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## *Modeling, control and design of AC microgrids in islanded mode*

**Juan Manuel Rey López**

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# Modeling, Control and Design of AC Microgrids in Islanded Mode

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DOCTORAL THESIS

**Juan Manuel Rey López**

Thesis Supervisors: Prof. Miguel Castilla Fernández  
Prof. Jaume Miret i Tomàs

July 2019



## Abstract

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The present doctoral thesis is focused on the analysis and design of control strategies for the secondary control layer of islanded AC microgrids without the use of communications. The work is submitted as a compendium of publications, composed by journals and international conference papers.

The first contribution is a control strategy for the secondary control layer based on a switchable configuration that does not require the use of communications. For stability analysis purposes, a closed-loop system modeling is presented, which is also used to determine design considerations for the control parameters.

The second contribution is a complementary control strategy that improves the frequency regulation of the previous proposed control, using a dynamic droop gain in the primary layer. For this purpose, a time protocol that drives the variable parameters is proposed which guarantees an effectively reduction of the maximum frequency error without relying on complex techniques, maintaining the simplicity of the base strategy and the non-use of communications.

The third contribution is a multi-layer hierarchical control scheme that is composed of a droop-based primary layer, a time-driven secondary layer and an optimized power dispatch tertiary layer. The proposed control guarantees an excellent performance in terms of frequency restoration and power sharing.

The fourth contribution is an improved secondary control layer strategy without communications, which presents superior operating performance compared with the previous proposals. The scheme is based on an event-driven operation of a parameter-varying filter which ensures perfect active power sharing and controllable accuracy for frequency restoration. A complete modeling that considers the topology of the MG and the electrical interaction between the DGs is derived for the stability analysis and is used to determine design guidelines for the key control parameters.

For the purpose of analyzing and verifying the operational performance of the control schemes, an experimental MG was implemented, where selected tests were carried out. The obtained results are discussed and its relation with the doctoral thesis objectives analyzed. The thesis ends presenting conclusions and future research lines.

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## Resumen

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La presente tesis doctoral se enfoca en el análisis y diseño de estrategias de control para la capa de control secundaria en microrredes aisladas de corriente alterna, sin el uso de comunicaciones. El trabajo se presenta en la modalidad de compendio, por lo que está compuesto por publicaciones previamente aceptadas en revistas y congresos científicos internacionales.

La primera contribución es una estrategia de control para la capa secundaria basada en una configuración conmutable, que no requiere el uso de comunicaciones. Con el propósito de analizar la estabilidad, se presenta el modelado del sistema de lazo cerrado, que también es usado para determinar reglas de diseño de los parámetros de control.

La segunda contribución es una estrategia de control complementaria que mejora la regulación de frecuencia de la propuesta anterior, usando una ganancia dinámica en la capa de control primaria. Se propone la variación de los parámetros siguiendo un protocolo de tiempo, garantizando la reducción del error máximo de frecuencia sin depender de técnicas complejas, manteniendo la simplicidad de la estrategia base y sin requerir comunicaciones.

La tercera contribución es un esquema de control jerárquico compuesto por una capa primaria basada en el método de la pendiente, una capa secundaria controlada por un protocolo de tiempo y una capa terciaria que optimiza el despacho de potencias. El control propuesto garantiza un excelente desempeño en términos de la regulación de la frecuencia y la compartición de potencias.

La cuarta contribución es una estrategia de control para la capa secundaria que no usa comunicaciones, la cual presenta un comportamiento operativo superior comparado con las propuestas anteriores. El esquema está basado en una operación controlada por eventos, de un filtro con parámetros variables que garantiza una perfecta compartición de potencias y una precisa restauración de frecuencia. Además, para el análisis de la estabilidad y la determinación de pautas de diseño de los parámetros se presenta un modelo que considera la topología de la microrred y las interacciones eléctricas de los generadores.

Con el objetivo de analizar y verificar el desempeño operativo de los esquemas de control, se implementó una microrred experimental donde se llevaron a cabo las pruebas requeridas. Se discutieron los resultados obtenidos y se analizó su relación con los objetivos de la tesis doctoral. El documento termina presentado las conclusiones así como futuras líneas de investigación.

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# O

## INTRODUCTION

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*This chapter introduces the main concepts about electrical microgrids, including operation modes, operation strategies for distributed generators, communication systems and hierarchical control. Then, the research motivations of the thesis are discussed. Finally, objectives, thesis outline and publications related to the doctoral work are presented.*

### Summary

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**0.1** Background

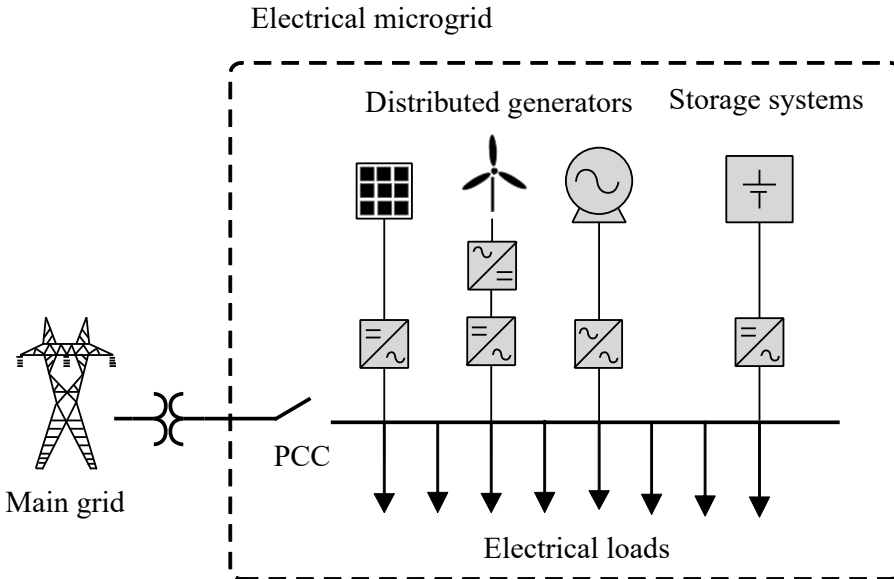
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Isolated electrical grids have existed for many decades as a solution for the supply of energy based on distributed generators (DGs). However, the development and improvement of control systems have changed the way we understand and design these networks, which are no longer seen as the sum of independent elements. The integration of the generation sources with the consumption in a way that transcends the simple injection of power has been possible due to the exchange of information and the capacity of enabling the elements with controllability. This paradigm shift has led to the emergence of new concepts, including the term MicroGrid (MG).

Some of the first introductions of the term MG in technical literature can be found in [1] and [2]. On these works, the MG is understood as a solution for the integration of DGs, energy storage systems and loads. With the advancement in research, more complex definitions have been proposed in which the MG is considered as a cluster of elements operating in coordination to reliably supply electricity [3]. According to [4], an installation of DGs can be defined as a MG if comprised of the following characteristics: it has defined electrical boundaries, a master unit operates the control of the generation and the loads as a single entity, and a reconfiguration is possible in case a critical peak load is presented. Later, it is analyzed why research advances in MGs control have made this definition outdated (regarding the fact that a master unit is always mandatory). Fig. 0.1 presents a general scheme of an electrical MG.

The interest in the study and implementation of MGs has grown notably in recent years, which is reflected in the increase of research works and experimental prototypes [5–11]. This trend has been influenced by many factors, highlighting the following:

- The growing interest of many countries to increase the penetration of renewable energies within their national energy matrices due to environmental, economic and political factors [12, 13].
- The advances in research have allowed to solve critical challenges related to design, control and operation of MGs [14–17].
- The continuously decreasing cost in the installation of DGs and energy storage systems, due to technological developments and increased scales of production, and also in the operation of MGs due to optimized energy management strategies [18, 19].



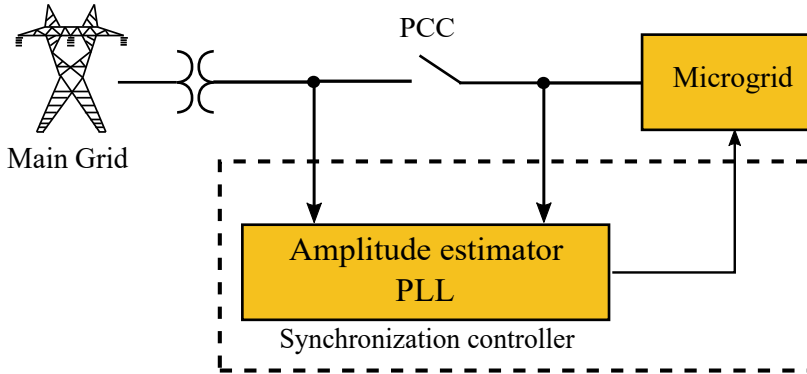
**Figure 0.1:** General scheme of an electrical microgrid.

### 0.1.1 Operation modes of the MGs

MGs can operate in two main modes: grid-connected or islanded. The physical point of connection between the MG and the grid is commonly called Point of Common Coupling (PCC). It devotes a special attention regarding the control of key variables that allow a smooth transition between operation modes (without overshoots and undesired current and voltage peaks) [20,21]. To give autonomy to the connection or disconnection process, the MG should be provided with means to measure the relevant electrical variables at both sides of the PCC.

Commonly, a synchronization controller is implemented for this purpose. It estimates the voltage amplitudes and the frequencies at both sides of the PCC switch using techniques such as the implementation of second order generalized integrators [22] and phase-locked loops (PLL) [23]. Fig. 0.2 presents a general scheme of a grid synchronization controller.

