micro-grid control with high frequency and voltage stability, obtained mostly through a droop control approach.

In this paper a novel static converter control strategy to obtain frequency and voltage regulation in islanded distribution grid is proposed. A small medium voltage grid will be considered as case study and two situations are investigated. In the former one synchronous generator and one static converter are connected to the grid; the synchronous generator is supposed to be prevalent in power with respect to the inverter. In the latter only two static converters are present and one of them is supposed to be prevalent in power with respect to the other. In both cases, converters are supposed to be powered by DC micro-grids comprising of generation and storage devices [1][3]. Since the main objective of this study is to investigate islanded operation performance, transition from grid connected to islanded operation and vice versa will not be considered.

Two control strategies will be developed with reference to grid topology. In the first case study inverters will be controlled to improve frequency stability through virtual inertia and to obtain efficient frequency and voltage regulation. Frequency regulation and virtual inertia will be integrated in a single PID regulator which provides active power reference depending on frequency deviation. The derivative action is tuned to emulate synchronous generator inertia in the beginning of transients, while proportional and integral actions realize primary and secondary frequency regulation. This approach allows to emulate a very high equivalent inertia, which reduces frequency transient amplitude, but also to realize fast primary and secondary regulation, which could not be possible with traditional mechanical regulators. Since during transients storage systems are supposed to be exploited to supply the requested power, to avoid prohibitive sizing active power should be equal to the initial value at end of the transient; a second regulator will be implemented to realize this function. Voltage regulation will be obtained through a PI regulator

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which provides reactive power reference depending on voltage deviation. In the second case study, a master-slave approach will be adopted to maximize frequency and voltage stability. The master converter will be operated at fixed frequency, so that the slave will not be involved in frequency regulation. Both converters will contribute to voltage regulation.

Control effectiveness will be verified through numeric simulations in MATLAB - Simulink.

The study will be organized as follow: chapter II will illustrate converters control strategies in both situations, chapter III will present control implementation, chapter IV will show simulation results and chapter five will report final conclusions.

II. CONTROL STRATEGIES

A. *First Case Study*

Grid topology in the first case is shown in Fig. 1. It consists of a medium voltage islanded feeder (V=20 kV) supplied by two active users, in detail one inverter (400 V, 1250 kVA) and one synchronous generator (400 V, 2000 kVA), which is supposed to be a regulating group. Three loads are connected to the grid: load 1 (20 kV, 1000 kW, 500 kVAR) and load 3 (400 V, 100 kW) are always connected, while load 2 (20 kV, 500 kW, 250 kVAR) is suddenly connected to the grid at a certain time. Line impedances have been considered but are not reported in figures for simplicity.

To allow islanded operation, frequency and voltage should be stable under heavy load variations, so this must be the main control objective. Under this assumptions, the proposed control strategy consists of a current controlled inverter which, following grid voltage and frequency, injects active power to contrast frequency variations and reactive power to contrast voltage variations. Current control is realized through a PI controlled current loop which provides voltage references for a PWM modulation. Reference active power is obtained through a PID regulator fed with frequency deviation, which integrates virtual inertia and primary and secondary frequency regulation.

Reference reactive power is obtained through a PI regulator fed with voltage deviation. All controls are based on space-vector approach for easier regulators adjustment [15]. The proposed strategy for inverter integration in frequency and voltage regulation allows to maximize grid stability without annihilating its usual dynamics and allows islanded operation within normative prescription.

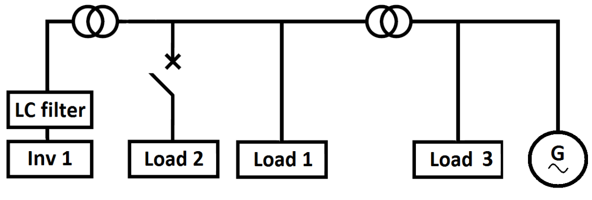

Figure 1 – Case study A grid topology

B. *Second Case Study*

Grid topology is reported in Fig. 2 and is totally equivalent to study case A except from active users (inverter 1, 400 V, 1250 kVA and inverter 2, 400 V, 2000 kVA). Loads are identical to study case A. Since there are no synchronous generators, there's no need to realize traditional voltage and frequency regulations. To maximize frequency and voltage stability, the proposed control strategy consists of a master (inverter 2) which imposes constant frequency and voltage and a slave (inverter 1) which injects a certain active and reactive power into the grid.

