UNIVERSITAT POLITÈCNICA DE CATALUNYA

Doctoral Programme:

AUTOMATIC CONTROL, ROBOTICS AND COMPUTER VISION

Doctoral Thesis

ACTIVE POWER SHARING AND FREQUENCY REGULATION IN INVERTER-BASED ISLANDED MICROGRIDS SUBJECT TO CLOCK DRIFTS, DAMAGE IN POWER LINKS AND LOSS OF COMMUNICATIONS

Carlos Xavier Rosero Chandi

Advisors: Manel Velasco García
Pau Martí Colom

January 2020

Abstract

Microgrids (MGs) are small-scale power systems containing storage elements, loads and distributed generators that are interfaced with the electric network via power electronic inverters. When an MG is in islanded mode, its dynamics are no longer dominated by the main grid. Then, the inverters, driven by digital processors that may exchange data over digital communication, must act as voltage source inverters (VSIs) to take coordinated actions to ensure power quality and supply.

The scope of this thesis is bounded to control strategies for active power sharing and frequency regulation in islanded MGs. The focus is on the analysis of prototype control policies when operating conditions are no longer ideal. In particular, the thesis covers the effect that a) clock drifts of digital processors, b) damage in power transmission lines, and c) failures in digital communications have in control performance. The work is submitted as a compendium of publications, including journal and international conference papers, where two main areas of research can be distinguished.

The first area refers to the analysis of the effect that clock drifts have on frequency regulation and active power sharing. VSI digital processors are equipped with oscillators which run at not necessarily identical frequencies. As consequence, the local clocks in the physically distributed inverters may differ. This part, reported in two conference papers and one journal paper, investigates state-of-the-art control policies when clocks of the computational devices drift.

The contributions related to this part are a) the reformulation of existing control policies in terms of clock drifts, b) the steady-state analysis of these policies that offers analytical expressions to quantify the impact that drifts have on frequency and active power equilibrium points, c) the closed-loop model capable of accommodating all the policies, d) the stability analysis of the equilibrium points, and e) the experimental results.

The second area copes with the analysis of the effect that electrical and communication failures have on frequency regulation and active power sharing. This investigation focuses on distributed/cooperative control policies where each inverter control action is computed using both local measures and data received from other inverters within the MG. This part, reported in one conference paper and two journal papers, investigates two control policies when the considered failures in terms of damage in power links and/or loss of communications between inverters provoke partitions within the MG.

The contributions related to this part are a) the formulation of the MG as two connected graphs corresponding to the electrical and communication networks where both type of failures lead to disconnected electrical/communication sub-graphs, named partitions, that co-exist within the MG, b) the closed-loop model integrating the Laplacian matrices of the two graphs, c) the stability analysis that identifies which type of partitions may lead to MG instability, d) the steady-state analysis that indicates how to compute the equilibrium points for the case of stable dynamics, e) a new control strategy based on switched control principles that avoids the instability scenario, and f) the experimental results.

For the purpose of verifying the operational performance of the analytical results, diverse experiments on a laboratory MG have been performed. The outcomes obtained are discussed and analyzed in terms of the objectives sought. Finally, conclusions and future research lines complete the thesis.

Resumen

Las microrredes (MRs) son sistemas de energía a pequeña escala que contienen elementos de almacenamiento, cargas y generadores distribuidos, acoplados a la red eléctrica a través de inversores de potencia. Cuando una MR funciona en modo aislado, su dinámica no está dominada por la red principal. Así, los inversores, comandados por procesadores digitales que pueden intercambiar información a través de comunicación digital, deben actuar como fuentes de voltaje para ejecutar acciones coordinadas que garanticen el suministro de energía.

Esta tesis se enmarca dentro de estrategias de control de última generación para compartir potencia activa y regular frecuencia en MRs aisladas basadas en inversores. Su enfoque se centra en analizar estas políticas cuando las condiciones de operación no son ideales. En particular, el presente trabajo cubre el efecto que a) desviaciones del reloj de los procesadores digitales, b) daños en las líneas de transmisión de energía, y c) fallas en las comunicaciones digitales, provocan en el rendimiento de control. El trabajo se presenta como un compendio que incluye publicaciones de revistas y de conferencias internacionales, donde se pueden distinguir dos temas principales de investigación.

El primer tema comprende el análisis del efecto que tienen las desviaciones de reloj sobre la regulación de frecuencia y la compartición de potencia activa. Los procesadores de los inversores están equipados con osciladores que funcionan a frecuencias no necesariamente idénticas. Como consecuencia, los relojes locales en los inversores distribuidos físicamente, pueden diferir. Esta parte, descrita a través de dos artículos de conferencia y uno de revista, analiza el comportamiento de las políticas de control cuando los relojes de los dispositivos computacionales se desvían.

Las contribuciones relacionadas con esta parte son a) reformulación de las políticas de control de última generación en términos de desviaciones de reloj, b) análisis de estado estacionario de estas estrategias que ofrece expresiones analíticas para cuantificar el impacto que las desviaciones de reloj tienen sobre los puntos de equilibrio de frecuencia y potencia activa, c) modelo de lazo cerrado adaptable a todas las políticas, d) análisis de estabilidad de los puntos de equilibrio, y e) resultados experimentales.

El segundo tema hace frente al análisis del efecto que las fallas eléctricas y de comunicaciones tienen sobre la regulación de frecuencia y el uso compartido de potencia activa. Esta parte se centra en políticas de control distribuido/cooperativo donde cada acción de control del inversor se calcula utilizando medidas locales y datos recibidos de otros inversores de la MR. Esta parte, descrita a través de un artículo de conferencia y dos de revista, investiga dos políticas de control cuando particiones en la MR son provocadas por daños en los enlaces de alimentación y/o por pérdida de comunicación entre inversores.

Las contribuciones relacionadas con esta parte son a) formulación de la MR como dos grafos correspondientes a las redes eléctrica y de comunicación donde ambos tipos de fallas conducen a sub-grafos eléctricos/comunicacionales desconectados, llamados particiones, que coexisten dentro de la MR, b) modelo de lazo cerrado que integra las matrices Laplacianas de los dos grafos, c) análisis de estabilidad que identifica las particiones que pueden conducir a inestabilidad en la MR, d) análisis de estado estacionario para calcular puntos de equilibrio cuando la dinámica es estable, e) nueva estrategia basada en principios de control conmutado para evitar el escenario de inestabilidad, y f) resultados experimentales.

Con el fin de verificar el rendimiento operativo de los resultados analíticos, se han realizado diversos experimentos sobre una microrred de laboratorio, los mismos que se discuten en términos de los objetivos de la tesis. El trabajo finaliza con las conclusiones y futuras líneas de investigación.

Acknowledgements

I thank professors Manel Velasco and Pau Martí for the guidance, scientific training and personal advices received during my career. It will be difficult to return all the valuable help they gave me.

I give special recognition to the members of the Research Group on Power and Control Electronics Systems (SEPIC), Professors Luis García de Vicuña, Miguel Castilla, Jaume Miret and Antonio Camacho, for the scientific collaboration, resource management, and lab facilities, useful to successfully overcome this work.

CONTENTS

1

INTRODUCTION

This chapter introduces key concepts related to islanded microgrids. First, the focus is on control policies for active power sharing and frequency regulation. Second, it is provided an explanation of the non-ideal operating conditions that are analyzed such as clock drifts, damage in transmission lines, and loss of communications. Third, a short description of the simulation and experimental setup is presented. Then, the research motivations of the thesis are discussed, leading to the formulation of the objectives. The thesis outline and publications are also detailed, which allows presenting the thematic unity of the compendium.

Summary

1.1 Background

1.1.1 Microgrids

The replacement of fossil fuels by various sources of renewable energy requires strategies to facilitate their integration into the energy system. One potential solution are microgrids (MGs) [1,2], which are expected to constitute a scalable power system with a high service standard by adequately combining advanced power electronics, information and communication technologies, and new control and management strategies [3,4]. In essence an MG consists of a combination of diverse distributed generation (DG) units, loads and storage systems managed by fast acting power electronics. The MG is connected to the distribution network through a single point of common coupling (PCC).

Microgrids have several specific features that make them differ from conventional power systems [5]. First, they must be able to operate despite intermittent behavior at the generators output and changes in loads. Second, they should offer a plug-and-play and scalability functionality in order to connect/disconnect the diverse units without reprogramming the control and management system. And third, when the main power grid is not available, they should operate independently, in islanded mode. The original definition of MG focuses on its islanding capability to protect itself from outages and interruptions, however, the concept and practice have evolved with an increased emphasis on generation and load management. The advanced microgrid is able to actively balance generation with demand, economically schedule and dispatch its generation resources, and attain high reliability and resiliency.

The MG islanded operational mode is significantly more challenging than the grid connected mode because the dynamics of the MG are no longer dominated by the main grid [6]. Islanded mode requires the implementation of accurate control mechanisms to achieve and maintain the demand-supply equilibrium, where MG DG units play a key role [7].

DG units can be highly heterogeneous, and can generate variable frequency AC power, e.g. wind turbines, or DC power, e.g. solar panels. The heterogeneity of generated power is interfaced with the synchronous AC MG via power electronic inverters (DC/AC or AC/AC converters). Inverters can be classified as current-source inverters (CSIs) or voltage-source inverters (VSIs). CSIs must be continuously synchronized with the grid via phase-locked loops and their main goal is to inject current to the grid (according to the specified reference power). VSIs do not need any external reference to stay synchronized with the grid and they can be used to guarantee energy quality in islanded operation [8].