In grid-connected mode, as the name indicates, the MG works connected to the main electrical grid or to a grid of MGs. This connection allows the exchange of power between the two systems, thus, if the generation and stored energy



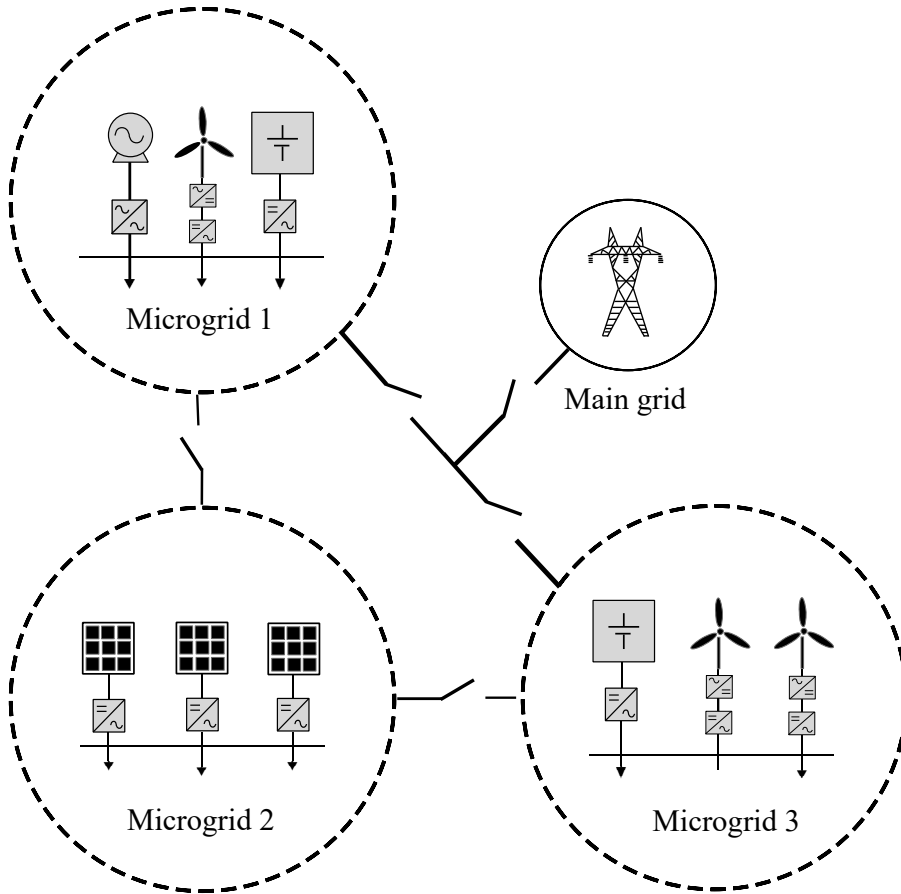
**Figure 0.2:** General scheme of the grid synchronization controller.

of the MG is insufficient to supply the loads, the grid provides the deficit of power. Also, in case the generated power is greater than the load demand and the storage systems are fully charged, the excess of power is injected to the grid, supporting the system operation. The connection to a dominant grid determines certain operation variables such as the frequency or the PCC voltage [24]. As expected, the bigger system imposes the inertia (frequency) and the MG can hardly change this condition.

In islanded mode, the MG works isolated. This disconnection can be intentional (scheduled, for economic or maintenance reasons) or unintentional (produced by electrical faults or non-scheduled events). Also, some MGs are designed to work permanently isolated in rural non-interconnected zones or maritime applications [25, 26]. In this operation mode, the DGs and the storage systems should supply the demanded load consumption, without the grid functioning as a backup system. This requires the proper design and sizing of the MG elements, aiming at the reduction of the probability of unsupplied load scenarios or, if it is the case, the load shedding [27, 28]. The absence of dominant references imposed by a main grid make the islanded mode a significantly more challenging scenario in terms of control and stability [29, 30]. This work is focused on the analysis of this MG operation mode.

Fig. 0.3 presents an scheme of multiple interconnected MGs. The switches that connect the MGs and the main grid can be opened and closed according to different operating criteria. The possibility to change between operation modes (connected/islanded) allows the reconfiguration of the electrical systems offering a flexible and reliable power supply.



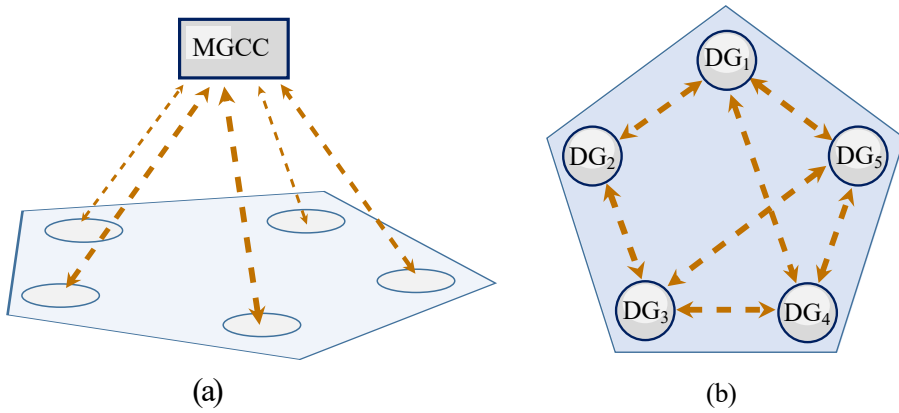


**Figure 0.3:** Multiple interconnected microgrids.

### 0.1.2 Operation of the DG converters

According to the operation characteristics, DG converters can be classified into grid-feeding and grid-forming [31,32]. Grid-feeding converters are controlled to inject active and reactive power based on established power references and energy availability. Commonly, the converter model in this mode of operation uses a power-controlled current source. On the other hand, grid-forming converters are controlled to regulate the output voltage, including variables as voltage amplitude and frequency. This operation characteristic is better modeled using power-controlled voltage sources.

The operation modes of the DG converters are closely related to the MG



**Figure 0.4:** Communication systems scheme: (a) Centralized approach, (b) Distributed approach.

operation modes. As previously discussed, when the MG is working in grid-connected mode, the presence of the main grid guarantees the imposition of certain variables. Due to this, it is preferable to operate the DGs as power injectors in grid-feeding mode, focusing control on the management and optimization of the power delivered. On the other hand, in islanded mode, the absence of a dominant frequency reference makes it necessary to include at least one unit working in grid-forming operation mode, because the MG is exclusively supported by the DGs.

### 0.1.3 Communication systems

As discussed at the beginning of this chapter, the possibility of controlling a MG through the exchange of information between their elements has allowed the exploration of strategies that improve the operation, minimize losses and guarantee a more reliable power supply. Communication systems are the basis for information exchange and according to the topology, they can be classified in two approaches: centralized and distributed.

The centralized approach requires a dedicated unit that works as a MG Central Controller (MGCC), which is connected through a communication channel with the rest of the controlled units [33]. The MGCC collects the measured data, executes the calculations and sends back control signals to all the units. Fig. 0.4(a) presents a scheme of the centralized communication approach, which follows a one-to-all topology. Notice that there are no direct communication links between the units, thus, any information exchange between DG converters

requires the information to be sent to the MGCC and then retransmitted. The main advantage of the centralized approach is its practicality in terms of design and operation. However, it is clear that the need for a central controller is a latent risk. An operation failure on the MGCC can cause serious problems in the MG performance. Also, this topology requires an extensive communication system that could result complex in spatially dispersed MGs or in scenarios that involve a large number of DGs.

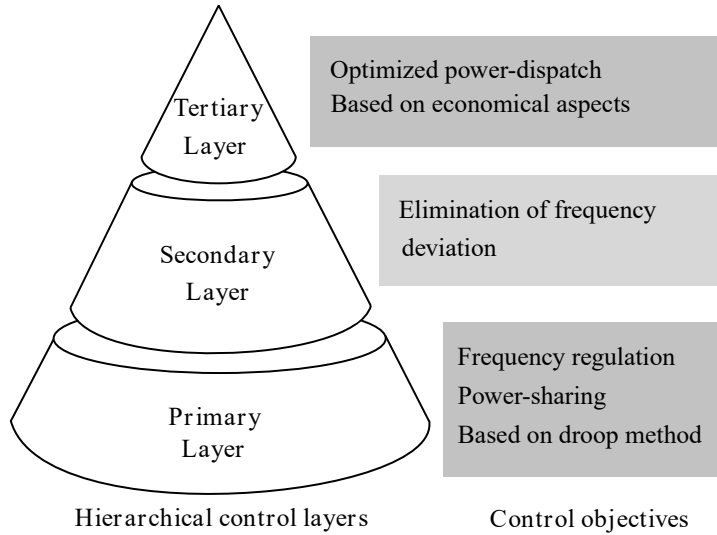
The distributed approach works with a sparse communication scheme which avoids the need for a MGCC [34, 35]. Instead of a centralized calculation, the control algorithms are executed in each one of the local controllers, which receive information from some DG units (called neighbors or adjacent DGs). Fig. 0.4(b) presents a scheme of the distributed communication approach. Evidently this approach avoids the single-point-of-failure risk. However, a precise (and not always simple) coordination of the communication system is essential to guarantee a stable operation performance. As the local control execution depends on the data reception, this makes the operation vulnerable to failures in the transmission of the information.

These two approaches represent different ways of coordinating the MGs communication systems. Beyond the communications topology used, the definition of the control objectives is fundamental to design the control strategies. Due to the complexity and the operation time-scales of the key control variables in a MG, multi-layer hierarchical schemes have become almost a standard for the design of these applications. Its characteristics and advantages are discussed below.

#### **0.1.4** Hierarchical control

Hierarchical control is characterized by dividing the variables and control objectives of a system in layers, according to their expected dynamics [36]. In islanded MGs, the critical control objectives are frequency stability, voltage regulation and power-sharing. The latter is understood as the ability of each DG to generate a steady-state power proportional to its nominal characteristics [37, 38]. Also, other control objectives such as the optimal operation of the MG in terms of power dispatching, can be implemented in slower speed of responses.

Commonly, the hierarchical control is divided in three control layers: primary, secondary and tertiary [39, 40]. These layers can be designed following particular control objectives as long as they decouple their dynamic by operating with different control bandwidths [41, 42].



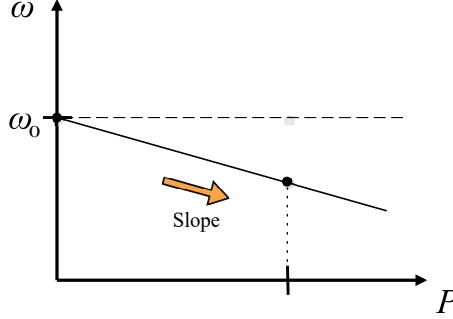
**Figure 0.5:** Hierarchical control objectives.

According to the current state-of-the-art, the most common design for hierarchical control layers is presented in the scheme of Fig. 0.5. In the following subsections, the characteristics of each control layer will be described in detail.

#### 0.1.4.1 Primary layer

This control level deals with the inner voltage and current control loops (which are commonly neglected in the modeling analysis considering their speed of responses) as well as with the frequency regulation and power-sharing, denominated as primary control objectives [43–45]. The most developed strategy for these purposes is the droop method (first introduced in [46]). It is based on the mimicking of the synchronous generator by generating an intentional frequency deviation. This method consists of subtracting a proportional part of the active power from a frequency reference to emulate a virtual inertia [47,48], which guarantees the convergence of a common deviated frequency (with respect to the nominal value) on the MG. Due to the local characteristic of the control (it works using exclusively local measurements), it does not require any type of communication between the DG controllers.

Droop method can be expressed mathematically as follows:



**Figure 0.6:** Primary layer control action.

$$\omega = \omega_0 - mP \quad (0.1)$$

where  $\omega$  is the angular frequency and  $\omega_0$  its reference,  $P$  the supplied active power and  $m$  the droop control gain. The second term of the equation ( $mP$ ), produces a deviation in the value of the frequency with respect to the reference (as shown in the Fig. 0.6), in exchange for obtaining the benefits of this control method (accomplishment of the control objectives).

Similarly, some works have adopted a voltage droop method which relates voltage amplitude and reactive power [49,50]. As the voltage is not a global variable (the voltage profile changes along the network according to the impedances and the power injection) larger deviations are allowed, which are then corrected in superior control layers.

