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Hierarchical Control of Droop-Controlled DC and AC Microgrids – A General Approach Towards Standardization

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Abstract – DC and AC Microgrids are key elements to integrate renewable and distributed energy resources as well as distributed energy storage systems. In the last years, efforts toward the standardization of these Microgrids have been made. In this sense, this paper presents the hierarchical control derived from ISA-95 and electrical dispatching standards to endow smartness and flexibility to microgrids. The hierarchical control proposed consists of three levels: i) the primary control is based on the droop method, including an output impedance virtual loop; ii) the secondary control allows restoring the deviations produced by the primary control; and iii) the tertiary control manages the power flow between the microgrid and the external electrical distribution system. Results from a hierarchical-controlled microgrid are provided to show the feasibility of the proposed approach.

Keywords: Distributed Generation (DG), Distributed Power Systems (DPS), Droop method, Hierarchical control, ISA-95, Microgrid, Parallel operation.

I. INTRODUCTION

Microgrids (MG), also named minigrids, are becoming an important concept to integrate distributed generation (DG) and energy storage systems. The concept has been developed to cope with the penetration of renewable energy systems, which can be realistic if the final user is able to generate, storage, control, and manage part of the energy that will consume. This change of paradigm, allows the final user to be not only a consumer but also a part of the grid.

DC and AC microgrids have been proposed for different applications, and hybrid solutions have been developed [1]-[12]. Islanded microgrids have been used in applications like avionic, automotive, marine, or rural areas. The interfaces between the prime movers and the microgrids are often based on power electronics converters acting as voltage sources (voltage source inverters, VSI, in case of AC microgrids). These power electronics converters are parallel connected through the microgrid. In order to avoid circulating currents among the converters without use any critical communication between them, the droop control method is often applied.

In case of paralleling DC power converters, the droop method consists of subtracting a proportional part of the output current to the output voltage reference of each module. Thus, a virtual output resistance can be implemented through this control loop. This loop, also called adaptive voltage

position (AVP) has been applied to improve the transient response of voltage regulation modules (VRMs) in low-voltage high-current applications. However, the droop method has an inherent trade-off between the voltage regulation and the current sharing between the converters [8]-[13].

On the other hand, in case of paralleling inverters, the droop method consists of subtracting proportional parts of the output average active and reactive powers to the frequency and amplitude of each module to emulate virtual inertias. These control loops, also called $P-\omega$ and $Q-E$ droops, have been applied to connect inverters in parallel in uninterruptible power systems (UPS). However, this method also has an inherent trade-off but between frequency and amplitude regulation in front of active and reactive power sharing accuracy [14]-[19].

To cope with this problem, an external control loop named secondary control has been proposed to restore the nominal values of voltage inside the microgrid. Further, additional tertiary control can be used to bidirectionally control the power flowing when the microgrid is connected to a stiff power source or the mains (in case of AC microgrids) [14].

In this paper, we propose a general hierarchical multilevel control for DC and AC microgrids. The paper is organized as follows. In Section II, a general approach of the hierarchical control stem from the ISA-95 is adapted to microgrids. In Section III, the hierarchical control is applied to DC microgrids, solving the trade-off of the droop method by implementing a secondary control loop, and able to share the load together with a stiff dc source, which can be either a DC generator or a DC distribution grid. In Section IV the approach is applied over an AC microgrid consisted of droop-controlled inverters, able to operate in grid-connected and islanded modes. Finally, Section V gives the conclusions.

II. A GENERAL APPROACH OF THE HIERARCHICAL CONTROL OF MICROGRIDS

The need for standards in microgrid control is related to the new grid codes that are expected to appear in the next future. In this sense, the ISO-95 standard deals with the integration enterprise and control systems. In this standard a multilevel hierarchical control is proposed, with the following levels:

Level 5: Enterprise. The enterprise level comprises the superior management policies of a commercial entity. This level has operational and development responsibility for the entire enterprise, including all of its plants and their respective production lines.