The thesis scope is focused on the MG islanded operation mode where physically distributed VSIs take coordinated actions to ensure synchronization, voltage regulation, power balance and load sharing [9, 10]. Within the wide number of control objectives being addressed, *the thesis focuses on active power sharing and frequency restoration.* Hence, the control objectives of the inverters are formulated in steady-state as follows:

- To provide accurate power sharing[i], as in

$$P_{i,ss} = \frac{P_L}{\sum_{j=1}^{n} \left(\frac{m_i}{m_j}\right)}, \tag{1.1}$$

  where $P_{i,ss}$ is the power supplied by each inverter in steady-state, P_L is the load power, and m_i and m_j are two parameters related to the rated power of the inverters.

- To regulate the frequency of the MG in steady-state ω_{ss} to its nominal value ω_0, which can be expressed as

$$\omega_{ss} = \omega_0. \tag{1.2}$$

The achievement of these control objectives, that are often addressed using hierarchical control schemes [11, 12], increasingly relies on the digital computation and communications architecture that supports the MG operation [7]. The interdependency between the electrical network and the information and communication technology (ICT) that makes the problems of reliability and operation more complex than in the traditional grid, has been treated in the literature. See [13] for a key contribution on interdependencies between infrastructures, and [14] for a recent review.

Damage in electric lines, or failures and unexpected operation in ICT infrastructure negatively impact power systems [15]. The most severe electrical failures are power outages because they disrupt the electricity supply for an extended time resulting in the loss of critical services, e.g. [16–18]. Complementary, ICT technologies can fail[ii] and they are also exposed to threats such as denial-of-service attacks that paralyze data communications. Hence, ICT behavior is no longer ideal and the operation of the power system may be strongly affected. The goal of reliable approaches to control and manage modern MGs is to ride-through electrical failures and ICT problems providing graceful degradation of power quality but without causing loss of power supply nor serious damage to hardware assets [19, 20]. The thesis also covers non-ideal operating conditions for the ICT infrastructure giving support to the control approaches for active power sharing and frequency restoration. *In particular, the focus is on the analysis of prototype control approaches subject to clock drifts of digital processors, damage in power transmission lines, and failures in digital communications.*

Figure 1.1 illustrates a generic scheme of an MG with all the key elements that are covered in this thesis. The AC MG operates in islanded mode, and

---

[i] The power provided by the inverter must be proportional to its power rating while guaranteeing the supply of the load.

[ii] Hardware behavior may not be as deterministic as assumed.

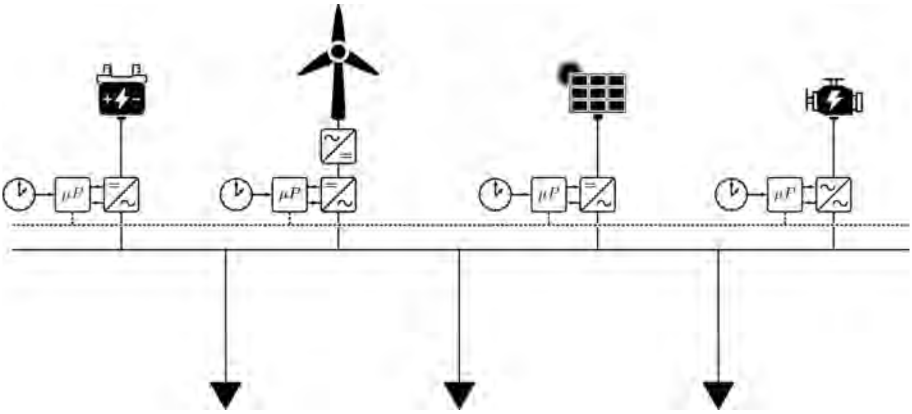


Figure 1.1: Scheme of the inverter-based islanded microgrid

comprises two sets of elements. The first set is related to power generation and supply, loads, and transmission lines (solid lines). From left to right, battery, wind turbine, solar panel, synchronous generator, all interfaced through power inverters, can be identified. The second set is related to computation technology and digital communication network (dashed lines). There, microprocessors that execute the control algorithms and exchange control data, and hardware clocks that enable the timely operation, can be recognized.

1.1.2 Active power sharing and frequency regulation

Islanded MGs should meet certain required reliability and adequacy standards, which demand all controllable units to be actively involved in maintaining the system voltage and frequency within acceptable ranges. However, due to the low system inertia and fast changes in both the output of distributed power sources and loads, the MG frequency can experience large excursions and thus easily deviates from nominal operating conditions [21], even when there are sufficient frequency control reserves. Hence, it is challenging to control the frequency around the nominal operating point [22].

Control strategies ranging from centralized to completely decentralized have been proposed to address these challenges [10, 23–28], and some of them have subsequently been aggregated into a hierarchical control architecture. This control hierarchy consists of three levels, namely primary, secondary and tertiary control.

The primary control is the first level in the control hierarchy and it is used to interconnect VSIs working autonomously in parallel for regulation of voltage frequency and amplitude. Its main goal is to compute the set-point frequency $\omega_i^*(t)$ and amplitude $V_i^*(t)$ for each inverter current and voltage internal control loops. For power sharing a common control approach is to apply the droop method [29–36], which is based on the principle that the inverter frequency and amplitude can be used to control active and reactive power flows for load sharing in MG islanded operation. This controller depends only on local sensed variables and it is based on dropping[iii] the output-voltage frequency and amplitude regarding the active and reactive power supplied by the source, respectively. This causes the divergence of frequency and amplitude with respect to their nominal values. Its basic formulation is given by

$$\omega_i^*(t) = \omega_{0i} - m_p P_i(t), \tag{1.3}$$

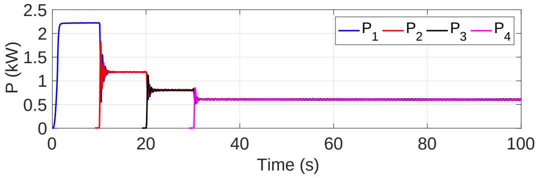
$$V_i^*(t) = V_{0i} - n_q Q_i(t), \tag{1.4}$$

where ω_{0i} and V_{0i} are the inverter nominal voltage frequency and amplitude, $P_i(t)$ and $Q_i(t)$ are the inverter output active and reactive power, m_p and n_q are the proportional control gains. Equation (1.3) is called frequency droop control and equation (1.4) is called voltage droop control. In the standard definition of droop, control actions are done relative to desired set-points for active and reactive power, P_{0i} and Q_{0i} respectively [29], which are determined by long-term objectives, e.g. tertiary control. In (1.3)-(1.4) these power set-points have been omitted but their inclusion would not alter the thesis results. In addition, the measured rather than the normalized values for active and reactive power are used because working with dimensionless values could hide the real impact of the non ideal conditions affecting the supporting platform. Hence, without loosing generality, all inverters are assumed to have the same nominal power.

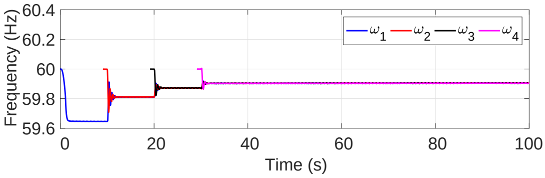
Both droop methods (1.3) and (1.4) introduce deviations in the frequency and amplitude, to be corrected by the secondary control [37]. Since the thesis investigation restricts the focus on frequency regulation and active power sharing, the considered droop method is the frequency droop control (1.3), that may be complemented with a corrective term for frequency restoration, thus leading to different secondary control policies. The standard voltage droop control (1.4) will not be further complemented but it is implemented in all the simulations and experiments. By considering this policy on all the scenarios, a common comparison framework is stablished for performance evaluation. In addition, to solve the negative performance effect on droop-based control caused by interconnecting mainly resistive line impedances [38], a popular approach also included in the thesis set-up, is the virtual impedance technique [39]. However, it is not formalized explicitly because it does not play any significant role in the problems being addressed.

Example 1. *For illustrative purposes, Fig. 1.2 shows the operation of the laboratory MG used in the thesis experiments when droop control (1.3) and (1.4) is implemented. The experiment has the following pattern. At times* $t = 0, 10, 20$ *and* 30 *s, each inverter implementing the droop control is activated, respectively.*

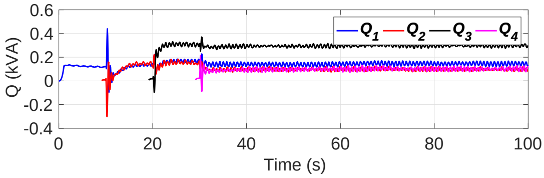
[iii] Dropping the output voltage emulates a conventional synchronous generator.



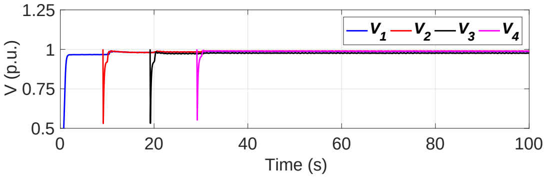
(a) Active power



(b) Frequency



(c) Reactive power



(d) Voltage amplitude

Figure 1.2: System dynamics for droop-only control

The first generator starts and fixes MG frequency and voltage to feed loads with an approximate power demand of 2.2 *kW. The activation of the second, third and fourth inverters is done by means of a phase-locked loop for synchronizing them to the MG voltage phase, and also they start contributing to feed the loads.*

Figure 1.2 shows the active power delivered by each inverter (sub-figure 1.2a), as well as the frequencies (sub-figure 1.2b), reactive powers (sub-figure 1.2c) and voltage amplitudes (sub-figure 1.2d). For illustrative purposes, the obtained dynamics are assumed to be acceptable although some performance features could be improved. As it can be observed, looking at the active power sub-figure, after each inverter new connection, active power sharing is achieved with the expected transient dynamics. In addition, looking at the frequency sub-figure, the droop control introduces a deviation in frequency (sub-figure 1.2b). For the sake of completeness, sub-figures 1.2c and 1.2d show the dynamics of the reactive powers and voltage amplitudes. It is worth noting that at each connection, the voltage transient dynamics (sub-figure 1.2d) exhibit a sag. These dynamics *could be enhanced by a fine tuning of the control parameters and/or by a smarter soft-start of each VSI. Additionally, the frequency droop observed in sub-figure 1.2b could violate existing standards if a proper tuning of the droop control strategy is not applied. However, the thesis contribution does not deal with these issues and its focus on the system dynamics whenever non-ideal conditions in the MG operation appear, once all inverters have been connected.*

Secondary control is the highest hierarchical control level in MGs operating in islanded mode and aims at guaranteeing that frequency and voltage deviations are eliminated after every load or generation change inside the MG. Apart from a few autonomous control approaches that avoid exchanging control data over a communication network, e.g. [40–45], many existing solutions have considered the use of some sort of communication channel among VSIs in order to meet the frequency and voltage restoration goals, see [46–70] to name a few. In general, the secondary control operates on a slower time frame as compared to the primary control. This allows achieving a decoupling between primary and secondary levels which helps easing the control design[iv].