### Example of droop control operation

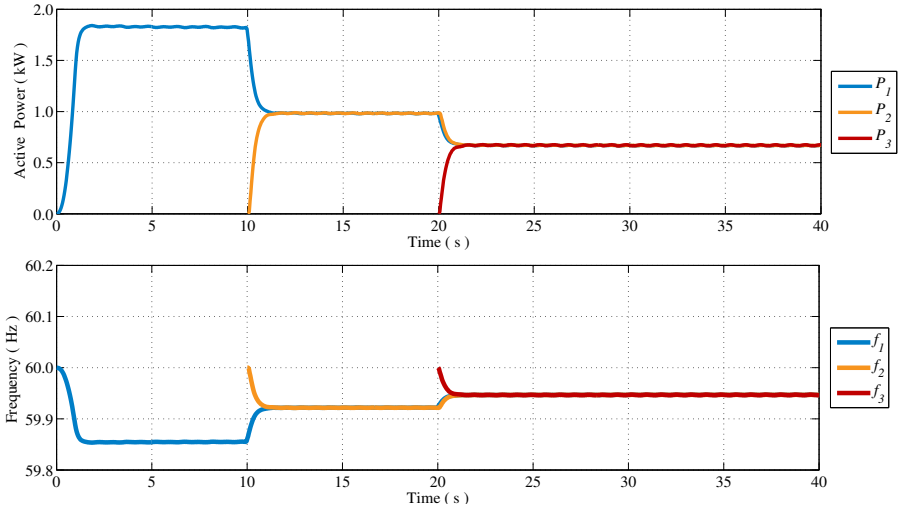
An example of the frequency/active power droop control implementation in MGs is presented below. To simplify the discussion, a MG with three DGs is considered.

First, considering (0.1), droop control can be expressed for each DG as

$$\omega_1 = \omega_{01} - m_1 P_1 \quad (0.2)$$

$$\omega_2 = \omega_{02} - m_2 P_2 \quad (0.3)$$

$$\omega_3 = \omega_{03} - m_2 P_3 \quad (0.4)$$



**Figure 0.7:** Experimental results using a primary control layer based on droop control. Top: Active powers. Bottom: Frequencies.

A valid assumption that can be made is that, if traditional droop control is considered, then the reference of the angular frequency is equal for each DG. Thus:

$$\omega_0 = \omega_{01} = \omega_{02} = \omega_{03}. \quad (0.5)$$

From (0.2), (0.3) and (0.4) it is possible to derive that, once the frequency regulation is completed and a common MG frequency achieved, the following terms are equals

$$m_1 P_1 = m_2 P_2 = m_3 P_3. \quad (0.6)$$

This equation shows that there is a close relationship between the design of the droop control gain and the supplied active of each DG. In fact, if all the DGs are implemented with the same droop control gain, a perfect power-sharing is achieved (all the DGs deliver the same active power value).

To illustrate this scenario, an experimental test was carried out considering three DGs (DG1, DG2 and DG3) operating with droop control. A sequentially black start was implemented. The experimental results (active powers and frequencies) are presented in Fig. 0.7.

The black start begins at  $t = 0$  s with the connection of GD1. The rest of DGs are disconnected from  $t = 0$  s to  $t = 10$  s and for this reason, DG1 supplies the total of the load during this time interval. By looking at the top of Fig. 0.7 (active powers), it can be noticed the increase in the power delivered by DG1. As a consequence of this, a reduction in the frequency of the DG is presented (as expected according to (0.1)), that can be appreciated in the bottom of Fig. 0.7 (frequencies). In this case, the local frequency of the DG corresponds during all the time interval to the global frequency of the MG, since it is the only generator working.

At  $t = 10$  s DG2 is connected. From  $t = 10$  s to  $t = 20$  s DG1 and DG2 are both active operating, while DG3 remains disconnected. As the same droop control gain was implemented for each DG, the total load is perfectly shared, as can be observed at the top of Fig. 0.7. Also, note that the frequencies of DG1 and DG2 match in steady state, i.e., a global frequency is achieved, in a higher value (less deviation with respect to the nominal value) compared with the steady state frequency presented in the time interval from  $t = 0$  s to  $t = 10$  s. The reason for this is the simultaneous operation of DG1 and DG2. Since the total load is shared between the generators, the frequency deviation is reduced.

Finally, at  $t = 20$  s DG3 is connected and DG1, DG2 and DG3 are together active operating from  $t = 20$  s to  $t = 40$  s. Again, a perfect power sharing is obtained, reducing the power delivered by each DG and thus, the steady state frequency deviation.

This example allowed to verify the performance of the frequency/active power droop control operation previously described. The strategy offers an appropriate frequency regulation and power-sharing, producing an inherent deviation in the global frequency.

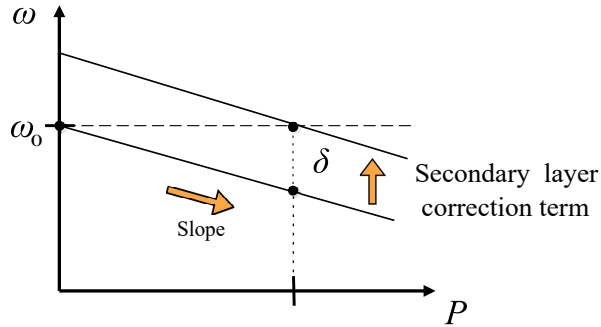
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#### **0.1.4.2** Secondary layer

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If the primary layer is based on the droop method, the secondary layer performs the main function of eliminating or adjusting the generated deviations [51]. In order to decouple the dynamics and facilitate the design of the control parameters, the secondary layer usually operates with a lower speed of response compared with the primary layer.

In a general form, the frequency/active power secondary control layer can be expressed mathematically as follows:



**Figure 0.8:** Primary and secondary layers control action.

$$\omega = \omega_0 - mP + \delta \quad (0.7)$$

where  $\delta$  is the term of the secondary layer that performs the desired correction. Thus, the frequency can be adjusted, as shown in the Fig. 0.8.

Other auxiliary control objectives can be performed in the secondary layer (e.g., voltage profile regulation, reactive power sharing, and voltage unbalance elimination at PCC, among others). Generally, secondary control layer strategies are classified according to the topology (or the absence) of the communication system.

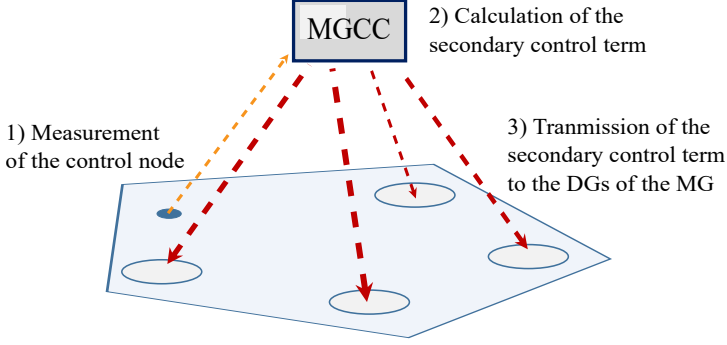
In the following subsections, centralized, distributed and communication-less strategies are presented. Some experimental examples are included in order to illustrate the basic aspects about its operation, as well as the impact of communication issues over the operation performance.

### Centralized secondary control operation

As previously discussed, a centralized control strategy relies on a communication systems which connects each DG to the MGCC [52]. For the secondary control layer, the MGCC can monitor a particular point of the MG in order to measure the variables of interest, execute the required calculations and send periodically the secondary terms to each DG. This process is illustrated in Fig. 0.9. Commonly, the control node is assigned in buses where special sensitive loads are connected or at the PCC, focusing on the control objectives related to the power injection and the voltage monitoring [53–56].

Regarding the frequency regulation, one of the simplest (but effective) alternative is implementing a proportional-integral (PI) controller as follows





**Figure 0.9:** Operation of centralized secondary control.

$$\delta = k_{pc} (\omega_0 - \omega_{con}) + k_{ic} \int (\omega_0 - \omega_{con}) dt \quad (0.8)$$

where  $k_{pc}$  and  $k_{ic}$  are the control parameters of the PI controller and  $\omega_{con}$  is the frequency measured at the control node. In order to illustrate the performance operation of centralized secondary control, an experimental example is presented below.

### Example of centralized secondary control operation

As was done in the previous example, to simplify the discussion, a MG with three DGs is considered

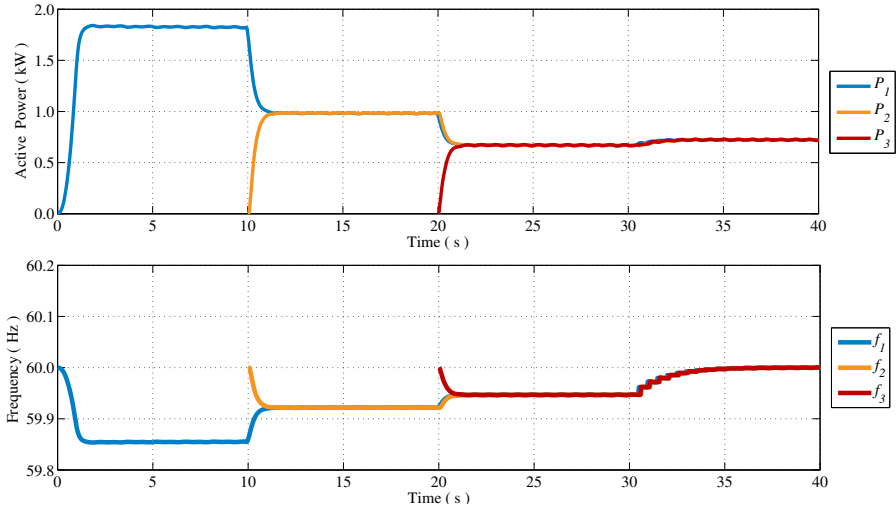
First, considering (0.7), the secondary control can be expressed for each DG as follows

$$\omega_1 = \omega_0 - m_1 P_1 + \delta_1 \quad (0.9)$$

$$\omega_2 = \omega_0 - m_2 P_2 + \delta_2 \quad (0.10)$$

$$\omega_3 = \omega_0 - m_3 P_3 + \delta_3 \quad (0.11)$$

As a centralized approach is considered, the secondary term is calculated at the MGCC and sent to all the DGs as indicated in (0.8). Thus,  $\delta$  is the same for all the DGs



**Figure 0.10:** Experimental results using a centralized secondary control layer. Top: Active powers. Bottom: Frequencies.