Level 4: Campus/Plant. The campus or plant level comprises superior management policies of a branch or operational division of an enterprise, usually including the elements of the enterprise financials that are directly associated with that business entity.

Level 3: Building/Production. The building or production level comprises the management and control policies required to administer the states and behaviors of a building and its environmental and production systems

Level 2: Area/Line. The area or production line level comprises the management and control policies required to administer states and behaviors of a specific area or production line.

Level 1: Unit/Cell. The unit or cell level comprises the management and control policies required to govern the states and behaviors of a unit of automation or a manufacturing cell.

Level 0: Device. The device level comprises the set of field devices that sense and provide actuation of physical processes within the environmental and production systems.

Each level has the duty of the command level and provides supervisory control over lower level systems. In this sense, it is necessary to ensure that the command and reference signals from one level to the lower levels will have low impact in the stability and robustness performance. Thus, the bandwidth must be decreased when increasing the control level.

In order to adapt ISA-95 to the control of a microgrid, zero to three levels can be adopted as follows (see Fig. 1) [7], [14]:

- Level 3 (*tertiary control*): This energy production level controls the power flow between the microgrid and the grid.
- Level 2 (*secondary control*): Ensures that the electrical levels into the microgrid are inside the required values. In addition, it can include a synchronization control loop to seamlessly connect or disconnect the microgrid to the distribution system (see Fig. 2).
- Level 1 (*primary control*): The droop control method is often used in this level to emulate physical behaviors that makes the system stable and more damped. It can include a virtual impedance control loop to emulate physical output impedance.
- Level 0 (inner control loops): Regulation issues of each module are integrated in this level. Current and voltage, feedback and feedforward, and linear and nonlinear control loops can be performed to regulate the output voltage and to control the current, while maintaining the system stable.

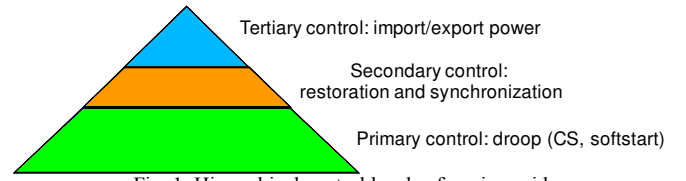


Fig. 1. Hierarchical control levels of a microgrid.

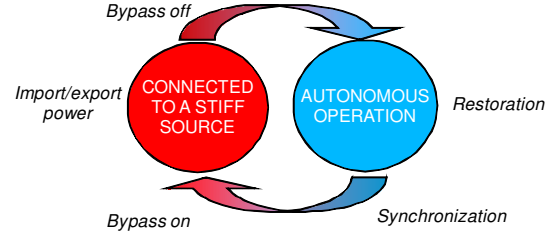


Fig. 2. Stiff-source connection and autonomous operations.

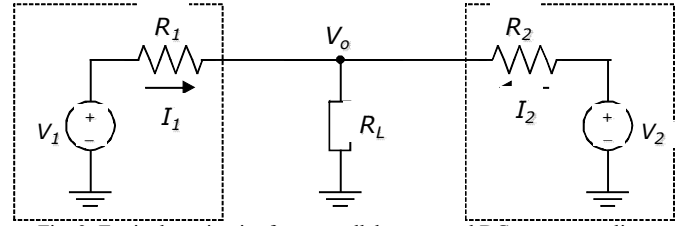


Fig. 3. Equivalent circuit of two parallel-connected DC power supplies.

III. DC MICROGRIDS

There are several problems associated with AC microgrids, such as the need for synchronization of the distributed generators, the inrush currents due to transformers, reactive power flow, harmonic currents, and three-phase unbalances. Furthermore, there is an increasing interest in integrate prime movers with DC output such as photovoltaic modules or fuel cells. This section deals with the hierarchical control of DC microgrids, consisted in the following three control levels.