Although not considered in this thesis, tertiary control is a management level in grid-connected operations and adjusts long term set-points for the entire power system. It is responsible for coordinating the operation of multiple MGs and for communicating needs or requirements from the host grid, see e.g. [71–76] and references therein.

Among the great variety of cited works on control policies for active power sharing and frequency restoration, this thesis selects several prototype methods that are analyzed when non-ideal conditions arise. Some of them are based on the hierarchical control approach and built on top of the frequency droop method (1.3). They are termed as droop-based policies, and follow the equation logics

$$\omega_i^*(t) = \omega_{0i} - m_p P_i(t) + \delta_i(t), \tag{1.5}$$

where $\delta_i(t)$ is a corrective term that operates as an integral-like control of the frequency error, and its particular structure and operation determines the

---

[iv] The difference in time frames also reduces the communication bandwidth since the sampled measurements exchanged over the network are minimized, regardless of the different traffic schemes that may apply, ranging from the one-to-all to the all-to-all.

features of the complete control scheme, resulting in

$$\textit{Local integrals} \quad \omega_i^*(t) = \omega_{0i} - m_p P_i(t) + k_{Il} \int_0^t (\omega_{0i} - \omega_i^*(t))\mathrm{d}t, \tag{1.6}$$

$$\textit{Centralized} \quad \omega_i^*(t) = \omega_{0i} - m_p P_i(t) + k_{Ic} \int_0^t (\omega_{0m} - \omega_m^*(t))\mathrm{d}t, \tag{1.7}$$

$$\textit{Decentralized} \quad \omega_i^*(t) = \omega_{0i} - m_p P_i(t) + k_{Id} \int_0^t (\omega_{0i} - \omega_m^*(t))\mathrm{d}t, \tag{1.8}$$

$$\textit{Averaging} \quad \omega_i^*(t) = \omega_{0i} - m_p P_i(t) + k_{Ia} \int_0^t (\omega_{0i} - \omega_a^*(t))\mathrm{d}t, \tag{1.9}$$

$$\begin{aligned}\textit{Consensus} \quad \omega_i^*(t) = {} & \omega_{0i} - m_p P_i(t) + k_c \int_0^t (\omega_{0i} - \omega_i^*(t) \\ & + \alpha\,(\delta_a(t) - \delta_i(t)))\mathrm{d}t.\end{aligned} \tag{1.10}$$

The first policy termed *Local-integrals* (1.6) is the straightforward extension of the frequency droop (1.3) because each corrective term is an integral controller of the frequency error locally computed at each VSI, not requiring the exchange of control data. The next four policies rely on a communication infrastructure.

In the policy termed as *Centralized* (1.7) [11] the corrective term is only calculated and sent by the MG central control unit (MGCC). This term is the integral of the error between the nominal frequency ω_{0m} and the MGCC frequency $\omega_m^*(t)$, which is then used by each VSI to apply the droop-based control (1.5).

In the *Decentralized* control policy (1.8) (see the overview given in [55]) the frequency error between the nominal frequency and the one received from MGCC, $\omega_m^*(t)$, is locally integrated at each VSI.

In the *Averaging* control policy (1.9) (see [57] or [61] for DC MG) the corrective term is calculated at each VSI using the averaged set-point frequency computed as

$$\omega_a^*(t) = \frac{1}{n}\sum_{j=1}^{n} \omega_j^*(t) \tag{1.11}$$

where $n-1$ frequencies have been received from the other MG VSIs.

The *Consensus* control policy (1.10) (see for example [58]) is characterized by a correction term that considers the frequency error, $\omega_{0i} - \omega_i^*(t)$, and the correction term error, $\delta_a(t) - \delta_i(t)$, where

$$\delta_a(t) = \frac{1}{n}\sum_{j=1}^{n} \delta_j(t). \tag{1.12}$$

Recent approaches propose different strategies for active power sharing and frequency regulation where the hierarchical approach is avoided or where modifications on the primary droop control are investigated, e.g. [77–81]. Thus, an additional policy named *Droop-free* [77] not following the hierarchical

Table 1.1: Control policies in terms of communication features

	Droop (1.3)	Local integrals (1.6)	Centralized (1.7)	Decentralized (1.8)	Averaging (1.9)	Consensus (1.10)	Droop free (1.13)
Communication	no	no	yes	yes	yes	yes	yes
Paradigm	n.a.	n.a.	M/S	M/S	Coop.	Coop.	Coop.

structure is also selected. In this case, the nominal frequency is modified by a proportional function of the inverter output active power $P_i(t)$ and the rest of $n-1$ MG inverters active power $P_j(t)$, provided that communications are available. It has the form

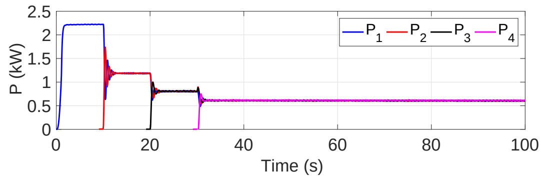
$$\omega_i^*(t) = \omega_{0i} + m_p' \sum_{j=1}^{n} a_{i,j}(P_j(t) - P_i(t)), \tag{1.13}$$

where m_p' is the control gain and $a_{i,j}$ are communication weights as design parameters to specify the connectivity structure of the MG.

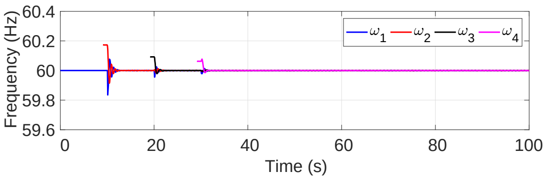
Table 1.1 summarizes the analyzed policies in terms of whether they require to exchange control data over a communication channel. Clearly, the first two policies, *droop-only* and *local integrals*, do not require communications and the concept of communication paradigm is not applicable (n.a.), while the rest of policies require communications. Within them, the *centralized* and *decentralized* policies follow a master/slave (M/S) communication paradigm characterized by the fact that the integral of the frequency error is computed at the master node or at each slave node, respectively. The three last policies, *averaging*, *consensus* and *droop-free* follow a cooperative (coop.) communication paradigm in the sense that all participating nodes do the same tasks.

Example 2. *Again, for illustrative purposes, Fig. 1.3 shows the operation of the laboratory MG used in the thesis when the droop-free control (1.13) is implemented. The experiment has the same pattern as in Example 1. At times* $t = 0, 10, 20$ *and* 30 *s, each inverter implementing the droop-free control is activated, respectively; all inverters exchange control data among them.*

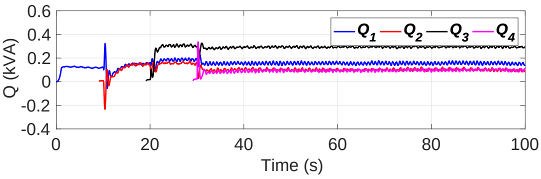
Figure 1.3 shows the active power delivered by each inverter (sub-figure 1.3a), as well as the frequencies (sub-figure 1.3b), reactive powers (sub-figure 1.3c) and voltage amplitudes (sub-figure 1.3d). As outlined before, the obtained dynamics are assumed to be acceptable although some performance features could be improved. In this case, it can be observed that the droop-free control is able to regulate the frequency at the set-point 60 *Hz (sub-figure 1.3b) while all inverters share the active power demand (sub-figure 1.3a).*



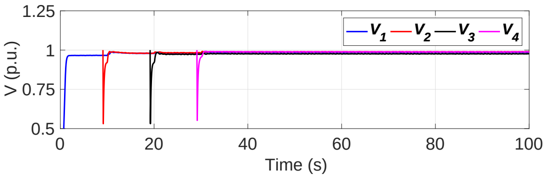
(a) Active power



(b) Frequency



(c) Reactive power



(d) Voltage amplitude

Figure 1.3: System dynamics for droop-free control

1.1.3 On the non-ideal operating conditions

The policies mentioned in Section 1.1.2 for frequency regulation and active power sharing were originally designed considering ideal conditions. That is to say, the logic of these control approaches is not affected by the way in which the platform comprising computing/communication devices, communication network and power grid works. In a realistic world, ideal conditions no longer hold and two sources of unpredictability arise. The first is related to failures in either the power lines or in the substations. The second considers failures in the communication network and/or unexpected operation of the computing/communication platform.

Power line failures may be the initial event that triggers consequent failures along the grid, which often leads to blackouts [16]. Power lines carry electric flows, which cannot be freely determined but follow the laws of physics. Once a power line fails, the energy flowing over the remaining lines is automatically redistributed, and these changes can cause one or more operating lines to exceed their capacity. Power lines can carry excessive flows for some period of time before they are heated up to a certain level and become inoperable. Cascading failures can be initiated once one or more power lines fail. Hence, fast and accurate detection and localization of power line outages are among the most important monitoring tasks in power grids [82]. These failures occur due to vegetation and climate, together with cyber-physical attacks [83, 84].