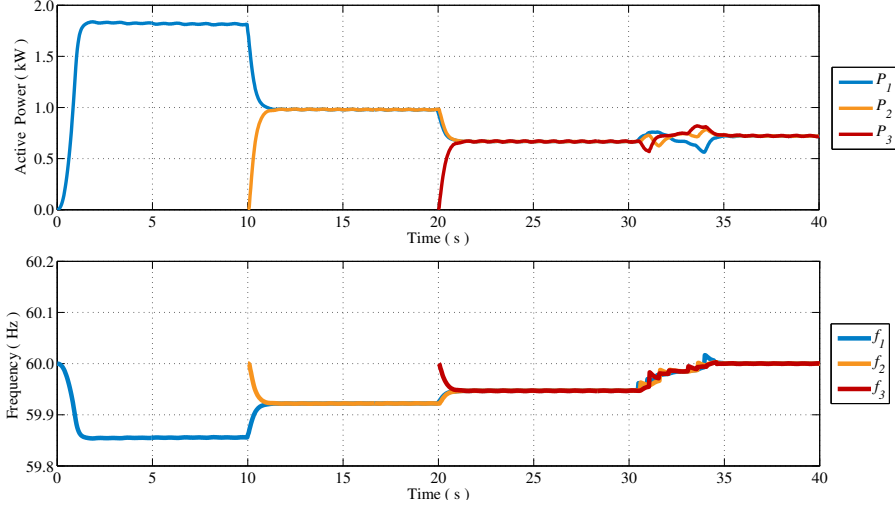
$$\delta = \delta_1 = \delta_2 = \delta_3. \quad (0.12)$$

An experimental test was carried out considering three DGs (DG1, DG2 and DG3) operating with a primary control layer based on droop control. A similar black start was implemented, compared with the example of droop control operation. The experimental results (active powers and frequencies) are presented in Fig. 0.10.

In this case, the centralized control was deactivated from  $t = 0$  s to  $t = 30$  s. At  $t = 30$  s the secondary control is activated until the end of the experiment. The activation of the secondary control implies the executions of the actions presented in Fig. 0.9. In this example the transmission rate was chosen as  $T_r = 0.5$  s. Control parameters values of  $k_{pc} = 0.005$  and  $k_{ic} = 0.6$  were considered for each DG.

By looking at the bottom of Fig. 0.10 (frequencies), it can be noticed the effect of the frequency restoration executed by the secondary control layer. The transient presents small changes by steps, corresponding to the transmission rate of the centralized secondary control. The frequency restoration is completed in approximately 5 s. Regarding the active powers, at the top of Fig. 0.10 is observed that these do not present any significant affectation with respect to previously obtained stable state values.

This example allowed to verify the performance of the centralized secondary



**Figure 0.11:** Experimental results using a centralized secondary control layer with 50% of packet losses. Top: Active powers. Bottom: Frequencies.

control operation. In optimal operating conditions, as is the case of the example, the strategy presents a good frequency recovery without affecting the active power sharing. However, the dependence on an extensive communications system makes the data transmission/reception failures a relevant concern. To analyze this effect, an example considering a percentage of packet losses is presented.

### Example of centralized secondary control operation considering packet losses

To appreciate the impact of communication issues over the performance of the centralized strategy, an example considering packet losses is presented. The same characteristics of the last example were replicated. However, in this case, an intentional induced percentage of 50% of packet losses was considered. To reproduce this scenario, the communications packets are filtered by a control in each DG receiver in which a randomizer decides, according to a predefined threshold, if the packet is used or discarded. The experimental results (active powers and frequencies) are presented in Fig. 0.11.

At  $t = 30s$  the secondary control is activated. The impact produced by the packet losses is clearly appreciated at both the bottom of Fig. 0.11 (frequencies) and the top of Fig. 0.11 (active powers).

Two interesting phenomena occur in this scenario:

- The loss of the packets sent by the MGCC causes transient differences in the secondary term implemented by each DG. This has an impact on the local frequencies, and therefore, on the powers delivered (temporally (0.12) is not fulfilled). Although power sharing and frequencies are severely affected, the response of the system is favorable to reach a steady state point in approximately 10 s, i.e., the affectations do not make the system unstable.
- Once the steady state point is reached, the mismatch in the frequencies (and therefore in the powers) disappears. This is because the system remains invariant. Even if there are packet losses in the data transmission of the MGCC, as long as the load and DGs connection/disconnection characteristics of the MG do not change, the secondary control terms remain in a static value.

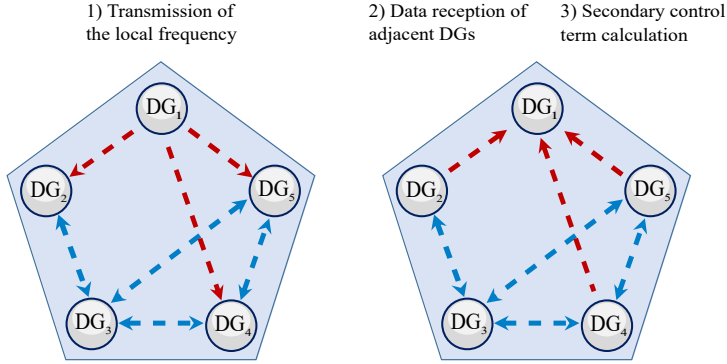
This example allowed to verify the impact of communication issues (packet losses) on a centralized secondary control strategy. The results show how the communication impairments may compromise the control performance.

It is worth noting that packet losses is only one type of communications issue that can occur during the operation of a centralized strategy. Other types of communications problems can effect more severely the MG operation. For example, a MGCC shutdown (single-point-of-failure risk) can compromise the stability of the system. This situation has motivated the development of distributed strategies for the secondary control layer, which are presented in the next subsection.

### **Distributed secondary control operation**

Systems with distributed control have been widely investigated due to the flexibility and reliability characteristics that they can offer to MGs operation. A fully distributed control eliminates the need to operate using a central controller, avoiding the single-point-of-failure risk. It worth to clarify that even with a secondary distributed control, for some applications the MG operation requires a MGCC which is used to control other functionalities, such as the DGs coordination during black start process. However, since fewer layers and operational actions depend on the MGCC performance, the MG will be more reliable.

In distributed control strategies, exchange of data is executed over a communication network. Due to the absence of the central controller, the design of the communication network becomes an important task. The aim is to define properly the communication links between the units to guarantee a proper function of the control strategy. An useful alternative for this purposes is to base the design on multi-agent systems theory [57,58].



**Figure 0.12:** Operation of distributed averaging secondary control.

Distributed secondary control approaches can be classified according to strategy utilized for the secondary control term calculation. The best known techniques are averaging and consensus [59–68]. Their operation principles are briefly explained below.

### Distributed secondary control operation - Averaging technique

In averaging technique, the control of the secondary layer is based on the computation of the average frequency. For this purpose, each DG estimates and sends its local frequency, then, with the received data from other DGs, calculates the secondary correction term using a PI controller as follows:

$$\delta = k_{pa} (\omega_0 - \omega_{ave}) + k_{ia} \int (\omega_0 - \omega_{ave}) dt \quad (0.13)$$

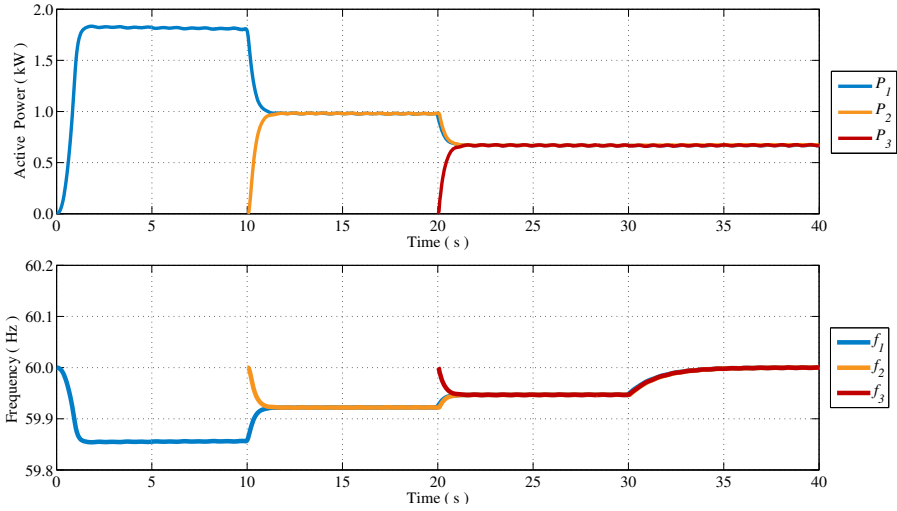
where  $k_{pa}$  and  $k_{ia}$  are the control parameters of the PI controller and  $\omega_{ave}$  is

$$\omega_{ave} = \frac{1}{n} \sum_{i=1}^n \omega_i \quad (0.14)$$

being  $n$  the number of units (DGs) connected to the DG through the communications system. This process is illustrated in Fig. 0.12.

In MGs with a low number of DGs, it is recommended the implementation of an all-to-all communication system (each DG is connected with all the others DGs of the MG). In that case, the value of  $n$  would be the total number of DGs of the MG.

### Example of averaging technique operation



**Figure 0.13:** Experimental results using an averaging secondary control layer. Top: Active powers. Bottom: Frequencies.

An example of averaging secondary control operation is presented below. To simplify the discussion, a MG with three DGs is considered. As the number of DGs is reduced, an all-to-all communication system is considered.

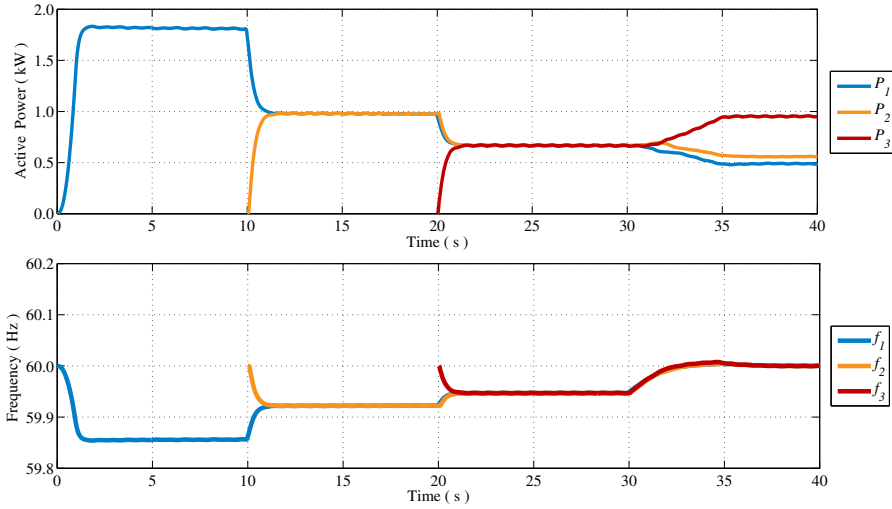
According to (0.13) and (0.14), the secondary control term for each DG can be expressed as

$$\delta = k_{pa} \left( \omega_0 - \frac{1}{3} \sum_{i=1}^3 \omega_i \right) + k_{ia} \int \left( \omega_0 - \frac{1}{3} \sum_{i=1}^3 \omega_i \right) dt \quad (0.15)$$

An experimental test was carried out considering a black start of three DGs (DG1, DG2 and DG3) similar to the previously presented examples. The experimental results (active powers and frequencies) are shown in Fig. (0.13).