Inverter 1 control is identical to case A. Reference active power is constant since frequency regulation is not needed, while reference reactive power is obtained as in case A to realize voltage regulation. Inverter 2 control needs to realize a very efficient voltage source, so a Sliding Mode Control has been chosen for its high dynamic and stability performances. A Smart Modulation algorithm is used to obtain direct current control and constant switching frequency [16][17][18][19].

III. CONTROL IMPLEMENTATION

A. *First Case Study*

Considered inverter topology is shown in Fig. 3 and consists of a standard two level, low voltage inverter. Since the control aim is to exchange a defined power with the grid, different approaches for inverter control and modulation are possible as long as they allow to control exchanged power.

Considering that there is no need for extremely high dynamic performances, a standard decoupled current control with PWM modulation can be used; more sophisticated control strategies and modulation (i.e. Sliding Mode Control and direct current control) can be used but are not necessary in this first case. Under this assumptions, the control algorithm should provide voltage references for PWM modulation. Those references can be obtained, considering v_c as phase reference, by mean of the following equations in d-q domain:

$$v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} - \omega L_s i_{sq} + v_{cd} \qquad (1)$$

$$v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + \omega L_s i_{sd} \qquad (2)$$

where v_s is equivalent converter voltage, v_c is capacitors voltage and v_g is grid voltage. Control equation based on (1), (2) can then be written:

$$v_{sd} = (k_{Pv} + \frac{k_{Iv}}{s})(i_{sd} - i_{sd\_measured}) - \omega L_s i_{sq} + v_{cd} \qquad (3)$$

$$v_{sq} = (k_{Pv} + \frac{k_{Iv}}{s})(i_{sq} - i_{sq\_measured}) + \omega L_s i_{sd} \qquad (4)$$

Being the aim of this control to transfer a defined power, i_{sd} and i_{sq} are to be considered as reference quantities.

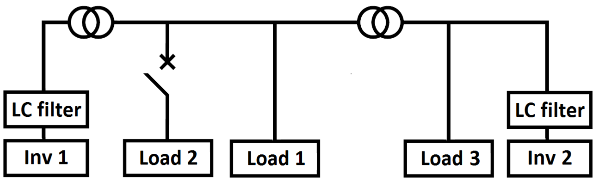

Figure 2 - Case study B grid topology

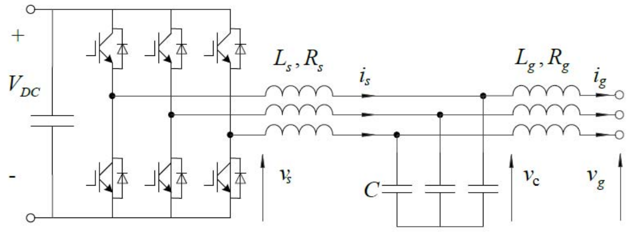

Figure 3 – Inverter topology

Since v_c is considered as phase reference, voltage has no imaginary part and reference currents can be obtained from reference active and reactive power by mean of:

$$i_{sd} = \frac{2}{3} \cdot \frac{P}{v_{sd}} \tag{5}$$

$$i_{sq} = \frac{2}{3} \cdot \frac{Q}{v_{sd}} \tag{6}$$

Defined the lower level of control, it is necessary to build reference active and reactive power in order to obtain voltage and frequency regulation; for this purposes, the grid will be considered prevalently inductive and hence decoupled. Voltage regulation can be generally realized locally or centralized: if centralized, a reference reactive power will be provided by the Distribution System Operator (DSO), while, if locally realized, a reference voltage should be provided by DSO. In the latter situation, voltage regulation can be implemented by mean of a PI regulator fed with voltage deviation; the regulator should provide a reactive power term which will be added to compensation term Q_c, which takes into account capacitors reactive power, to build reference reactive power. The resulting control scheme is shown in Fig. 4. In order to obtain integrated virtual inertia and frequency regulation, a PID regulator is necessary. This regulator must provide reference active power depending on frequency deviation. The resulting control scheme is shown in Fig. 5.