A. Primary control

This control level adjusts the voltage reference provided to the inner current and voltage control loops (level 0). It includes the virtual output impedance loop, in which the output voltage can be expressed as:

$$v_o^* = v_{ref} - R_D \cdot i_o \quad (1)$$

where i_o is the output current, R_D is output impedance, and v_{ref} is the output voltage reference at no-load. Assuming that \mathcal{E}_v is the maximum allowed voltage deviation, R_D and v_{ref} must be designed as following:

$$v_{ref} = v_n - \mathcal{E}_v / 2 \quad (2)$$

$$R_D = \mathcal{E}_v / i_{max} \quad (3)$$

being v_n the nominal output voltage and i_{max} the maximum output current.

This control loop provides resistive output impedance to the power converters to compensate for the difference between the voltage references $\Delta v_o^* \triangleq v_{o1}^* - v_{o2}^*$. Thus, the current sharing between two converters $\Delta i_o \triangleq i_{o1} - i_{o2}$ (see Fig. 3) can be expressed as follows:

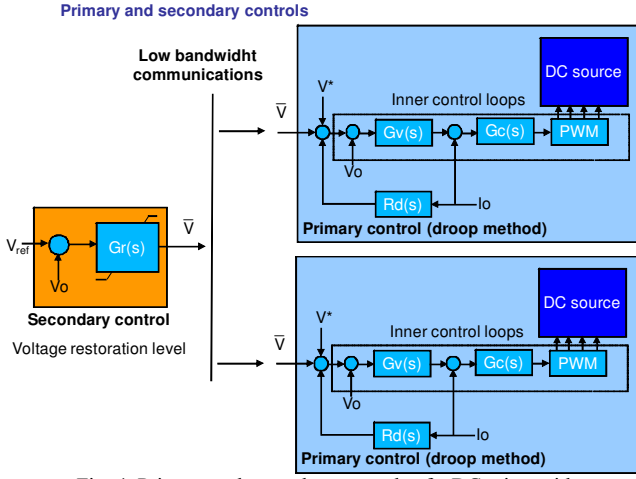


Fig. 4. Primary and secondary controls of a DC microgrid.

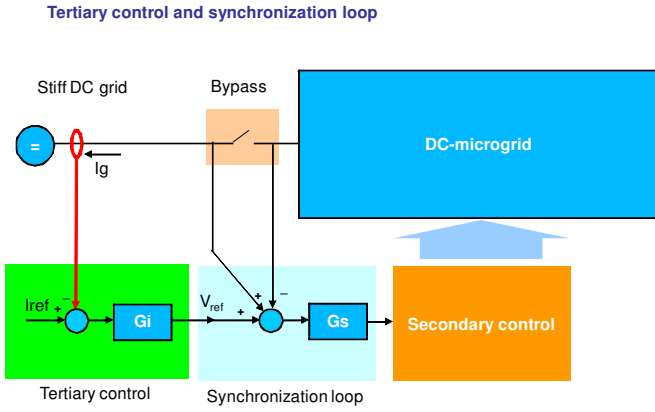


Fig. 5. Tertiary control and synchronization loop of a DC microgrid.

$$\Delta i_o = \Delta v_o^* / R_D i_o \quad (4)$$

This control loop not only allows the parallel operation between the converters, but also improves the dynamic performance of the output voltage. However, it has the inherent load-dependent voltage deviation.