The distributed secondary control was deactivated from  $t = 0$  s to  $t = 30$  s. At  $t = 30$  s, the secondary control is activated, and remains working until the end of the experiment. The activation of the control implies the execution of the actions presented in Fig. 0.12. In this example the transmission rate of  $T_r = 0.5$  s was used. Control parameters values of  $k_{pa} = 0.005$  and  $k_{ia} = 0.6$  were considered.

The results are very similar to those presented for the centralized secondary control. The frequency restoration is completed in approximately 5 s, without any perturbation or affection in the active power delivery.



**Figure 0.14:** Experimental results using an averaging secondary control layer with 50% of packet losses. Top: Active powers. Bottom: Frequencies.

By looking at the bottom of Fig. 0.13 (frequencies), it can be observed that this control strategy presents a smoother dynamic (without small changes by steps) compared with the observed for centralized control. This is because the calculation of the secondary term is done locally, not centralized as in the previous case.

This example allowed to verify the performance of the averaging distributed control operation. As expected, in ideal operating condition the strategy presents an excellent frequency recovery. To evaluate the technique in the presence of communication failures, an example considering packet losses is presented in the next subsection.

### Example of averaging technique operation considering packet losses

To appreciate the effect of a non ideal communication channel over the performance of the averaging distributed strategy, an example considering packet losses is presented. In this case, an intentional induced percentage of 50% of packet losses was considered. The experimental results (active powers and frequencies) are presented in Fig. 0.14.

At  $t = 30$  s the secondary control is activated. The effect produced by the packet losses is clearly appreciated at both the bottom of Fig. 0.14 (frequencies) and the top of Fig. 0.14 (active powers).

When the secondary control is activated, the failures in the transmission produce small mismatches in the local frequencies. Although the effect over the frequency is reduced (in fact, the frequency recovery is completed, presenting a good performance) the differences in the calculations of the secondary terms done locally with the received data, lead to different steady-state values in the active powers. This can be appreciated at the top of Fig. 0.14, where the final active powers are considerably different even though the DGs are operating with the same droop gains.

From these experimental results it is possible to conclude that the averaging technique exhibits a direct relationship between the power-sharing error and the packet losses. It is important to notice that this packet losses percentage is a considerable large induced value compared with realistic scenarios. However, it allows illustrating how communications can have significant impacts on the MG performance.

### Distributed secondary control operation - Consensus technique

In consensus technique, each DG calculates the secondary control term using the local and received frequencies, as well as the received secondary control terms of the adjacent DGs. Each DG repeats the process of estimate the local frequency to send it to the DGs connected to it through the communication system (similarly to the operation described for the averaging technique, presented in Fig. 0.12). However, in this case it is also necessary to send the last value of the secondary control term, which is used in the consensus algorithm as is explained below.

The secondary term is obtained according to the following consensus equations:

$$\delta = k_{con} \left( \int (\beta e + \gamma \xi) dt - \omega \right) \quad (0.16)$$

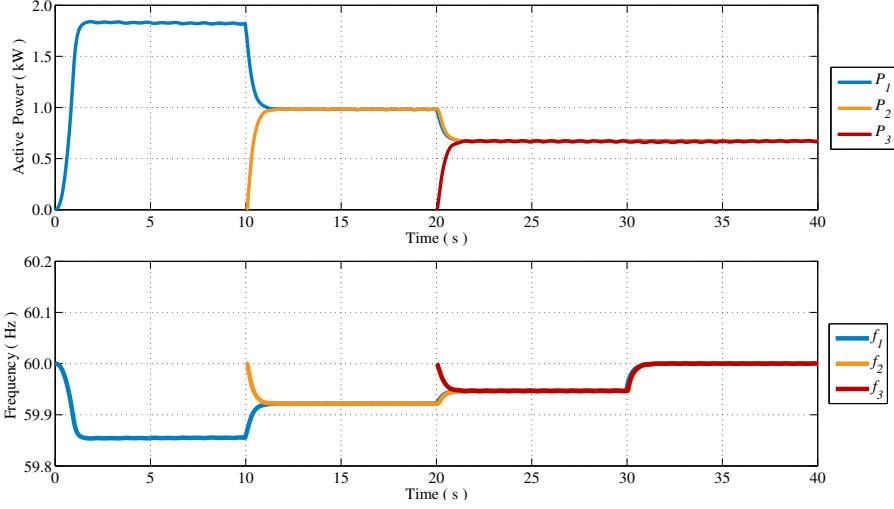
being  $k_{con}$ ,  $\beta$  and  $\gamma$  control parameters. The consensus requires the calculation of two terms  $e$  and  $\xi$ , which can be expressed as follows

$$e = \sum_{i=1}^n (\omega_i - \omega) + \alpha (\omega_0 - \omega) \quad (0.17)$$

$$\xi = \sum_{i=1}^n (\delta_i - \delta) \quad (0.18)$$

where  $\alpha$  is a control parameter.





**Figure 0.15:** Experimental results using a consensus secondary control layer. Top: Active powers. Bottom: Frequencies.

Notice that the calculation of the term  $e$  requires the local frequencies of the  $n$  adjacent DGs, while the calculation of the term  $\xi$  requires the values of its secondary control terms. To illustrate the operation of the consensus technique, an example is presented below.

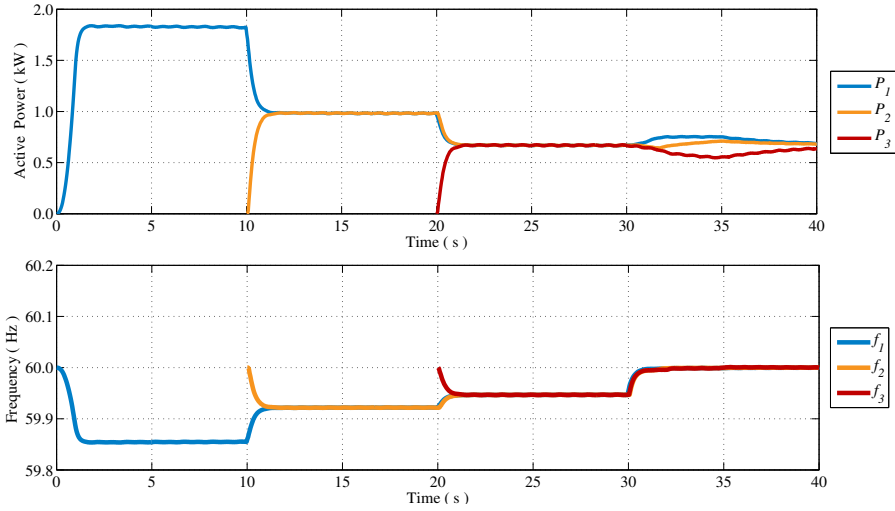
### Example of consensus technique operation

An experimental test was carried out considering the same black start process of three DGs (DG1, DG2 and DG3) previously presented. The experimental results (active powers and frequencies) are presented in Fig. (0.15).

The distributed secondary control was deactivated from  $t = 0$  s to  $t = 30$  s. At  $t = 30$  s the secondary control is activated, until the end of the experiment. The activation of the control implies the execution of the actions previously discussed (measurement of the local frequency, calculation of a secondary control and transmission of both values to the adjacent DGs). In this example the transmission rate was chosen as  $T_r = 0.5$  s. Control parameters values of  $k_{con} = 2$ ,  $\beta = 0.01$ ,  $\gamma = 0.1$  and  $\alpha = 200$  were considered for each DG.

The results obtained show an excellent performance in terms of frequency restoration and power sharing. In fact, while in the previous techniques the regulation of the frequency was completed in approximately 5 s, for this technique the transient is finished in 1.5 s.

In general, this technique is characterized by faster convergence times compared with similar techniques. However, to obtain the best operation features, a



**Figure 0.16:** Experimental results using a consensus secondary control layer with 50% of packet losses. Top: Active powers. Bottom: Frequencies.

proper selection of the control parameters is required. To evaluate the technique in the presence of communication failures, an example considering packet losses is presented in the next subsection.

#### Example of consensus technique operation considering packet losses

To appreciate the effect of communication failures over the performance of consensus distributed strategy, an example considering packet losses is presented. In this case, an intentional induced percentage of 50% of packet losses was considered. The experimental results (active powers and frequencies) are presented in Fig. 0.16.

At  $t = 30$  s the secondary control is activated. The effect produced by the packet losses characteristic is clearly appreciated at both the bottom of Fig. 0.13 (frequencies) and the top of Fig.0.13 (active powers).

When the secondary control is activated, the failures in the transmission produce small mismatches in the local frequencies. However, similarly to averaging technique, although the effect over the frequencies and the global frequency recovery is negligible, considerable transitory mismatches in the values of the powers delivered are appreciated. This can be observed at the top of Fig. 0.16.

In this case, from  $t = 30$  s to  $t = 40$  s, the affectation on the active power sharing is noticeable. The nature of the consensus control allows to dynamically

eliminate the deviations, leading to a correct power-sharing at the end of the experiment.

From these experimental results it is possible to conclude that the consensus technique is a more robust distributed control strategy compared with averaging technique, since it offers better dynamic properties even in the presence of large induced communication issues. However, as the experimental results confirm, failures in the communications are a major concern for the proper operation of communication-based control strategies. This has motivated the development of alternatives for secondary control layer, based on strategies that do not require the use of communications.

### Secondary control without communications

In the literature, a few proposals can be found which present secondary control schemes based on strategies that do not require communications, as is the case of [69–71].

Commonly, the communication-less strategies are based on low-pass filters, which can be mathematically expressed as follows

$$\delta = k_s \frac{\omega_s}{s + \omega_s} (\omega_0 - \omega) \quad (0.19)$$

being  $k_s$  the gain and  $\omega_s$  the cut-off frequency.

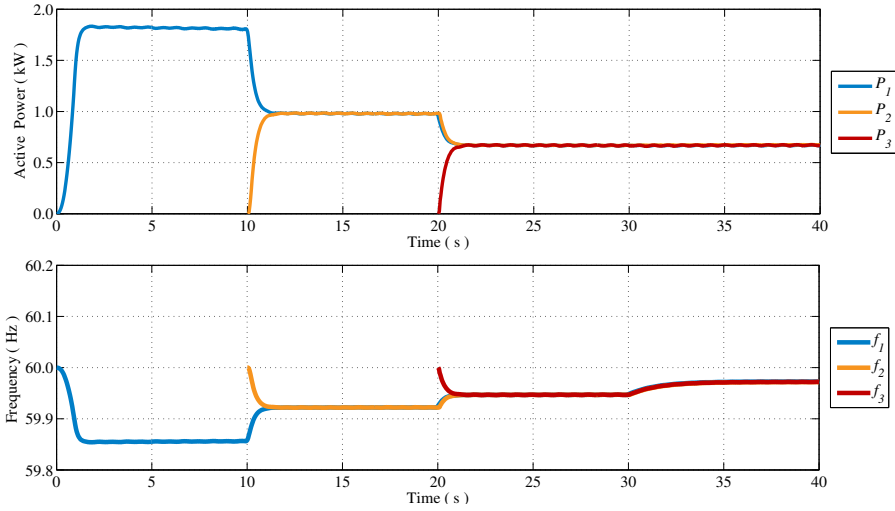
This configuration presents an unavoidable steady-state frequency error, which can be reduced with a proper selection of its control parameters, in exchange for increasing the time required to complete the frequency restoration. This leads to a design trade-off that relates the frequency restoration and the time of response. In order to illustrate the performance operation of secondary control without communication, an experimental example is presented below.