The proposed control strategy is aimed to emulate synchronous generators behaviour just in the beginning of transients, so only rotor swing equation will be considered in order to design the derivative action coefficient k_D. The equation can be written as

$$P_m - P_e = \frac{d}{dt}\left(\frac{1}{2} J \omega^2\right) \tag{7}$$

where P_m is mechanical power, P_e is electrical power, J is rotor moment of inertia and ω is rotor angular speed.

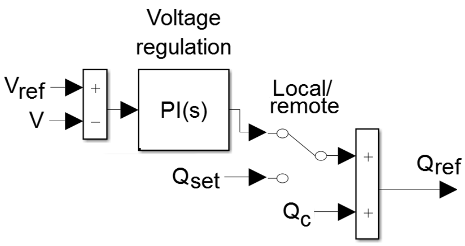

Figure 4 - Voltage regulation control scheme

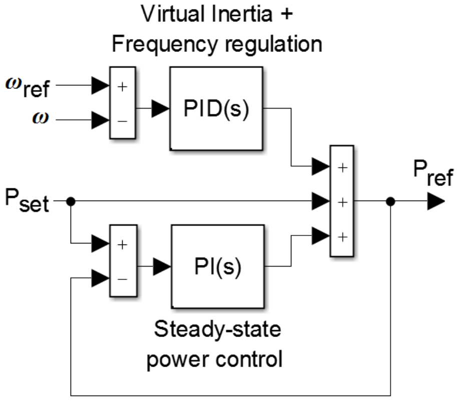

Figure 5 - Frequency regulation with integrated virtual inertia control scheme

The derivative term which is present in (7) can be linearized, assuming frequency deviation to be relatively small, obtaining:

$$\frac{d}{dt}\left(\frac{1}{2} J \omega^2\right) = J\omega \frac{d\omega}{dt} \cong J\omega_s \frac{d\omega}{dt} \tag{8}$$

where ω_s is synchronism angular speed and can be considered constant. Hence, linearized swing equation can be considered

$$P_m - P_e = J\omega_s \frac{d\omega}{dt} \tag{9}$$

$$k_{D\_rotor} = J\omega_s \tag{10}$$

Consequently, the derivative action naturally performed by synchronous generator rotor con be approximated by the product of rotor moment of inertia J and synchronism angular speed ω_s (10). In order to realize virtual inertia, the derivative action coefficient of the PID regulator should be chosen, according to

$$k_D = J_{eq}\omega_s \ . \tag{11}$$

This allows to emulate a certain equivalent rotor inertia J_{eq} during the first part of frequency transients. Note that this approach allows to emulate a very high equivalent inertia, which reduces frequency transient amplitude, but also to realize fast primary and secondary regulation, which could not be possible with traditional mechanical regulators because of mechanical constraints. Proportional and integral coefficients k_P and k_I will be chosen in order to obtain efficient primary and secondary regulation, while the additional pole frequency N will be chosen to filter fast frequency oscillations. Note that because high values of k_D are used in this application, N value may be unusually low with respect to usually PID regulators parameters. Once k_D has been chosen, it is possible to fix k_I by mean of

$$k_I = 4k_D \tag{12}$$

in order to avoid unnecessary oscillation due to complex PID regulator zeros. k_P can be chosen by mean of the derivative action time constant T_D according to

$$k_P = \frac{k_D}{T_D} \tag{13}$$

Simulation result presented in Chapter IV are obtained considering J_{eq}=500 kg·m^2, $T_D = 2/\pi$ s, ω_s =100π rad/s and N=5 rad/s.