B. Secondary control

To solve the problem of the voltage deviation, a secondary control is proposed. The voltage level in the microgrid v_{MG} is sensed and compared with the voltage reference v_{MG}^* , and the error processed through a compensator is send to all the units δv_o to restore the output voltage (see Fig. 4). The controller can be expressed as follows:

$$\delta v_o = k_p (v_{MG}^* - v_{MG}) + k_i \int (v_{MG}^* - v_{MG}) dt \quad (5)$$

being k_p and k_i the control parameters of the secondary control compensator. Notice that δv_o must be limited in order to do not exceed the maximum voltage deviation. Finally, equation (1) becomes:

$$v_o^* = v_{ref} + \delta v_o - R_D \cdot i_o \quad (6)$$

In order to connect the microgrid to a DC stiff source, first, we have to measure the voltage of this stiff source and that will be the reference of the secondary control loop. After the

transient, the microgrid can be connected to the DC stiff source through the static bypass switch. At that moment, the microgrid does not have any exchange of power with the external DC source.

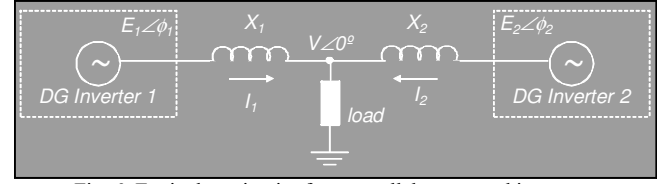


Fig. 6. Equivalent circuit of two parallel-connected inverters.

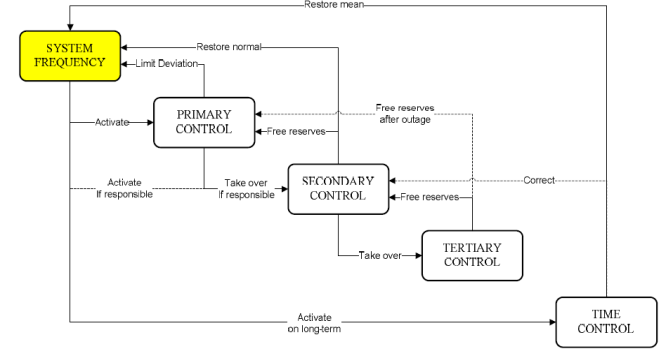


Fig. 7. Frame for the multilevel control of a power system, defined by UCTE.

C. Tertiary control

Once the the microgrid is connected to the DC source, the power flow can be controlled by changing the voltage inside the microgrid. As can be seen in Fig. 5, by measuring the current (or the power) through the static bypass switch i_G , it can be compared with the desired current i_G^* (or power) positive or negative, depending on if we want to import or export energy.

The controller can be expressed as following:

$$\delta v_o = k_p (i_G^* - i_G) + k_i \int (i_G^* - i_G) dt \quad (7)$$

being k_p and k_i the control parameters of the tertiary control compensator. Here, δv_o is also saturated in case of being outside of the limits of $\pm \epsilon_v$. Notice that, depending on the sign of I_G^* , the power flow can be exported ($I_G^* > 0$) or imported ($I_G^* < 0$).

IV. AC MICROGRIDS

AC microgrids are now in the cutting edge of the state of the art [20]-[25]. However, the control and management of such a systems needs still further investigation. This section deals with the hierarchical control of AC microgrids, consisted in the same three control levels as presented in last section related to DC microgrids.

A. Primary control

When connecting two or more inverters in parallel, circulating active and reactive power can appear (see Fig. 6). This control level adjusts the frequency and amplitude of voltage reference provided to the inner current and voltage control loops. It uses the well known P/Q droop method:

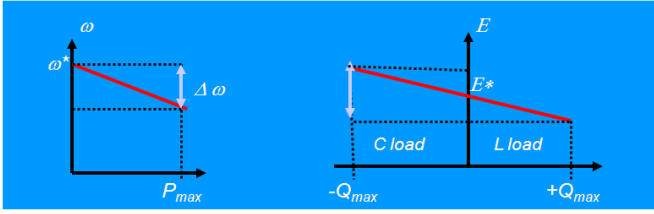


Fig. 8. P/Q droop functions.