### Secondary control without communications operation

An experiment test was carried out considering a black start of three DGs (DG1, DG2 and DG3) similar to the previously presented examples. The experimental results (active powers and frequencies) are shown in Fig.0.17.

The distributed secondary control was deactivated from  $t = 0$  s to  $t = 30$  s. At  $t = 30$  s, the secondary control is activated, and remains working until the end of the experiment. Control parameters values of  $k_s = 10$  and  $\omega_s = 30$  were considered in each DG.

By looking at the bottom of Fig. 0.17 (frequencies), it can be noticed the effect of the frequency restoration executed by the secondary control, which, as previously discussed, presents a steady-state frequency error. It is possible



**Figure 0.17:** Experimental results using secondary control layer without communications. Top: Active powers. Bottom: Frequencies.

to reduce this value by adjusting the control parameters. However, according to the application, it is not always convenient to increase the response time of the secondary control. In the next chapters an in-depth discussion about these characteristics will be presented, as well as alternatives to overcome these operational drawbacks.

### 0.1.4.3 Tertiary layer

This layer deals with power dispatching, aiming to optimize it according to economical and efficiency aspects. As a result, an operation scheduling is obtained, which can be reevaluated according to real-time measurements of the available power generation [72]. The nature of the controlled variables allows the execution of the operation in time steps of several seconds or minutes [73–75].

Most of the tertiary control layer proposals are focused on the optimal power flow dispatch, considering different scenarios such as: the possibility to connect/disconnect the MG to a main grid, the presence of different types of storage systems or reactive power flows optimization, among others [76–84]. Also, similarly to the secondary control layer, the works can be categorized according to the required communication system. Currently, the interest is focused on distributed proposals which require sparse communication systems and the exchange of some specific variables between neighboring units [85–87].

## 0.2 Research Motivations

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In this section, a brief discussion about the state-of-the-art review is presented in order to draw some general conclusions and identify research motivations. The scope of this thesis covers the primary and secondary control layers. Regarding these, the a review of the state-of-the-art allowed to conclude the following ideas:

Firstly, the research on the primary control layer has focused on developing the potentialities of the droop method [88, 89]. A lot of proposals have been presented in the literature inspired on this strategy including proportional [90], proportional-integral [91, 92], adaptive [93, 94] and improved alternatives for specific applications [95, 96], among others. The fact that it is a decentralized method (communication-less), easy to design and implement, and whose deviations can be corrected by a secondary control layer, makes it almost an accepted standard strategy for the operation of MGs. It is possible to affirm that this is a mature research area.

Secondly, the research works on the secondary control layer have presented good results in communication-based proposals. The centralized secondary strategies are a mature research field, while research on distributed strategies is a hot-topic in which several advances have been presented in the last years. However, it is observed that the development of secondary layer techniques without communications is still an open research field.

The implementation of a secondary control layer without communications does not necessarily eliminate the need of a communication system for other functionalities of the MG, such as the coordination of the units during black starts, real-time monitoring of power quality variables or superior control layers. However, avoiding the use of communications, at least in one more control layer, represents an improvement on the reliability of the MGs and provides some important advantages. The most important is the elimination of the risk of malfunctioning produced by communication issues such as delays, packet losses, traffic scheduling, or interruptions. Basically, the less dependent on communication systems, the lower will be the impact of its failures over the control objectives and the operation of the whole MG control. The impact of some communications issues over the secondary layer has been studied in some works [97–99]. Also, the reduction of the communication system complexity offers security in terms of communication vulnerability, a field that will be better explored in the future with the development of concepts as multi-MGs and community MGs [100–103].

Considering this argumentation, the objectives of this doctoral thesis are presented in the next section.

### 0.3 Objectives

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- Design alternatives for the secondary control layer in islanded microgrids without using communications.
- Determine suitable design considerations for the secondary control layer strategies based on stability and transient response analysis and a proper mathematical modeling.
- Analyze and verify the operational benefits and drawbacks of the proposed control schemes compared with other structures previously presented in the literature.

### 0.4 Thesis outline

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The present doctoral thesis has been organized following the structure presented below:

- **Chapter 0:** introduces the main concepts about electrical microgrids, discussing the research motivations and presenting the objectives, the thesis outline and the publications related to the doctoral work.
- **Chapter 1:** presents the first contribution, which is a secondary control layer strategy based on a switchable configuration that does not require the use of communications.
- **Chapter 2:** presents the second contribution, which is a complementary strategy to improve the frequency regulation of the control proposed in Chapter 1.
- **Chapter 3:** presents the third contribution, which is a hierarchical control that considers a droop-based primary layer, a time-driven secondary layer and a tertiary layer with an optimization algorithm for power dispatching.

- **Chapter 4:** presents the fourth contribution, which is an improved secondary control layer strategy without communications that presents superior operating performance compared with the previous proposals.
- **Chapter 5:** summarizes the contributions of the thesis, analyzing their relation with the doctoral thesis objectives and discussing the obtained results.
- **Chapter 6:** presents the conclusions of the doctoral thesis and proposes some potential research guidelines for future works.

## 0.5 Publications

The following are the journal and conference papers considered in the thesis compendium:

- **Chapter 1:** J. M. Rey, P. Marti, M. Velasco, J. Miret, and M. Castilla, "Secondary Switched Control With no Communications for Islanded Microgrids", *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8534 - 8545, Nov. 2017.
- **Chapter 2:** J. M. Rey, P. P. Vergara, M. Castilla, A. Camacho, and J. Miret, "Local Hierarchical Control for Industrial Microgrids with Improved Frequency Regulation", *ICIT - 2018 IEEE International Conference on Industrial Technology*, pp. 1019 - 1024, Lyon, France, 2018.
- **Chapter 3:** J. M. Rey, J. Solano, J. Torres-Martinez, J. Miret, M. M. Ghahderijani, and M. Castilla, "Multi-layer Active Power and Frequency Control Strategy for Industrial Microgrids", *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 2588 - 2593, Beijing, China, 2017.
- **Chapter 4:** J. M. Rey, C. X. Rosero, M. Velasco, P. Marti, J. Miret, and M. Castilla, "Local Frequency Restoration for Droop-Controlled Parallel Inverters in Islanded Microgrids", *IEEE Transactions on Energy Conversion*, in press.

Other contributions that were made simultaneously during the thesis (that were not included in the compendium) are the following:

Journal Papers:

- E. Mojica-Nava, J. M. Rey, J. Torres-Martínez and M. Castilla, "Decentralized Switched Current Control for DC Microgrids", *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 1182 - 1191, Feb. 2019.
- J. M. Rey, M. Castilla, J. Miret, A. Camacho and R. Guzman, "Adaptive Slope Voltage Control for Distributed Generation Inverters with Improved Transient Performance", *IEEE Transactions on Energy Conversion*, in press.

Book Chapters:

- J. M. Rey, J. Torres-Martínez, and M. Castilla, "Secondary Control for Islanded Microgrids" in *Microgrids Design and Implementation*. Springer, pp. 171–193, 2019.
- P. P. Vergara, J. C. Lopez, J. M. Rey, L. C. P. da Silva, and M. J. Rider, "Energy Management in Microgrids" in *Microgrids Design and Implementation*. Springer, pp. 195–216, 2019.
- J. Solano, J. M. Rey, J. D. Bastidas-Rodríguez, and A. I. Hernández, "Stability Issues in Microgrids" in *Microgrids Design and Implementation*. Springer, pp. 287–310, 2019.
- J. M. Rey, P. P. Vergara, J. Solano, and G. Ordóñez, "Design and Optimal Sizing of Microgrids" in *Microgrids Design and Implementation*. Springer, pp. 337–367, 2019.

Book title: Microgrids Design and Implementation.

<https://www.springer.com/la/book/9783319986869>

Conference Papers:

- J. Torres-Martínez, M. Castilla, J. Miret, M. Moradi-Ghahderijani and J. M. Rey, "Experimental study of clock drift impact over droop-free distributed control for industrial microgrids", *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 2479 - 2484, Beijing, China, 2017.
- M. M. Ghahderijani, M. Castilla, J. M. Rey, J. Torres-Martínez and M. A. Garnica López, "A communication-less control scheme for a variable air-gap wireless energy transfer system using current source resonant converter", *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 509 - 514, Beijing, China, 2017.



## 0.6 Thematic unity of the thesis

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In this section is presented the thematic unity of the thesis. As indicated above, the work is submitted as a compendium of publications. The present doctoral thesis is composed by journals and international conference papers that constitute the chapters of the thesis and contributions of the work.

Chapter 1 presents a journal paper in which a novel secondary control layer strategy with no communications is presented.

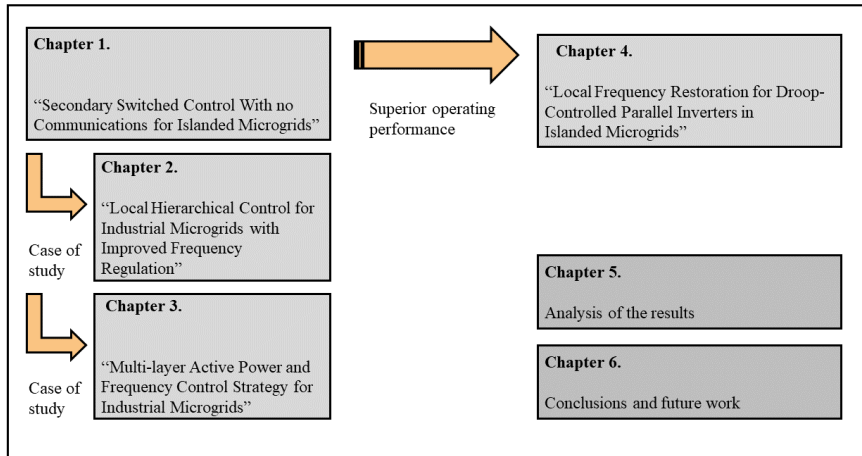
Case studies of this novel control strategy are presented in Chapter 2 and 3.

Chapter 2 presents an international conference paper that proposes a complementary strategy to improve the frequency regulation of the control technique presented in Chapter 1. Chapter 3 presents an international conference paper that evaluates a hierarchical scheme including a similar secondary control.

Based on an analysis of the operating characteristics, Chapter 4 presents a journal paper in which is proposed a control strategy that presents superior operating performance compared with the previous proposals.

A complete analysis of the results and the relation with the doctoral thesis objectives is discussed in Chapter 5, while the conclusion are presented in Chapter 6.

A schematic diagram of the thematic unity of the thesis is shown in Fig. 0.18.