Failures in the communication system can be understood as simple losses of information exchange among nodes. But also communication failures can be caused by sophisticate attacks on exchanged data leading to immediate physical missbehavior of power systems [85, 86]. These attacks can be, for example, in measurements to disrupt awareness of the situation, or in control signals for components of the power grid, including generation units and loads.

Complementary, unexpected operation of the computing/communication devices refers to the effect that inherent properties of the platform[v] may have on the application performance. Each device is equipped with a hardware clock which counts the events generated by its quartz oscillator. Since oscillators work at slightly different frequencies[vi], events are generated at different rates, creating an ever widening gap in perceived time, known as clock drift [87, 88]. This situation leads to inaccurate and inefficient operation of many applications and protocols [89].

In addition, whenever a digital network is placed within the control loop, then the system is classified as a networked control system (NCS). All definitions found in literature for NCSs have one key aspect in common: the time sensitive information (reference and control inputs, plant outputs, etc.) is exchanged at discrete time instants among the control system components (sensor, controller, actuator) using a shared network [90]. The analysis and design of NCS usually accounts for the set of inherent properties that these systems have, such as message dropouts, time delays, and transmission intervals, to name a few, see e.g. [91, 92]. Finally, simply looking at the individual computing devices, controllers are often implemented as one or several tasks on a microprocessor[vii]. The CPU time can hence be viewed as shared resources for which the tasks compete, and where quantization and task scheduling and allocation also determine the application performance [93, 94].

Existing literature has started to deal with these issues in terms of power systems and specifically covering MGs, see for example [95–108] and references therein. *The thesis focus, not covered by the literature, is on the effect that drifts and failures have in islanded MGs controlled by physically distributed*

---

[v] From a platform point of view, MGs are distributed systems consisting of a collection of physically dispersed computation devices, communicating with each other to accomplish collective goals.

[vi] Clock drift is a change in rate that depends on the clock's quality, sometimes on the stability of the power source, on the ambient temperature, and on other subtle environmental variables.

[vii] A microprocessor also runs tasks for other functions, e.g. communication and user interfaces.

voltage source inverters for active power sharing and frequency regulation.

The impact of clock drifts on frequency control and power sharing in MGs has been recently investigated in [105,109–113]. The work in [109] shows that droop-controlled VSI-based MGs are robust to clock drifts, although small steady-state deviations in active power sharing are observed. An extension providing a deeper modeling, analysis and experimental validation is presented in [105]. In [110] it is shown that local clock drifts in local integral controllers designed for frequency regulation make the MG unstable, results that are illustrated with simulations and reproduced in this thesis. The work done by [111] provides a steady-state analysis of several distributed secondary frequency control strategies with consideration to clock drifts, illustrated with simulation results. In [112], and focusing in angle droop control, stabilizing controllers based on consensus are derived to remove the negative effects that drifts have on frequency control and power sharing. Simulation results are also used to corroborate the control proposal. Finally, [113] analyses the impact of clock drifts on secondary control schemes that do not exchange control data.

The considered failures cover damage in power links and/or loss of communications between nodes in such a way that the MG is partitioned. The analytical method adopted in this thesis is based on a widely used modeling approach where both electrical and communication networks are represented by two graphs whose Laplacian matrices provide the characterization of electrical and communication connectivities. See e.g. [58,62,63,79,114–117] for MG control approaches where the electrical network is modeled as a graph. It is important to note the majority assume lossless networks, while the approach presented in this thesis does not use this assumption. And see e.g. [58,63–66,77,118] for MG control approaches where the communication network is modeled as a graph.

None of the previous works have evaluated partitions of the considered graphs. Specific control policies such as consensus algorithms with changing graphs in terms of switching topologies or connectivity robustness have been previously considered, see [119] for a generic study, or [63,65,120] for an analysis with application to MGs. Only in [77] it is studied the resiliency of the droop-free control to a single communication link failure when it does not alter the connectivity of the communication graph, and in [121] it is presented a robust secondary control to restore the voltage and frequency to their nominal values with a novel feature that ensures the performance continuity during a communication failure. However, the double partitioned scenario covered in this thesis leading to disconnected electrical/communication sub-graphs, named partitions, that co-exist within the MG, has not been previously reported. Hence, an electrical partition generates isolated sub-MGs that are controlled by a single cooperative control algorithm. A communication partition results in several cooperative control algorithms working in parallel on the same physical MG.

1.1.4 Modeling

The main actors considered in this thesis require a proper modeling effort in order to obtain valid theoretical results. Both electrical and communication networks are modeled as graphs, where nodes correspond to VSIs interfacing DGs. Nodes actively control frequency, voltage and power, and they may exchange control data over a communication channel. Hence, satisfactory control solutions require the development of model-based controller design techniques that often may go beyond the classical simplified linearized models, i.e. the so-called small-signal models, that may not capture fundamental aspects of the problem [122–126].

Regarding control analysis, it is interesting to note that MG modeling can be categorized into two classes. The first focuses on applications involving several inverter-based DG units but the model is restricted to individual generators. Hence, both current and power flows among different units are not considered explicitly. The second includes electrical network interactions but the derived model is often based on linearization. The problem of determining which model is appropriate for a specific control analysis and design can not be established in general because any model involves certain assumptions.

When control solutions are based on the exchange of control data, modeling approaches can also be divided into two classes. The first one considers the exchanged control data as a perturbation in the local closed-loop control, while the second class includes the interaction of the exchanged control data.

The modeling approach based on graph theory developed in this thesis makes use of several existing strategies, but always tries to capture all the significant interactions in both electrical and communication domains. The MG electrical network is a generic connected grid with inverter-based DG units in charge of the control of frequency and voltage, as well as loads are modeled by balanced three-phase constant impedances. Still, graph-based models developed from first principles describing dynamics of the power electronics inverters, as well as the network interactions, become complex. This calls for the development of reduced-order models that capture the relevant dynamics of higher order models with a lower dimensional state-space while not compromising modeling fidelity. To do so, the Kron reduction [127–130] is performed by eliminating the graph nodes in which the current does not enter or leave, which allows obtaining a lower dimensional dynamically-equivalent model described by ordinary differential equations.

The reduced electrical network is modeled as a connected undirected graph $\mathcal{G}_e = \{\mathcal{N}_e, \mathcal{E}_e\}$ where the n_e nodes $\mathcal{N}_e$ represent DGs interfaced with VSIs and edges $\mathcal{E}_e \subseteq \mathcal{N}_e \times \mathcal{N}_e$ represent the power lines. Nodes are characterized by a phase angle θ_i and a voltage amplitude v_i. Edges represent line admittances between nodes i and j as $y_{ij} = g_{ij} + \mathrm{j}b_{ij} \in \mathbb{C}^+$, where $g_{ij} \in \mathbb{R}^+$ is the conductance and $b_{ij} \in \mathbb{R}^+$ is the susceptance. The electrical network is represented by the symmetric bus admittance matrix $Y \in \mathbb{C}^{n_e} \times \mathbb{C}^{n_e}$, where the off-diagonal elements are $Y_{ij} = Y_{ji} = -y_{ij}$ for each edge $\{i, j\} \in \mathcal{E}_e$, and the diagonal elements are given by $Y_{ii} = \sum_{i=1}^{n_e} y_{ij}$. It is assumed that the reduced MG is connected. For balanced AC microgrids, the active power injected by each i^{th} node of the n-node MG is described using the power flow equation as

$$p_i(t) = g_{ii}v_i^2(t) + \sum_{j=1, j\neq i}^{n} \left[g_{ij}\cos(\theta_i(t) - \theta_j(t)) + b_{ij}\sin(\theta_i(t) - \theta_j(t))\right] v_j(t)v_i(t), \tag{1.14}$$

or simplified to

$$p_i(t) = v^2 \sum_{j=1}^{n} g_{ij} + v^2 \sum_{j=1}^{n} b_{ij}(\theta_i(t) - \theta_j(t)) \tag{1.15}$$

by assuming that nodes phase angles are similar and voltages are constant and equal, as often adopted in power systems modeling, e.g. [131], and also in MG modeling, e.g. [132].

The communication network can also be represented by a connected undirected graph $\mathcal{G}_c = \{\mathcal{N}_c, \mathcal{E}_c\}$ where the n_c nodes $\mathcal{N}_c$ represent VSIs that implement particular control policies for frequency regulation and active power sharing, and edges $\mathcal{E}_c \subseteq \mathcal{N}_c \times \mathcal{N}_c$ represent communication links. The graph is characterized by the adjacency matrix of $\mathcal{G}_c$ whose elements a_{ij} will permit to specify existence of communication in the implemented control solution. In particular, $a_{ij} = a_{ji} = 1$ if VSI nodes i and j can exchange their information and $a_{ij} = 0$ otherwise. It is considered that nodes in the electrical and communication graph are the same, i.e. $\mathcal{N}_e \equiv \mathcal{N}_c$, hence $n_e = n_c = n$, which is the habitual situation in MGs, e.g. [133].

The last actor playing a key role in the analysis of MGs under non-ideal conditions is time. Each control algorithm is implemented by each inverter[viii] in local time coordinates t_i given by local clocks. Let the time progression at each VSI be defined as a function of the global time, specifically, let $t_i \in \mathbb{R}^+$ denote the local times at each inverter and let $t \in \mathbb{R}^+$ denote the global time. Hence, VSIs local times can be described by

$$t_i = d_i t \tag{1.16}$$

where d_i is the drift rate of the i^{th} VSI local clock. Note that in the local time definition (1.16), the clock offset[ix] is explicitly omitted. This is done on purpose because although not all clocks are initially synchronized, the phase-locked loop connection of each VSI allows to adjust the phase of the generated signals.