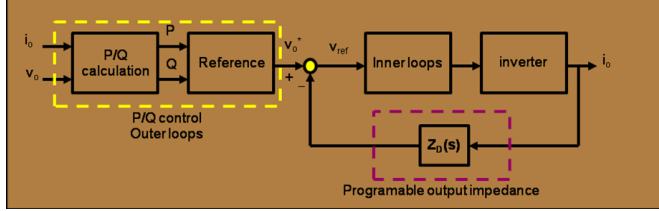


Fig. 9. Virtual impedance loop.

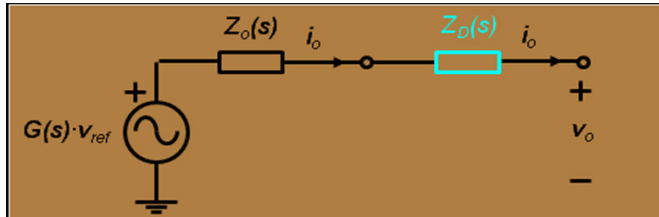


Fig. 10. Equivalent circuit of an inverter with the output impedance loop.

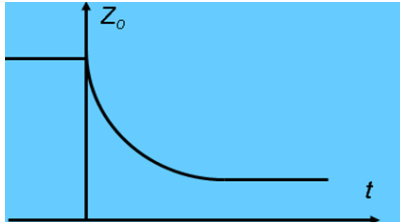


Fig. 11. Hot-swap operation of the output impedance control loop.

$$\omega = \omega^* - G_p(s) \cdot (P - P^*) \quad (8)$$

$$E = E^* - G_Q(s) \cdot (Q - Q^*) \quad (9)$$

being ω and E the frequency and amplitude of the output voltage reference, ω^* and E^* their references, P and Q the active and reactive power, P^* and Q^* their references, and $G_P(s)$ and $G_Q(s)$ their corresponding transfer functions (typically proportional droop terms shown in Fig. 8). Note that the use of pure integrators is not allowed when the microgrid is in island mode, since the total load will not coincide with the total injected power, but they can be useful in grid connected mode to have a good accuracy of the injected active and reactive power. Nevertheless, this control objective will be achieved by the tertiary control level.

The secondary control level can also include the virtual output impedance loop, in which the output voltage can be expressed as (see Figs. 9 and 10) [17]:

$$v_o^* = v_{ref} - Z_D(s) \cdot i_o \quad (10)$$

where $Z_D(s)$ is the virtual output impedance transfer function, which normally ensures inductive behavior at the line-frequency. By properly changing the value of the virtual

impedance as depicted in Fig. 11, hot-swap operation can be obtained.

These control loops allows the parallel operation of the inverters. However, it have an inherent trade of between P/Q sharing and frequency/amplitude regulation.

B. Secondary control

In order to compensate for the frequency and amplitude deviations, a secondary control is proposed. The frequency and amplitude levels in the microgrid ω_{MG} and E_{MG} are sensed and compared with the references ω_{MG}^* and E_{MG}^* the errors processed through compensators are send to all the units $\delta\omega$ δE to restore the output voltage.

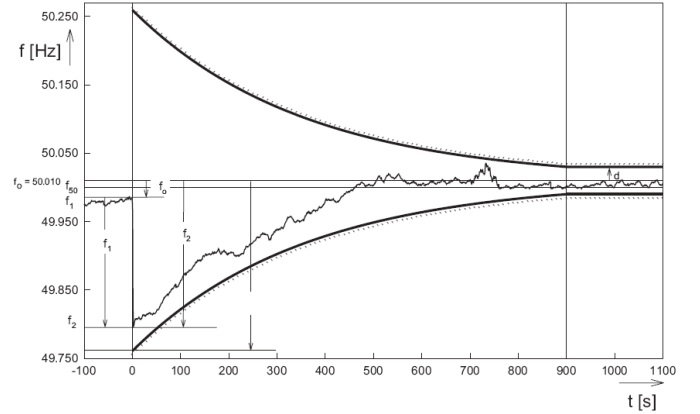


Fig. 12. Frequency control restoration achieved by the secondary control action.