Note that this approach does not directly control steady-state exchanged active power, which can be very different from set-point active power before transient. This may be a non-negligible issue when frequency regulation is based on storage devices, which has natural energetic constraints, or when higher level optimization is performed and active power set-points are periodically sent by the DSO. The proposed solution to this issue is a PI regulator (Fig. 5) which performs steady-state active power control by mean of an additional term which depends on the difference between exchanged active power and set-point active power. In order to allow efficient frequency regulation, this second regulator should have pretty low proportional and integral gains, which drastically increase transient duration but keep frequency deviation into a small range. Faster transient behavior can be obtained with higher gains, but this will interfere with frequency regulation and cause greater frequency deviation. Conversely, from the frequency point of view the best solution is to have no steady-state power control.

B. *Second Case Study*

In this second situation Inverter 1 control can be exactly the same type which has been used in the former case study, except for frequency regulation, which is not needed in slave converters. Active power reference will consequently be equal to set-point active power, with on regulators involved. The control strategy exploited to obtain voltage regulation is perfectly equivalent to the one used in the former case study.

On the contrary Inverter 2, which is the grid master in this case, should behave as a high performance voltage source. Considering voltage phase and frequency, there are no specific issues as long as the converter is operated at fixed frequency. In this case frequency can be chosen arbitrarily, generally equal to its nominal value, and the reference phase is equal to frequency integral over time. In order to avoid heavy voltage transients which may occur during fixed frequency operation, converter control should have high stability and dynamic performance. For this reason, in this paper a Sliding Mode Control with Smart Modulation algorithm has been used. Detailed discussion on this control approach can be found in [18][19].

Under this assumptions, Sliding Mode Control should provide current references for Smart Modulation Algorithm. From voltage error damped dynamic equation it is possible to define the Sliding Function in d-q domain

$$\begin{aligned}\bar{\sigma} = \frac{d}{dt}(\bar{v}_c - \bar{v}_{c\_ref}) + g_1(\bar{v}_c - \bar{v}_{c\_ref}) + \\ +g_2\int(\bar{v}_c - \bar{v}_{c\_ref})dt\end{aligned} \tag{14}$$

where g_1 and g_2 are gains which should be chosen in order to obtain optimal damping. Considering inductor and capacitor fundamental equations, it is then possible to define modulation reference current

$$\begin{aligned}\bar{i}_{s\_ref} = j\omega C\bar{v}_{c\_ref} + \bar{i}_g + g_1 C(\bar{v}_c - \bar{v}_{c\_ref}) + \\ +g_2 C\int(\bar{v}_c - \bar{v}_{c\_ref})dt\end{aligned} \tag{15}$$

Once the reference current i_{s_ref} has been obtained, Smart Modulation algorithm can be applied. Fundamental reasons which led to this control approach are its dynamic response and stability properties, while the Smart Modulation algorithm allows to obtain direct current control and constant switching frequency. Furthermore, this approach can easily be extended to modular converters to obtain greater flexibility, fault resilience, harmonic distortion cancellation and power transfer capabilities [21].

IV. SIMULATION RESULTS

A. *First Case Study*

At time t=0 the grid is in steady state and load 2 is not connected. At time t=5 s, load 2 suddenly connects to the grid. The consequent frequency transient is shown in Fig. 6. One can notice that maximum frequency deviation is about 0.16 Hz and after 5 s from the beginning of the transient frequency deviation is less than 50 mHz. At the end of oscillations in frequency transient (t=15 s), one can notice that inverter active power is still significantly shifted from its initial value. The proposed control will force active power back to its initial value with a very slow action, so that grid frequency is almost not affected: the whole transient which reduces to zero frequency and power deviation lasts about ten minutes. Frequency transient amplitude and duration are a compromise solution due to inverter necessity to return to reference active power in a limited time. Longer recovery time allows smaller frequency deviation, while shorter recovery time reduces control effectiveness. Inverter 1 power transient is shown in Fig. 7, while synchronous generator power transient is not reported since its exchanged power is equal to the difference between load requested power and inverter 1 exchanged power. Load voltages are reported in Fig. 8 and Fig. 9 and, since line impedances are small, they are almost equal. Voltage deviation is restrained but inevitable since due to line voltage drop; initial voltage dip depth and duration are compatible with CEI 0-16 and 0-21 prescriptions. Note that, since converter switching has much faster dynamics than analyzed transients, equivalent models with no switching modelling have been used for case A simulation, hence voltage and power has no ripple.