[viii] A VSI microprocessor uses local measures and possibly data received from other VSIs to compute the control action.

[ix] An offset is the difference from local time t_i to global time t, i.e. $t_{0,i}$ is not the same for all VSIs.

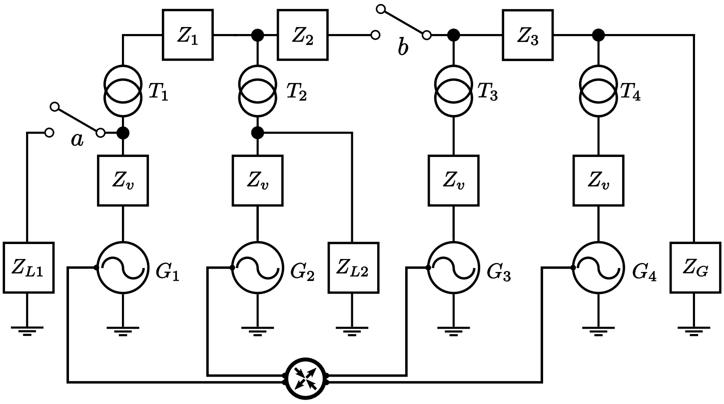


Figure 1.4: Scheme of the laboratory MG

Table 1.2: Nominal values of the laboratory MG components

Symbol	Description	Nominal value
v	Grid voltage (rms line-to-line)	$\sqrt{3}$ 110 V
ω_0	Grid frequency at no load	$2\pi 60$ rad/s
Z_1	Line impedance 1	$0.75\Omega@90°$
Z_2	Line impedance 2	$0.30\Omega@90°$
Z_3	Line impedance 3	$0.30\Omega@90°$
T_1	Transformer impedance	$0.62\Omega@37.01°$
T_2	Transformer impedance	$0.62\Omega@37.01°$
T_3	Transformer impedance	$1.31\Omega@9.87°$
T_4	Transformer impedance	$1.31\Omega@9.87°$
Z_v	Virtual impedance	$3.76\Omega@90°$
P_G	Nominal global load power	1.5 kW
Z_G	Global load impedance	$22\Omega@0°$
$P_{L1,L2}$	Nominal local load power	0.5 kW
$Z_{L1,L2}$	Local load impedances	$88\Omega@0°$

1.1.5 Experimental setup and simulation

The MG equipment used in the thesis experiments is located in the laboratory of the Power and Control Electronics Systems Research Group (SEPIC) at the School of Engineering (EPSEVG) of the Technical University of Catalonia (UPC), in Vilanova i la Geltrú, whose extended description can be found in [134]. It is worth mentioning that the growing interest in MG research has lead to several publications describing MG laboratory setups for research and educational purposes such as [134–143]

The experimental setup is a low-power three-phase small-scale laboratory microgrid, schematically illustrated in Fig. 1.4. The values of the components are listed in Table 1.2. The system is composed by four generation nodes $G_{1,2,3,4}$ in which the power generation of distributed energy sources is emulated. Each generation node consists of a 2 kVA three-phase full-bridge IGBT power inverter

MTLCBI0060F12IXHF from GUASCH and a damped LCL output filter. For the energy supply an AMREL SPS-800-12 DC power source is used. The tested controller strategy (enabled with virtual impedance Z_v) of each inverter is implemented on a dual-core Texas Instruments Concerto board. It consists in a C28 floating point digital signal processor (DSP) that implements the control algorithms, and an ARM M3 processor that is used for communication purposes, both using a hardware clock that has a drift rate upper bounded by 1.00002 [144], that is, each inverter clock accuracy error is lower than ±20 parts per million (ppm). The MG uses the User Datagram Protocol over a switched Ethernet to allow communication among the four inverters. In the diagram, the circle with small arrows at the bottom represent the Ethernet switch that has a point-to-point ethernet cable to each generator (M3 processor). Three-phase inductances in series with resistors are implemented to emulate the wires of the distributed lines, termed as $Z_{1,2,3}$. The diagram also includes isolation transformers $T_{1,2,3,4}$ connected at the output of each inverter. The MG feeds a global load with impedance Z_G and two local loads with impedance Z_{L1} and Z_{L2}. Single-phase resistive heaters are used as loads, connected in wye configuration with a floating neutral node. The scheme in Fig. 1.4 also includes two interruptors a and b in the form of electronic relays governed by a digital board. Interruptor a is used to connect or disconnect the local load Z_{L1} while b allows the electrical partitioning of the MG. The communication partitioning is performed at the Ethernet switch by disabling specific communication ports.

The main components of the laboratory MG are shown in Fig. 1.5. In particular, the MG is organized in four shelfs, see the left picture of Fig. 1.5, each one containing an inverter and both control and sensing boards, detailed in the right picture of Fig. 1.5.

The simulation of the laboratory MG has been created to imitate the electrical components (generators, loads, transmission lines, etc.) and their interactions, as well as the computing components (processors, clocks, digital network) and their interactions. In fact, the MG simulation is a networked computing system that implements a control application, namely *active power sharing and frequency regulation*, that requires closing feedback control loops over a communication network. Hence, it puts together multi-disciplines such as computational science, communication network, and control theory.

Diverse methods to simulate MGs can be found in the literature, ranging from approaches more focused on the power electronics part, to co-design approaches covering both power electronics and computing systems, e.g. see recent results [145–151] and references therein. In this thesis, it is used a co-simulation approach based on Simscape Power Systems Matlab toolbox [152] and Truetime Matlab toolbox [153]. Simscape is focused on the modeling and simulation of electronic, mechatronic, and electrical power systems. Truetime facilitates the simulation of the temporal behavior of networked multitasking realtime kernels executing controller tasks in charge of controlling processes that are modeled as ordinary Simulink blocks.

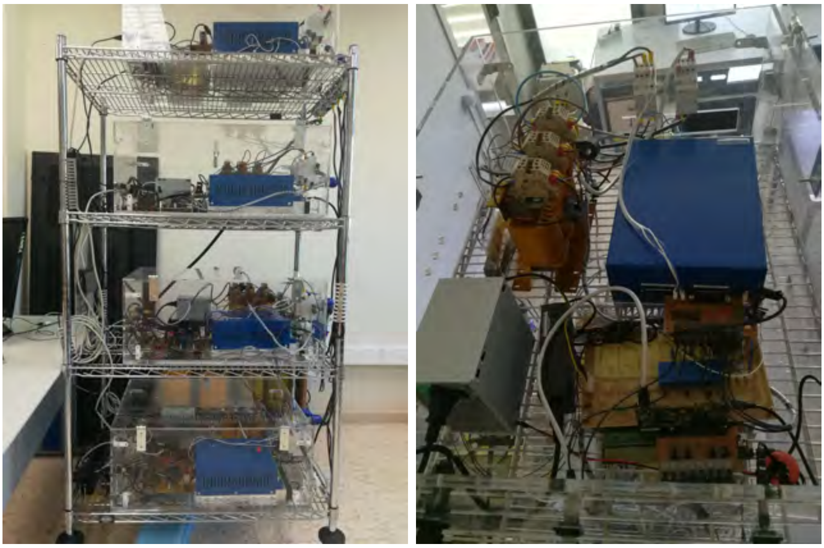


Figure 1.5: Four generators laboratory MG

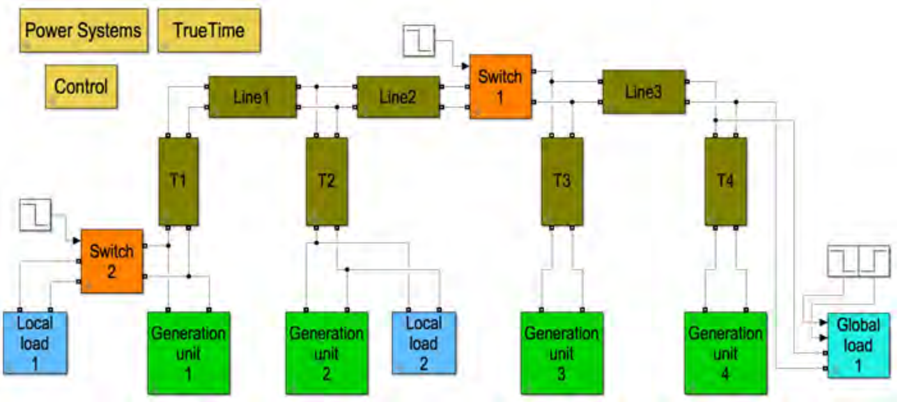


Figure 1.6: *Simscape Power Systems* and *TrueTime* simulation set-up

The main simulation setup for the laboratory MG is shown in Fig. 1.6, following the same scheme previously given in Figure 1.4. The main actors are the four generation units, each one having the structure shown in Figure 1.7. Each generation unit contains a Truetime kernel as well as a controlled voltage source. The kernel simulates the execution of the control algorithms under analysis. It allows to specify a clock drift, as well as it permits a networked operation over a TrueTime network.