Taking into account the grid exigencies [7], the secondary control should correct the frequency deviation within allowable limit, e.g. ± 0.1 Hz in Nordel (North of Europe) or ± 0.2 Hz in UCTE (Union for the Co-ordination of Transmission of Electricity, Continental Europe). It is defined as:

$$\delta P = -\beta \cdot G - \frac{1}{T_r} \int G dt \quad (11)$$

where δP is output set point of secondary controller, β is the gain of the proportional controller, T_r is time constant of secondary controller, and G is the Area Control Error (ACE) which is normally calculated in about five to ten second intervals by computers in the dispatch center as:

$$G = P_{meas} - P_{sched} + K_{ri} (f_{meas} - f_0) \quad (12)$$

with P_{meas} being the sum of the instantaneous measured active power transferred at the PCC, P_{prog} being the resulting exchange program, K_{ri} being the proportional factor of the control area set on the secondary controller, and $f_{meas} - f_0$ being the difference between the instantaneous measured system frequency and the set-point frequency. From equation (11), note that the control action δP increases by integral formula, if the deviation of ACE remains constant (PI-type controller). This controller is also called Load-Frequency Control (LFC) or Automatic Gain Controller (AGC) in USA.

Fig. 12 shows the restoration process of the grid frequency by using the secondary control.

In case of an AC microgrid, the frequency and amplitude restoration controllers can be obtained similarly as follows [14]:

$$\delta\omega = k_{p\omega}(\omega_{MG}^* - \omega_{MG}) + k_{i\omega} \int (\omega_{MG}^* - \omega_{MG}) dt \quad (13)$$

$$\delta E = k_{pE}(E_{MG}^* - E_{MG}) + k_{iE} \int (E_{MG}^* - E_{MG}) dt \quad (14)$$

being $k_{p\omega}$, $k_{i\omega}$, k_{pE} and k_{iE} the control parameters of the secondary control compensator. In this case, $\delta\omega$ and δE must be limited in order to do not exceed the maximum allowed frequency and amplitude deviations.

In order to connect the microgrid to the grid, we have to measure the frequency and voltage of the grid and that will be the reference of the secondary control loop. The phase between the grid and the microgrid will be measured and send to all the modules to synchronize the microgrid phase. After the synchronization process, the microgrid can be connected to the mains through the static bypass switch. At that moment, the microgrid does not have any exchange of power with the mains.

C. Tertiary control

When the microgrid is operating in grid-connected mode, the power flow can be controlled by adjusting the frequency (changing the phase in steady state) and amplitude of the voltage inside the microgrid [14]. As can be seen in Fig. 7, by measuring the P/Q through the static bypass switch P_G and Q_G they can be compared with the desired P_G^* and Q_G^* . The control laws can be expressed as following:

$$\delta\omega = k_{pP}(P_G^* - P_G) + k_{iP} \int (P_G^* - P_G) dt \quad (14)$$

$$\delta E = k_{pQ}(Q_G^* - Q_G) + k_{iQ} \int (Q_G^* - Q_G) dt \quad (15)$$

being k_{pP} , k_{iP} , k_{pQ} , and k_{iQ} the control parameters of the tertiary control compensator. Here, $\delta\omega$ and δE are also saturated in case of being outside of the allowed limits. Notice that, depending on the sign of P_G^* and Q_G^* , the active and reactive power flows can be exported or imported independently.

D. Results

Some simulation results from a two inverter microgrid where performed. First, the two-inverter system connected to the grid where start-up. The grid reference was fixed at 1 kW, while the other two inverters give 2 kW each one. At $t=4$ s, a non-planned islanding scenario occurs, and the grid is disconnected from the microgrid. The microgrid is operating in autonomous (islanded) operation. Afterwards, at $t=6$ s, one inverter is disconnected suddenly from the grid, and inverter #1 gives all the power to the local loads.