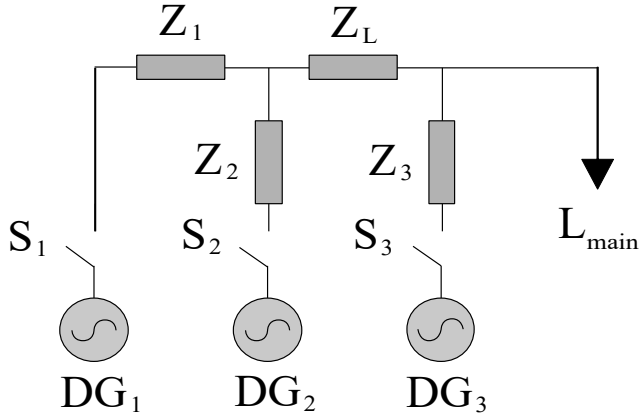
**Figure 0.18:** Schematic diagram of the thematic unity of the thesis.

## 0.7 Experimental setup

This section presents a general description of the experimental setup used to carry out the tests related to the doctoral thesis. The setup is located in the laboratory of the Power and Control Electronics Systems Research Group (SEPIC) from the Vilanova i la Geltrú School of Engineering (EPSEVG) - Technical University of Catalonia.

The experimental setup is a low-power three-phase small-scale laboratory microgrid. The system is composed by multiple generation nodes in which the power generation of distributed energy sources is emulated. Each generation node consists of a 2 kVA three-phase full-bridge power inverter MTL CBI0060F12IXHF from GUASCH and a damped LCL output filter. For the energy supply is used an AMREL SPS-800-12 DC power source. The controller of each inverter is implemented on a dual-core Texas Instruments Concerto board consisting in a C28 floating point digital signal processor (DSP) that implements the control algorithms and a ARM M3 processor that is used for communication purposes. Fig. 0.19 shows a schematic diagram of the experimental setup.

Three-phase inductances in series with resistors were implemented to emulate the wires of the distributed lines. For the loads, single-phase resistive heaters were used, connected in wye configuration with a floating neutral node. The values of the components are listed in Table 0.1.



**Figure 0.19:** Schematic diagram of the experimental setup.

**Table 0.1:** Parameters of the experimental setup

Element	Symbol	Quantity
Line impedance 1	$Z_1$	$0.5 + 1.13 j \Omega$
Line impedance 2	$Z_2$	$0.5 + 0.38 j \Omega$
Line impedance 3	$Z_3$	$1.13 + 0.23 j \Omega$
Line impedance L	$Z_L$	$0.3 j \Omega$
Main load	$L_{main}$	1.5 kW

For the supervision and visualization of the variables in real time, a computer was linked to the controller using an Ethernet network. This computer is also used to program and debug the control algorithms that are executed in the DSPs. For this purpose was used the Texas Instruments integrated development environment (IDE) Code Composer Studio<sup>TM</sup> (CCS).

More detailed information about sensing and communication stages of the experimental system is presented in [9]. A photo of the setup is shown in Fig. 0.20.

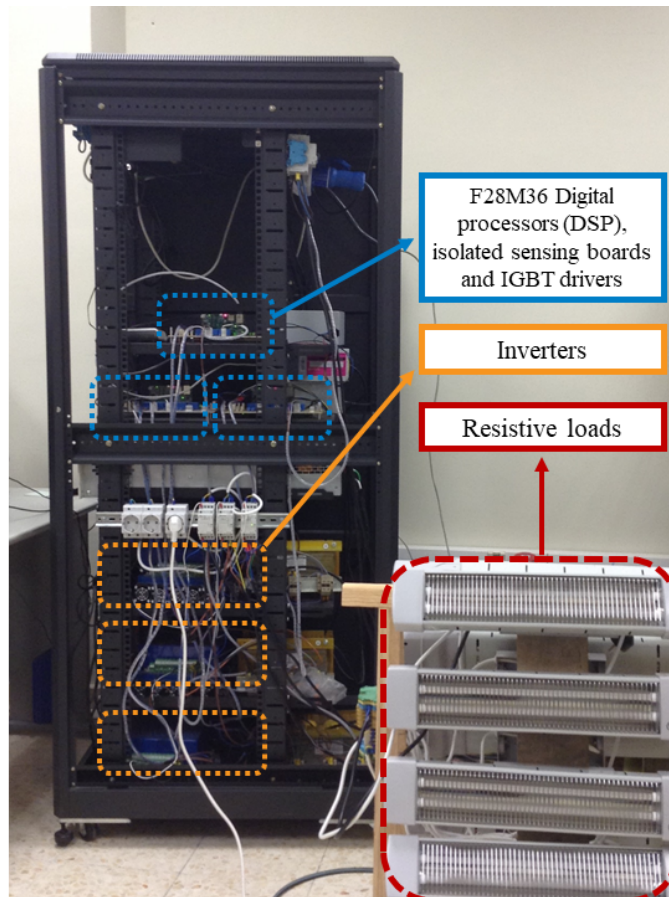


Figure 0.20: Experimental microgrid.



# PUBLICATIONS



# 1

## Paper I:

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### Secondary Switched Control With no Communications for Islanded Microgrids

J. M. Rey, P. Marti, M. Velasco, J. Miret, and M. Castilla, "Secondary Switched Control With no Communications for Islanded Microgrids", *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8534 - 8545, Nov. 2017.

#### **ATTENTION;**

Pages 38 to 50 of the thesis are available at the editor's web  
<https://ieeexplore.ieee.org/document/7927469>

### **Summary**

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# 2

## Paper II:

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### Local Hierarchical Control for Industrial Microgrids with Improved Frequency Regulation

J. M. Rey, P.P. Vergara, M. Castilla, A. Camacho, and J. Miret, "Local Hierarchical Control for Industrial Microgrids with Improved Frequency Regulation", *ICIT - 2018 IEEE International Conference on Industrial Technology*, pp. 1019 - 1024, Lyon, France, 2018.

#### **ATTENTION;**

Pages 52 to 58 of the thesis are available at the editor's web  
<https://ieeexplore.ieee.org/document/8352318>

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# 3

## Paper III:

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### Multi-layer Active Power and Frequency Control Strategy for Industrial Microgrids

J. M. Rey, J. Solano, J. Torres-Martinez, J. Miret, M. M. Ghahderijani, and M. Castilla, "Multi-layer Active Power and Frequency Control Strategy for Industrial Microgrids", *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 2588 - 2593, Beijing, China, 2017.

#### ATTENTION;

Pages 60 to 66 of the thesis are available at the editor's web  
<https://ieeexplore.ieee.org/document/8216435>

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# 4

## Paper IV:

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### Local Frequency Restoration for Droop-Controlled Parallel Inverters in Islanded Microgrids

J. M. Rey, C. X. Rosero, M. Velasco, P. Marti, J. Miret, and M. Castilla, "Local Frequency Restoration for Droop-Controlled Parallel Inverters in Islanded Microgrids", *IEEE Transactions on Energy Conversion*, in press.

#### ATTENTION;

Pages 68 to 78 of the thesis are available at the editor's web  
<https://ieeexplore.ieee.org/document/8572796>

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ANALYSIS AND CONCLU-  
SIONS



# 5

## ANALYSIS OF THE RESULTS

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*This chapter summarizes the contributions of the thesis, analyzing their relation with the doctoral thesis objectives and discussing the obtained results.*

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As mentioned in the Introduction (Chapter 0), the design of the secondary control layer strategies proposed in previous chapters has as a starting point a droop-based primary control layer. Considering this, the secondary layer is designed in order to correct the inherent deviations. The frequency/active power loop can be expressed as

$$\omega = \omega_0 - mP + \delta \quad (5.1)$$

where  $\omega$  is the angular frequency and  $\omega_0$  its reference,  $P$  the supplied active power,  $m$  the droop control gain and  $\delta$  the term of the secondary layer. Thus, the challenge is to properly design  $\delta$  to achieve three main goals:

- Guaranteeing the correction of the frequency deviation, which according to (5.1) implies a steady-state value of  $\delta$  as close as possible to  $mP$ .
- Allowing the proper functioning of the droop method, which achieves the power-sharing through the action of its virtual inertia dynamics.
- Using exclusively local variables, considering that the objective is to design a secondary control layer without the use of communications.

Regarding these tasks, in [69] is presented an alternative based on a low-pass filter which offers limited static and dynamic properties. In this proposal, the term  $\delta$  is designed as follows

$$\delta = k_s \frac{\omega_s}{s + \omega_s} (\omega_0 - \omega) \quad (5.2)$$

being  $k_s$  the gain and  $\omega_s$  the cut-off frequency of the low-pass filter. Notice that this configuration presents an unavoidable steady-state frequency error, that can be calculated inserting (5.2) in (5.1). It can be expressed as

$$(\omega_0 - \omega) = \frac{mP}{1 + k_s}. \quad (5.3)$$

Thus, considering that  $m$  is a design parameter of the primary layer and  $P$  depends on the power-sharing, the error can be reduced (an almost eliminated) if the value of  $k_s$  is highly increased. This, on the other hand, requires a proper selection of the frequency  $\omega_s$  to guarantee the stability of the system, leading



to a design trade-off: a high value of the gain requires a low value of the cut-off frequency which represents a good frequency restoration but a slow speed of response. On the contrary, a low value of the gain and a high cut-off frequency results in a poor frequency restoration and a fast speed of response.

This analysis is the starting point of the strategies proposed in this work, which are discussed in the next sections.

## 5.2 Secondary Switched Control

---

Chapter 1 presented the first contribution of this work [104], which corresponds to a secondary control strategy based on a switchable configuration that takes advantage of the operational trade-off of the low-pass filter-based proposal. First, (5.2) is rewritten as follows

$$\delta = \frac{k_i}{s + kk_i}(\omega_0 - \omega). \quad (5.4)$$

Notice that comparing (5.2) with (5.4), is possible to obtain that  $\omega_s = kk_i$  and  $k_s = \frac{1}{k}$ . The parameter  $k$  has a direct influence over both the gain and the frequency of the low-pass filter, which implies the possibility to modify the dynamic (speed of response) and static (final frequency error) characteristics of the secondary control. Thus, to seek the best performance of these features,  $k$  is assumed as a variable parameter which is modified using a time-dependent protocol. Rewriting the steady-state frequency error (i.e., inserting (5.4) in (5.1)), it is obtained

$$(\omega_0 - \omega) = \frac{kmP}{k + 1} \quad (5.5)$$

expression that allows to appreciate the impact that the parameter  $k$  can have on the final error.

As explained in Chapter 1, the protocol aims to vary the parameter  $k$  from an initial value  $k_{max}$  to a final value equal to 0. This variation is made in a conveniently manner so that the power-sharing dynamic executed by the primary layer is guaranteed and (with the reduction of  $k$ ) the frequency error is eliminated by the secondary layer. The time-dependent protocol is launched by an event detection, which can be based on different strategies including the well-known send-on-delta.