Example 3. *For comparative and validation purposes of the simulation setup, Figures 1.8 and 1.9 show the simulated system dynamics for the case of droop control (1.3) and droop-free control (1.13), respectively. These two figures should be compared to the equivalent experiments previously shown in Figures 1.2*

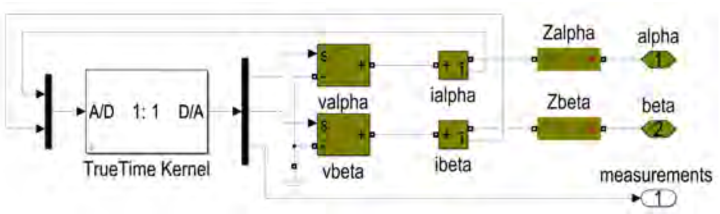
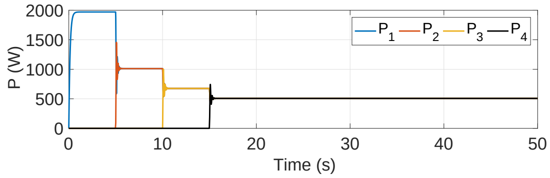
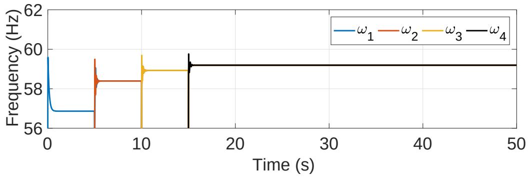


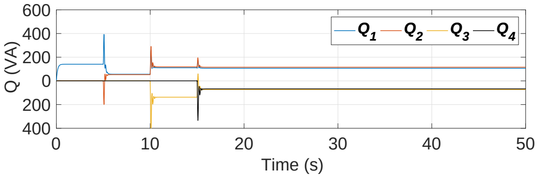
Figure 1.7: Generation unit in the simulation setup



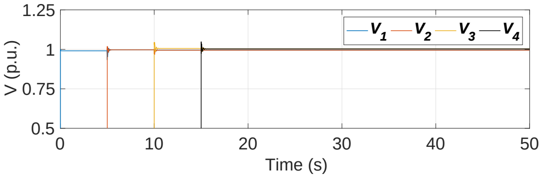
(a) Active power



(b) Frequency



(c) Reactive power

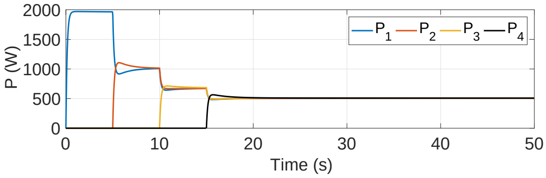


(d) Voltage amplitude

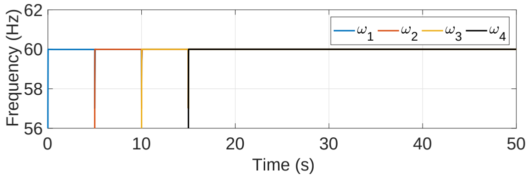
Figure 1.8: Simulation of system dynamics for only droop control

and 1.3.

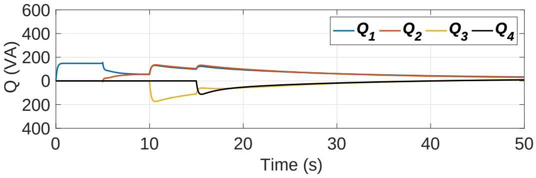
Like in the experimental result, the droop method only achieves active power sharing at the expenses of introducing a deviation in frequency. However, the droop-free control is able to guarantee active power sharing while keeping the frequency at its set-point. Small differences between the experiments and the simulation set-up are due to unmodeled dynamics and/or different control settings that have been introduced to obtain better responses in terms of illustrating



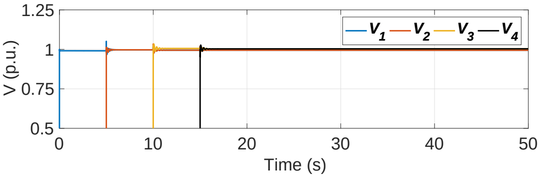
(a) Active power



(b) Frequency



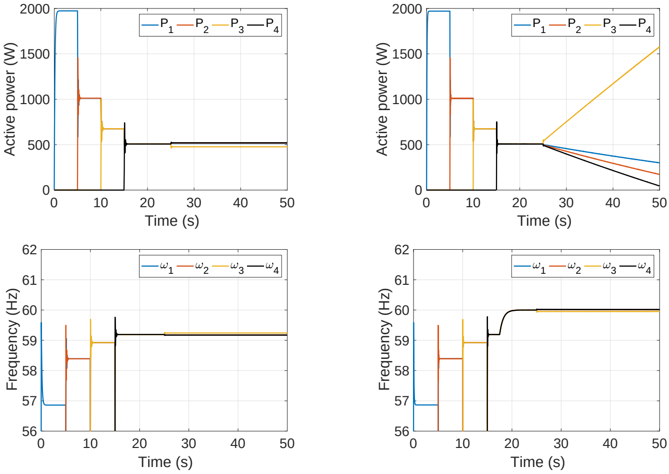
(c) Reactive power



(d) Voltage amplitude

Figure 1.9: Simulation of system dynamics for droop-free control

the thesis results. For example, looking at the droop policy, the induced frequency deviation in the simulation (sub-figure 1.8b) is by far much more larger than in the experiments (sub-figure1.2b). This difference is mainly caused by the droop control gain, which in the simulation is $m_p = 0.01$ *mrad/(Ws) while in the experiments is* $m_p = 0.001$ *mrad/(Ws). In addition, the simulation time is half of the experimental time, and therefore, VSIs become active every* 5 *s instead of every* 10 *s.*



(a) Droop method **(b)** Local integrals

Figure 1.10: System dynamics for droop method and local integrals control due to drifts

1.2 Research motivations

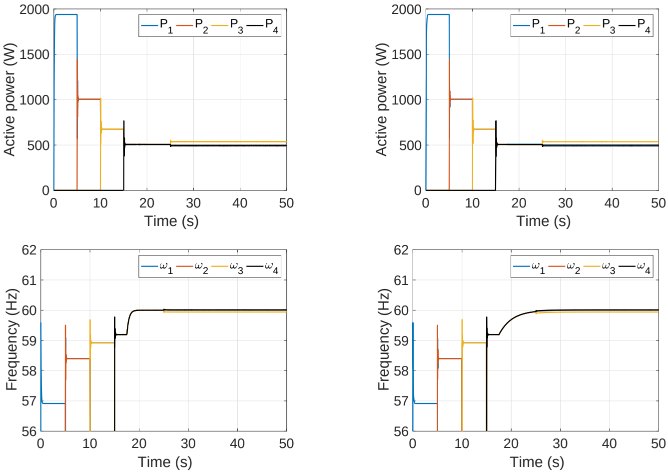
As identified in Section 1.1.2, active power sharing and frequency regulation in islanded MGs can be achieved following a great variety of control approaches. Table 1.1 summarized these prototype policies, classifying them in terms of whether they require communications for control purposes, and also considering the communication paradigm that they follow. Complementary, two non-ideal conditions that have a negative impact into the MG operation were identified in Section 1.1.3. One refers to the drift that exists in any clock and provoke different timing in MG VSIs, and the other involves the partitions that can affect an MG transmission line or can cause loss of communications among VSIs.

The effect that clock drifts have on different policies, has been identified in previous works using theory and/or simulated/experimental results [105, 109–111]. Main conclusions say that the primary control based on the droop method (1.3) is robust to drifts while local integrals (1.6) is a secondary control approach very sensitive to drifts because it leads the MG to instability. The alarming conclusions in [110] for the local integrals control strategy triggers the need for analyzing what is the impact of clock drifts on other existing secondary control policies.

In order to quickly assess this impact, simulations were carried out for all the polices listed in Table 1.1 using the following imposed drift rates $d_i = \{1.000, 1.0001, 0.999, 1.0002\}$ on the four VSIs Truetime kernels executing the evaluated control algorithms. Note that these drift rates can be slightly

Table 1.3: Control parameters for all policies

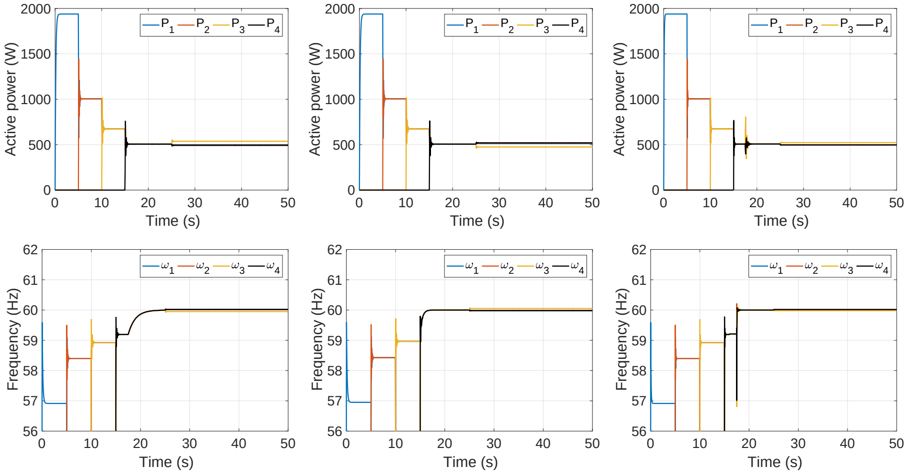
Symbol	Description	Value
m_p	Proportional gain of frequency droop	0.01
k_{Il}	Integral gain of local integrals	0.7
k_{Ic}	Integral gain of centralized	1.2
k_{Id}	Integral gain of decentralized	1.2
k_{Ia}	Integral gain of averaging	0.7
k_c	Integral gain of consensus	15
α	Proportional gain of consensus	18
m_p'	Gain for coupling powers of droop-free	0.001
a_{ij}	Connectivity parameters of droop-free	1
$\{T_r, T_p\}$	Times for freq. restoration and power sharing	$\{2.5, 2.5\}$ s
$\{k_{min}, k_{max}\}$	Filter gains of local frequency restoration	$\{0.25, 4\}$
ω_c	Filter cut-off freq. of local frequency restoration	3.77 rad/s



(a) Centralized control **(b)** Decentralized control

Figure 1.11: System dynamics for M/S control policies due to drifts

higher than ones found in the experimental setup because Concerto clocks have a drift rate upper bounded by 1.00002 [144]. However, they are magnified for illustrative purposes. In each simulation run, all the VSI start sequentially every 5 s, executing only the droop control policy. At time $t = 17.5$ s each secondary control policy starts executing (including the droop-free control). In addition, up to time $t = 25$ s clocks are ideal, from this time instant, the imposed drift rates start taking effect and both active power and frequency exhibit different dynamics. The control parameters for the tested policies *droop method* (1.3), *local integrals* (1.6), *centralized* (1.7), *decentralized* (1.8), *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13) are given in Table 1.3, which also includes parameters that will be introduced later in this document.