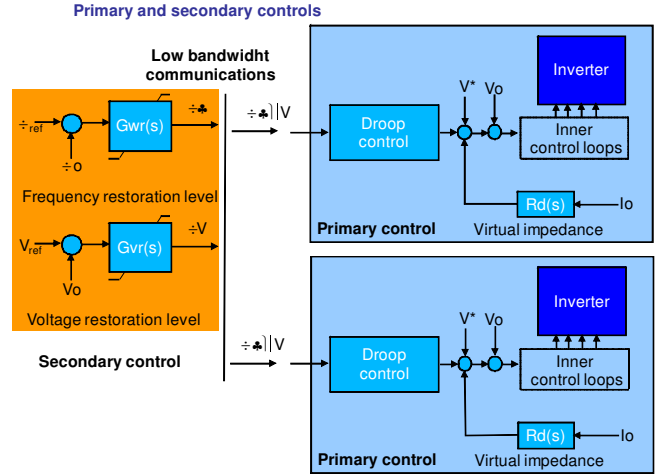


Fig. 13. Primary and secondary controls of an AC microgrid.

Tertiary control and synchronization loop

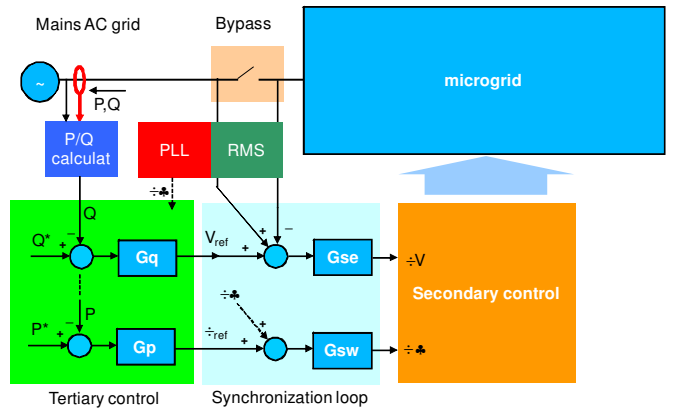


Fig. 14. Tertiary control and synchronization loop of an AC microgrid.

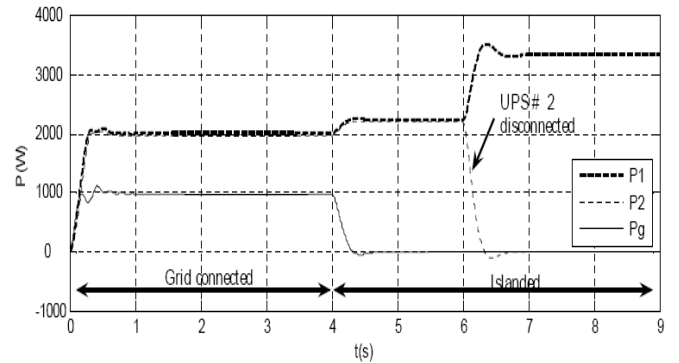


Fig. 15. Active power transient response of a two-inverter AC microgrid.

V. CONCLUSION

The paper has presented a general approach of hierarchical control for microgrids. The hierarchical control stems from ISA-95. A three-level control is applied to DC and AC microgrids. On the one hand, the hierarchical control of DC microgrids present novel features that can be useful in DPS

applications such as telecom DC voltage networks, among others. On the other hand, the control of AC microgrid mimics a large-scale power system AC grid, pointing out the similarities between both systems.

Consequently, flexible microgrids are obtained which can be use full for DC or AC interconnection with a DC or AC distribution system, controlling the power flown from the microgrid to these systems. In addition, these microgrids are able to operate in both island or stiff-source connected modes, as well as to achieve a seamless transfer from one mode to the other.

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