Examining (5.4) and (5.5), it is clear that the reduction of the parameter  $k$  to values close to zero has a twofold effect: on the one hand, the control behaves similarly to an integral controller, which is desirable considering that this will guarantee the elimination of the frequency deviation, and, on the other hand, if the parameter remains in this value once the deviation is eliminated, it can risk the stability of the system considering the problems that this type of controllers have in systems with DGs working in parallel. For this reason, to avoid this drawback, a switched characteristic is implemented.

The principle of the switching control is based on the value assigned to  $k$ . When this parameter has a non-zero value, the control behaves as (5.4), and when it has a zero value, the control (secondary control layer term) remains constant in the last value calculated until a new event is detected and the time protocol is re-launched. To correctly design the key control parameters, Chapter 1 presents some design guidelines and to guarantee the stability an analysis based on a Lyapunov function approach is developed. To validate the results and predicted characteristics a series of experimental tests performed on a MG prototype are reported, including: tests using only the primary layer and the low-pass filter-based control, tests without the switched characteristic and tests in scenarios where multi-events are detected.

The obtained results show an excellent performance in terms of flexibility, reliability, and dynamics and static features. The work developed is in line with the objectives of the thesis as it presents an alternative for the secondary control in islanded MGs without using communications. A closed-loop system modeling is presented as a basis for the stability analysis and control parameters design. As a modeling approach, an equivalent circuit of an electronically coupled DG system is considered. However, the interaction between the DGs of the MG is omitted since the equivalent circuit seen from the DG connection point is modeled as an ideal voltage source. Evidently, this constitutes an approximation that allows a limited analysis but, as explained in Chapter 1, sufficient for the proper design of the control parameters. Regarding this point, a more complete modeling approach is presented in the following chapters.

Regarding the analysis of the operational benefits of the proposed control scheme, the experimental results allow to clearly verify the contributions, identifying the improvements in respect to the state-of-the-art. To complement the analysis of the operation of this control proposal, two scenarios are presented in the next chapters: a complementary strategy to improve the frequency regulation, and a hierarchical scheme in which a quite similar secondary control is introduced.

Chapter 2 presented a complementary strategy to improve the frequency regulation of the control proposed in the previous chapter [105]. The strategy is based on the reduction of the maximum error, which occurs in the initial part of the time-driven protocol. To this end, the droop gain is not considered static, but dynamic, driven by a time protocol which uses the same time intervals of the secondary control layer protocol. This aspect favors the design simplicity and the operation synchronization. As expected, the value of the droop gain  $m$  presents a design trade-off: a small value of  $m$  provides a slower speed of response, but reduces the maximum frequency error. Thus, the main idea consists of taking advantage of this characteristic, defining an appropriate variation.

The time protocol proposed to drive  $m$  aims to vary the gain parameter from an initial value  $m_{min}$  to a final value equal to  $m_{max}$  (unlike the secondary control, the dynamic parameter  $m$  increases its value during the execution of the protocol). Thus, with a proper selection of these two limit values, a reduction of the frequency error in the first interval and an accurate power sharing are achieved. It is worth noting that at the end of the protocol, the frequency error is completely eliminated by the action of the secondary layer, as is expected.

Experimental results obtained on a laboratory microgrid are presented to validate the features of the proposed complementary strategy, showing an excellent operation performance. In general, this work allows to conclude that the secondary control layer proposed in Chapter 1 is susceptible to operational improvements without losing its main characteristics.

Chapter 3 is intended to analyze the operation of a time-driven secondary control (with some similar characteristics to the control proposed in the previous chapters), framed in a hierarchical scheme [106]. The proposal considers a droop-based primary layer, while for the tertiary layer an optimization algorithm is implemented to set the dispatching of the power references. Regarding the secondary layer, a control scheme based on a distributed low-pass filter

controlled by a time protocol is implemented. In this case, the secondary term  $\delta$  is rewritten as

$$\delta = \frac{k_0}{s + k}(\omega_0 - \omega) \quad (5.6)$$

being  $k_0$  an static parameter and  $k$  a variable parameter controlled by the protocol.

Unlike the previous proposals, in this case the time protocol varies the parameter  $k$  from an initial value  $k_{max}$  to a final non-zero value  $k_{min}$ . Because of this, the implementation of the switched characteristic becomes unnecessary. Also, in the proposed scheme, it is considered that the time protocol is launched by a signal sent by the MGCC (not by an event detection). This signal is generated when a scheduled event occurs on the MG, as programmed changes in the load, actions of the tertiary control layer or both simultaneously. It is important to clarify that the execution of the secondary control is done locally, in each DG controller.

Experimental results were obtained from a laboratory MG, showing good performance in terms of frequency restoration, power sharing and tracking of the dispatched power references. Even though the secondary control requires communications for the launching of the time protocol, the results allows to conclude that the local time-driven secondary control schemes present a good performance when they are framed in hierarchical schemes. Particularly, with superior control layers associated with control objectives such as the optimal power dispatch.

From a general perspective, the results of the works presented in Chapter 2 and 3 are in line with the objectives of the thesis, as they explore and analyze the benefits and potentialities of the secondary control proposed in Chapter 1. In the next section, an improved secondary control scheme is discussed, which is based on the weaknesses of the previous proposal.

## 5.5 Improved Secondary Control

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An important characteristic of the control strategy presented in Chapter 1 is that it has a time protocol that is launched each time a predefined strategy detects an event in the system. For this reason, a possible operation scenario is the multi-event detection (which occurs when a new event is detected before a protocol previously launched has finished its execution). According to the

system characteristics, this can have a relevant impact over the MG performance. For example, under certain operation a cascade triggering of the event condition could generate a continuous multi-event detection, which affects the normal functioning of the system.

One possibility to overcome this risk is designing the event detection strategy with more stringent thresholds, which, in some cases, could hinder the detection of certain events. Another possibility is to disable the event detection during a safety time interval, which is a fundamental part of the strategy adopted in the proposal of Chapter 4 [107]. This ensures that the event detection will become activated again whenever it is expected to have the active power and frequency in steady-state, meaning perfect power sharing and restored frequency.

Chapter 4 presents a time-driven secondary control without communications. In this case, the secondary term  $\delta$  is expressed as

$$\delta = \tilde{k}_s \frac{\omega_s}{s + \omega_s} (\omega_0 - \omega) \quad (5.7)$$

where  $\tilde{k}_s$  is a dynamic gain, which, considering the design trade-off discussed in previous sections, can improve the control layer performance by the temporal variation driven by a protocol. Notice that, to obtain the desired performance, a variation that produces an increase in the variable  $\tilde{k}_s$  is expected. Indeed, the time-driven protocol proposed aims to vary the parameter  $\tilde{k}_s$  from an initial value  $k_{min}$  to a final value  $k_{max}$ . Due to this, the switched characteristic is unnecessary.

The experimental results show the advantages in respect to the control strategies proposed in previous chapters. Selected tests are presented to illustrate this comparison. A test where the performance of the control is evaluated for different anomalous triggering of the event condition allows to draw some conclusions. In particular, two scenarios are presented: the first in which the event detection strategy implemented in one DG does not detect a load change. In this case, it is observed that the active power presents slow and oscillatory dynamics instead of the desired fast one. The second in which a desynchronized detection produces slow variations. In both cases, the failures in the detection produce unexpected dynamics, but the system is still driven to the desired steady-state values, achieving excellent power-sharing and frequency restoration.

Regarding the inclusion of the event detection safety time, experiments in which some local loads are connected and disconnected when the time protocol is being executed (the detection is deactivated), show that the power-sharing

dynamics reach the desired set-points exhibiting acceptable transient variations, while the frequency presents small changes that are negligible.

For this proposal, a modeling approach which includes the interaction between the DGs of the MG was presented. To this end, the complete topology of the MG is considered to obtain the corresponding transfer functions. This modeling is used in the stability analysis and to determine design guidelines for the key control parameters. This modeling approach represents a remarkable advantage compared with the work presented in Chapter 1, where each DG is analyzed omitting the rest of the MG since the point of connection with the MG is represented using an equivalent voltage source.

Considering the above, it is concluded that the proposal presented in Chapter 4 has better operating characteristics than the previous ones. This work is in line with the objectives of the thesis as it presents an improved alternative for the secondary control layer without using communications. Also, the work presents design considerations for the proper selection of the key parameters as well as an experimental verification of its benefits and advantages compared with other proposals.



# 6

## CONCLUSIONS AND FUTURE WORK

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*This chapter presents the conclusions of the doctoral thesis and proposes some potential research guidelines for future works.*

### Summary

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The following are the general conclusions of the doctoral thesis:

- This doctoral thesis has been focused on the analysis and design of alternatives for the secondary control layer of islanded microgrids, with the special feature that the use of communications is not required (or is reduced to launch signals). The elimination of the communications in the secondary control layer execution does not necessarily avoid the need for a communication channel for other functionalities of the MG. However, this characteristic represents an improvement on the reliability of the MG operation since it reduces the risks of malfunctioning produced by communications issues, offers security in terms of vulnerability and favors the design of simpler operation schemes.
- The discussion of the main results presented in Chapter 5 allows to conclude that the control strategies presented in the doctoral thesis have as starting point the analysis of the operational trade-off of the low-pass filter-based control scheme. To take advantage of its characteristics (instead of being a limitation), the use of variable control parameters driven by time protocols is proposed. This alternative allows to obtain excellent results in terms of the dynamic and steady-state properties, as the experimental results corroborate.
- For the control strategies presented in Chapter 1 and Chapter 4, design guidelines were determined based on circuit modeling and stability and transient response analysis. In the first case, a simplified and limited equivalent circuit model was considered, while in the second case a more complete modeling was proposed including the topology of the microgrid and, in this way, the electrical interaction between the DGs. The experimental results validated the theoretical predictions using the modeling approaches, as well as the operational features expected according to the design considerations.
- For the purpose of analyzing and verifying the operational benefits and limitations of the proposed control schemes, an experimental MG was implemented. The MG used is a low-power three-phase grid in which the power generation of the DGs is emulated with a power source, guaranteeing the repeatability of the experimental scenarios. Selected tests were implemented in order to examine the operational performance of the control proposals and to compare it with other structures previously presented in the literature. The results obtained clearly show that the

proposed control strategies represent a contribution to the research field and, therefore, an advance in the state-of-the-art of the control and design of electrical MG working in islanded mode.

## 6.2 Future works

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Some potential research lines for future works are the following:

- The proposals presented in this doctoral thesis are focused on the design of strategies for the active power/frequency control loop. Future work will be focused on extending the main ideas of the secondary control layer with no communications to the reactive power/voltage control loop to achieve a robust voltage regulation.
- Considering the fundamental role of the event detection strategy in some of the previously presented proposals, future works will be focused on the study in depth of the performance of different event detection strategies in multi-event scenarios and MG operating in different applications.
- The secondary control layer strategies presented in this doctoral thesis are mainly focused on control objectives as frequency regulation and power-sharing. A possible line of future work consists of exploring alternatives to achieve other control objectives related to the control of negative-sequence and harmonic voltages, following the secondary control layer scheme without the use of communications.

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