(a) Averaging control **(b)** Consensus control **(c)** Droop-free control

Figure 1.12: System dynamics for cooperative control policies due to drifts

Figure 1.10 reproduces the existing results in the literature that cover the impact of clock drifts on the control problem of active power sharing and frequency regulation in the cases of *droop* method (sub-figure 1.10a) and *local integrals* secondary policy (sub-figure 1.10b). As it can be observed, the droop method exhibits a small (or negligible) deviation in its active power and frequency steady-state values while the case of local integrals is completely different and active power dynamics become unstable. Note that the frequency restoration in the local integrals policy appears from time $t = 17.5$ s, when integral actions are applied.

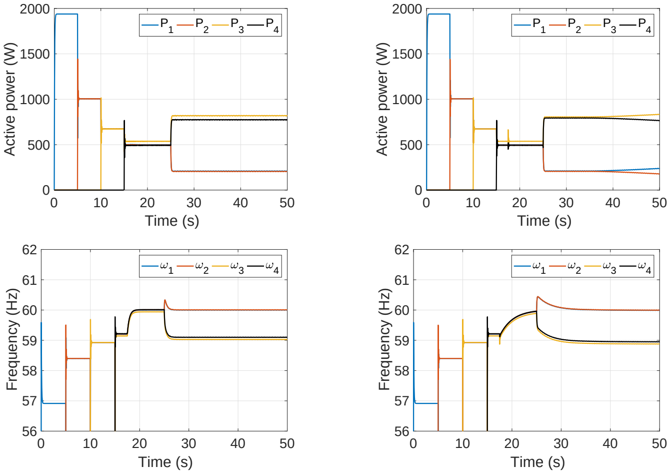
This type of simulation also applies to the rest of policies in Table 1.1, which are characterized by the use of different communication schemes for the exchange of control data. Figure 1.11 shows the results that correspond to the case of M/S control policies, i.e. *centralized* (1.7) and *decentralized* (1.8) in sub-figures 1.11a and 1.11b respectively. Figure 1.12 shows the results for the case of cooperative control policies, i.e. *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13) in sub-figures 1.12a, 1.12b and 1.12c respectively. As it can be observed, all policies exhibit small deviations in the steady-state values of active power and frequency; the exact values depend on the control parameters that characterize each method. But more important, none of these policies lead the MG to instability like the local integrals control policy did (recall sub-figure 1.10b).

Therefore, although the conclusions of the simulation study of the communication-based secondary control policies are not as alarming as in the local integrals control policy, the identified deviations in active power and frequency steady-state values motivate a thorough analysis. It is surprising that some policies cause instability while other do not (at least for a given set of control parameters). And it is of interest to be able to predict the steady-state deviations in terms of the control parameters characterizing each policy and in terms of the clock drifts. Hence, for completeness, the study should include a theoretical study covering both stability and steady-state analyzes, and an experimental evaluation, for all the policies listed in Table 1.1.

From an electrical point of view, uncertainty in terms of the impact of failures in lines and transformers, large fluctuations of load consumption, and renewable power generation, have been largely analyzed for MGs in the power systems community, see e.g. [154, 155] and references therein. In addition, MGs may suffer full blackouts when confronted with unexpected disruptions due to man-made faults or natural disasters. How to quickly restore the power supply of microgrids by making use of local distributed energy resources (DERs) is therefore a practical issue to help microgrids ride through full blackouts, see e.g. [156, 157] and references therein. In the end, control approaches for frequency restoration and active power sharing considering both properties and constraints in communications have also been addressed, e.g. [106, 158].

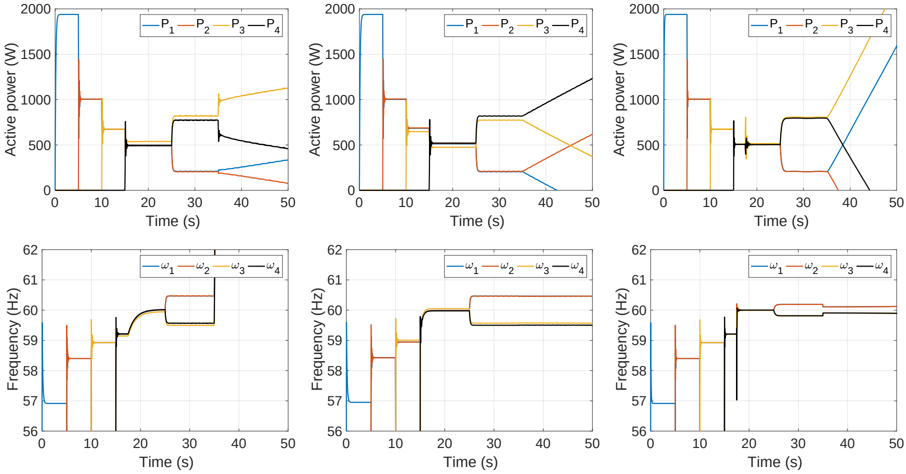
Taking into account *failures in the transmission lines and/or loss of communications that lead to partitions in the MG*, three main scenarios can be identified: only failures in the electrical network, only failures in the communication network, or a combination of both type of failures. Regarding Table 1.1, failures in the electrical network could be analyzed for all policies while failures affecting communications should be analyzed for those policies based on data exchange. However, partitions in the electrical network when the control algorithm is local (case of *droop method* and *local integrals*) are not relevant because this is the same as analyzing two separate stable MGs. Indeed, after the electrical decoupling of the partition happens, power flows can not be transferred among the isolated MGs. It is important to point out that cascading failures could occur if each sub-microgrid supply-demand would not be able to reach the equilibrium. However, this thesis assumes that MG capacity has been dimensioned as well as control gains have been designed such that this equilibrium can be always reached for all the analyzed policies. Hence, after the electrical partition occurs, each sub-MG will reach different steady-state equilibrium points for both *droop* and *local integrals* depending on DGs and loads.

In order to assess this impact, simulations were carried out for the algorithms based on communications in Table 1.1. In particular, they covered *centralized* (1.7), *decentralized* (1.8), *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13) control policies. In each simulation run, all the VSI start sequentially every 5 s, executing only droop control with ideal clocks. At time $t = 15$ s drifts start affecting, what is different than the cases previously shown in Figures 1.10 to 1.12, where clock drifts started to introduce small deviations at time $t = 25$ s. Then, each secondary control policy including the droop-free control starts executing at time $t = 17.5$ s. Up to time $t = 25$ s the MG is not



(a) Centralized **(b)** Decentralized

Figure 1.13: System dynamics for M/S control policies due to partitions



(a) Averaging **(b)** Consensus **(c)** Droop-free control

Figure 1.14: System dynamics for cooperative control policies due to partitions

affected by failures, however, as of this moment an electrical failure occurs (by opening *Switch 1* in the simulation setup of Figure 1.6), leading to an electrical scenario where two separate sub-MGs co-exist, one with generation units 1 and 2 feeding a local load, and the other with generation units 3 and 4 feeding the global load. And on top of this scenario, at time $t = 35$ s a communication failure occurs, leading to connectivity that depends on the particular policy.

Figure 1.13 shows the simulation results that correspond to the case of the M/S *centralized* (1.7) and *decentralized* (1.8) control policies, sub-figures 1.13a and 1.13b respectively. For these simulations, the communication partition is such where generation unit 1 acting as master can communicate with unit 3 and vice-versa, and where generation units 2 and 4 work in isolation[x]. Hence, only one M/S control algorithm exists in terms of communications between generation units 1 and 3. From the beginning, both policies exhibit a small deviation in their active power and frequency steady-state values due to drifts. After the electrical partition at time $t = 25$ s, active power steady state values achieve different equilibrium points depending on the loads that each sub-MG supplies. However, after the communication partition that occurs on top of the drift effect and of the electrical partition at time $t = 35$ s, different dynamics depending on the analyzed policy can be observed. For the *centralized*, the dynamics are stable but the steady-state values depend on the particular generation and load units involved in each sub-MG. The M/S scheme of the sub-MG composed by generation units 1 and 3 that still can communicate is affected by the electrical partition that impairs the power exchange between these units. Generation units 2 and 4 work in isolation, and since they do not receive the corrective term $\delta_i(t)$ sent by the master, they only apply the primary droop control. Hence, for the *centralized*, active power and frequency steady-state values depend on the electrical and communication configurations after partitions have occurred. The case of the *decentralized* policy is different. After the electrical partition at time $t = 25$ s, diverse steady-state values for frequency and active power are reached. However, after the communication partition, the active power dynamics start diverging, exhibiting unstable behavior.

Figure 1.14 shows the simulation results that correspond to the case of the cooperative control policies *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13), sub-figures 1.14a, 1.14b and 1.14c respectively. For these simulations, the communication partition is such that generation unit 1 can communicate with unit 3 and vice-versa, and where generation unit 2 can communicate with unit 4 and vice-versa. Hence, two cooperative control algorithms coexist in terms of communications, one with generation units 1 and 3, and the other with generation units 2 and 4. As it can be observed, all policies exhibits the same type of dynamics. From the beginning, all policies show small deviations in their active power and frequency steady-state values due to drift. After the electrical partition at time $t = 25$ s occurs, active power steady-state values achieve different equilibrium points depending on the loads attached. However, after the communication partition at time $t = 35$ s, the active power dynamics become unstable.