B. *Second Case Study*

At time t=0 the grid is in steady state and load 2 is not connected. At time t=0.1 s, load 2 suddenly connects to the grid. Fig. 10 and Fig. 11 report, respectively, inverter 1 and inverter 2 voltage transients, while Fig. 13 shows load 1 and load 2 voltage transients; load 3 voltage is equal to inverter 1 voltage. Inverter 1 power transient is not shown since the converter is controlled to exchange constant active power; inverter 2 active power transient, even if converter exchanged power is equal to the difference between load requested power and inverter 1 exchanged power, is reported in Fig. 12 to show resulting control dynamics. All voltage transients are small and very fast, especially at Inverter 2 connection point, where voltage remains substantially constant. CEI 0-16 and 0-21 prescriptions are totally fulfilled. Note that, since power converters can have very fast dynamics, for case B simulation complete inverter models have been used, hence ripples are present on voltages.

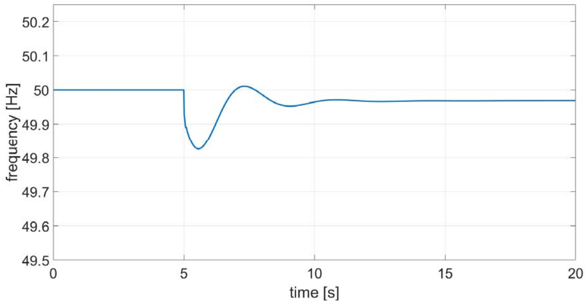

Figure 6 - Frequency transient consequent to load 2 connection

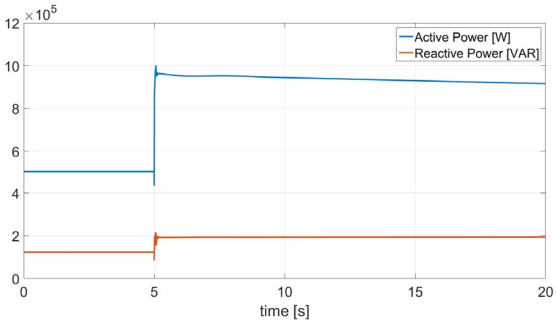

Figure 7 - Inverter 1 active and reactive power transient consequent to load 2 connection

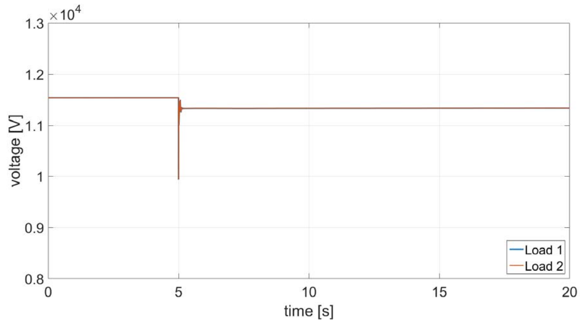

Figure 8 – Load 1 and Load 2 voltage transients consequent to load 2 connection

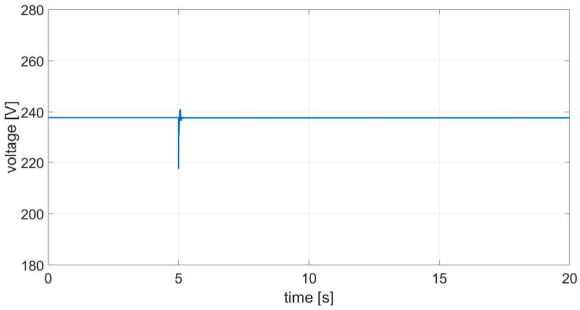

Figure 9 – Load 3 voltage transient consequent to load 2 connection

V. CONCLUSION

This paper proposes two control strategies to obtain voltage and frequency regulation in two different islanded-operated grid topologies: the first one considers a grid where synchronous generation is prevalent, while the second considers a grid where only static generation is present.

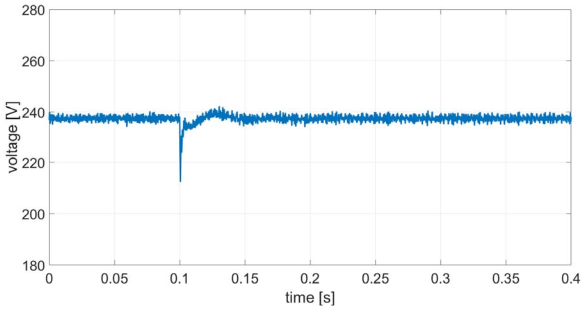

Figure 10 - Inverter 1 voltage transient consequent to load 2 connection

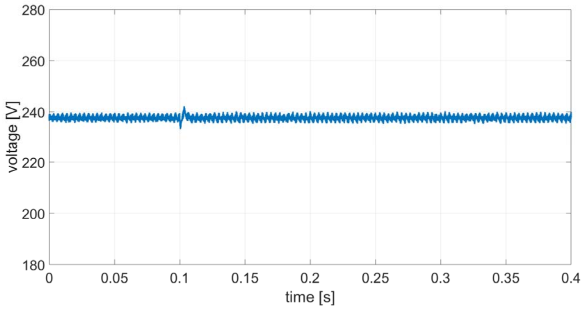

Figure 11 - Inverter 2 voltage transient consequent to load 2 connection

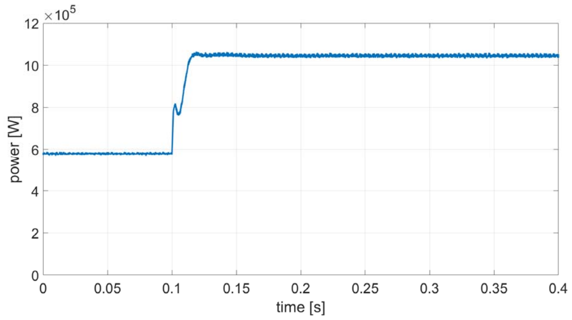

Figure 12 - Inverter 2 power transient consequent to load 2 connection

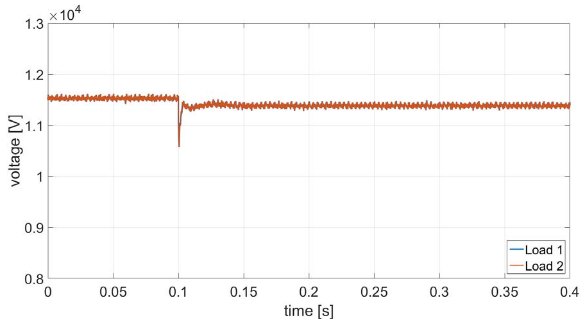

Figure 13 - Load voltage transient consequent to load 2 connection

In the first case study, where frequency stability is the main issue, the proposed control effectively reduces frequency deviation amplitude and frequency oscillation. Transient total duration is related to DC micro-grids energy availability, hence on storage devices sizing. To avoid prohibitive storage sizing, compromise solution similar to the proposed one are generally needed. Nevertheless, maximum frequency stability can be obtained if active power is not forced to its initial value at the end of transients, but this approach limits islanded operation in that very large storage devices would be necessary.

In the second case, where voltage stability is the main issue because of fixed frequency operation, voltage transients are successfully restrained. Better results in load sharing between converters can be obtained with different approaches, but, as long as the Master is capable of fulfilling load changes, Master-Slave approach assures maximum service quality. Note that this approach can be easily extended to grids where synchronous generation is present but static generation is prevalent.

In conclusion and with reference to simulation results, the proposed control strategies allow islanded operation in both examined situations in full compliance with CEI 0-16 and CEI 0-21 prescriptions.

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