Considering this preliminary simulation analysis covering electrical and communication partitions, it can be concluded that the communication-based secondary control policies are very sensitive to partitions. It is again surprising that some policies cause instability while other do not, at least for a given set of control parameters. And it is also of interest to analyze why some

---

[x] Do not receive nor send information from/to master unit.

dynamics are unstable, and to predict the steady-state deviations in terms of both control parameters and electrical network topology, whenever stability is guaranteed. Hence, for completeness, the study should include a theoretical study covering both stability and steady-state analyzes, and an experimental evaluation, covering all the policies listed in Table 1.1.

In addition, looking at both non-ideal conditions, it is also required to design novel control strategies able to guarantee stability regardless of drifts and partitions. Control policies suffering instability are mainly found in Figures 1.13 and 1.14, which is the case of communication-based control policies that being subject to drifts and to any electrical partition, suffer a communication partition. Different is the case shown in Figure 1.10, and in particular for the local integrals method subject to drifts (sub-figure 1.10b). For this situation, two alternative solutions have been developed recently in [44] and [45] that permit to achieve frequency regulation and power sharing with a high degree of accuracy even in presence of clock drifts. Therefore, new proposals are required for the communication-based control policies.

In order to solve some of the challenges posed in this section and by considering the discussion and the preliminary simulation results above, the objectives of this doctoral thesis are detailed in next section.

1.3 Objectives

Taking as baseline the control policies for active power sharing and frequency regulation in islanded MGs, those summarized in Table 1.1, two main objectives are given for this thesis according to the described non-ideal conditions:

1. To analyze the impact of clock drifts.
2. To analyze the impact of electrical and communication partitions.

Each main objective includes the following set of specific objectives:

a. To simulate each policy.

b. To make a theoretical analysis that includes

   i. To develop an MG closed-loop model capable of accommodating all the policies.

   ii. To develop a stability analysis that permits assessing which control policies are stable and which are unstable.

   iii. To develop a steady-state analysis of the stable policies for quantifying by analytical expressions the impact that the considered non-ideal conditions has on frequency and active power equilibrium points.

c. To validate the simulation and theoretical results with experimental ones.

d. To develop new control strategies for avoiding the instability scenarios identified in the simulation analysis, and in particular, in Figures 1.13 and 1.14.

1.4 Thesis outline

The thesis structure is as follows

- **Chapter 1:** provides an overview of microgrids, with special emphasis on control policies for active power sharing and frequency regulation as well as on non-ideal conditions in the MG electrical and computational parts that may affect its operation; then, the motivation for the research carried out in this work is explained, objectives are summarized, and the thematic unity of the thesis is described.

- **Chapter 2:** presents the first contribution, which is a conference paper that covers the impact of clock drifts in the performance of islanded MGs governed by the consensus algorithm for active power sharing and frequency restoration.

- **Chapter 3:** presents the second contribution, which is also a conference paper that covers the impact of clock drifts in the performance of islanded MGs when they are governed by the averaging control policy.

- **Chapter 4:** presents the third contribution, which is a journal paper that generalizes the previous results of the two conference papers. It covers the analysis of the impact of clock drifts in the performance of islanded MGs governed by the prototype (and common) policies for active power sharing and frequency restoration.

- **Chapter 5:** presents the fourth contribution, which is a conference paper that starts the study of the impact of communication partitions in the performance of islanded MGs governed by the consensus algorithm.

- **Chapter 6:** presents the fifth contribution, which is a journal paper that borrowing the preliminary results of the previous conference paper, covers the impact of electrical and communication partitions in the performance of islanded MGs when they are governed by the consensus algorithm.

- **Chapter 7:** presents the sixth contribution, which is a journal paper that complements the previous journal paper by covering the analysis of the impact of electrical and communication partitions in the performance of islanded MGs governed by the droop-free algorithm; a new control strategy based on switched control principles is also proposed.

- **Chapter 8:** summarizes the thesis contributions and analyzes their relation with the thesis objectives; it provides a discussion of the obtained results.

- **Chapter 9:** presents the thesis conclusions and identifies topics for future research.

- **Appendix A:** presents a journal paper that is not part of the thesis compendium but permits a more complete understanding of the thesis work.

1.5 Publications

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

- **Chapter 2:** C. X. Rosero, P. Martí, M. Velasco, M. Castilla, J. Miret and A. Camacho, "Consensus for active power sharing and frequency restoration in islanded microgrids subject to drifting clocks," in *2017 IEEE 26th International Symposium on Industrial Electronics (ISIE)*, pp. 70-75, Edinburgh, June 2017. Short identification: IEEE ISIE17
- **Chapter 3:** C. X. Rosero, H. Carrasco, M. Velasco and P. Martí, "Impact of clock drifts on active power sharing and frequency regulation in distributed-averaging secondary control for islanded microgrids," in *2017 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, pp. 1-6, Mexico, November 2017. Short identification: IEEE ROPEC17
- **Chapter 4:** P. Martí, J. Torres-Martínez, C. X. Rosero, M. Velasco, J. Miret and M. Castilla, "Analysis of the effect of clock drifts on frequency regulation and power sharing in inverter-based islanded microgrids," in *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10363-10379, December 2018. Short identification: IEEE TPEL18
- **Chapter 5:** C. X. Rosero, M. Velasco and P. Martí, "Analysis of consensus-based active power sharing with respect to network topology in islanded microgrids," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 115-120, Xina, November 2017. Short identification: IEEE IECON17
- **Chapter 6:** C. X. Rosero, M. Velasco, P. Martí, A. Camacho, J. Miret and M. Castilla, "Analysis of consensus-based islanded microgrids subject to unexpected electrical and communication partitions," in *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5125-5135, September 2019. Short identification: IEEE TSG19
- **Chapter 7:** C. X. Rosero, M. Velasco, P. Martí, A. Camacho, J. Miret and M. Castilla, "Active power sharing and frequency regulation in droop-free control for islanded microgrids under electrical and communication failures," in *IEEE Transactions on Industrial Electronics*, in press, 2019. Short identification: IEEE TIE19

A contribution that was made simultaneously during the thesis and that has not been included in the compendium is the following:

- J. M. Rey, C. X. Rosero, M. Velasco, P. Martí, J. Miret and M. Castilla, "Local frequency restoration for droop-controlled parallel inverters in islanded microgrids," in *IEEE Transactions on Energy Conversion*, vol. 34, no. 3, pp. 1232-1241, September 2019.

It appears at Appendix A.

Table 1.4: Topics covered in this thesis

	Droop (1.3)	Local integrals (1.6)	Centralized (1.7)	Decentralized (1.8)	Averaging (1.9)	Consensus (1.10)	Droop free (1.13)
Communication paradigm	n.a.	n.a.	M/S	M/S	Coop.	Coop.	Coop.
Drift sim.	√	√	√	√	√	√	√
Drift the.	√	√	√	√	√	√	√
Drift exp.	√	√	√	√	√	√	√
Part. sim.	n.a.	n.a.	x	x	x	√	x
Part. the.	n.a.	n.a.				√	√
Part. exp.	n.a.	n.a.				√	√

1.6 Thematic unity of the thesis

The thesis is submitted as a compendium of publications that includes three journal and three international conference papers. They constitute the main chapters and contain the thesis contributions. The scope is islanded MGs where physically distributed VSIs are in charge of enforcing active power sharing and frequency regulation following diverse control strategies, summarized in Table 1.1. The problem to be solved is the analysis of these policies when electrical or computational conditions are not ideal as often assumed in the literature. In particular, the non-ideal conditions covered are *clock drifts* and communication and electrical failures that lead to *MG partitions*.

All publications contribute in this argumentation line. Chapters 2, 3 and 4, that correspond to two conference papers and one journal paper, cover the analysis of clock drifts in the performance for the set of control policies. Chapters 5, 6 and 7, that correspond to one conference paper and two journal papers, cover the analysis of partitions in the performance only for *consensus* and *droop-free* control.

Table 1.4, built from Table 1.1, summarizes the topics covered by all publications included in this thesis and detailed in Section 1.5. It includes six new raws, three corresponding to the analysis of drifts, from simulation (labeled as *Drift sim.*), theoretical (*Drift the.*) and experimental (*Drift exp.*) points of view, and three more corresponding to the analysis of partitions, also from simulation (*Part. sim.*), theoretical (*Part. the.*) and experimental (*Part. exp.*) points of view. Cells with "√" means that the work has been done and more important, that it has been published; cells with "x" means that the work is included in this document; empty cells means that the work has not been published nor included in this document because it is being saved for near future publications. In addition, "n.a." means not applicable. Thus, Table 1.4 provides a picture of the thematic unity of the thesis that has been reported in the publications gathered in this compendium.

Table 1.5: Topics covered by all publications included in the compendium

	P1-Conf. IEEE ISIE17 (1.3)	P2-Conf. IEEE ROPEC17 (1.6)	P3-Jour. IEEE TPEL18 (1.7)	P4-Conf. IEEE IECON17 (1.8)	P5-Jour. IEEE TSG19 (1.9)	P6-Jour. IEEE TIE19 (1.10)
Problem	Drift	Drift	Drift	Part.	Part.	Part.
Sim.	√	√		√	√	
Th-CLM			√		√	√
Th-ST			√		√	√
Th-SS	√	√	√	√	√	√
Exp.			√		√	√
Policies	Consensus	Averaging	All	Consensus	Consensus	Droop free
Contrib.	A	A	A	A	A	A/P

Table 1.5 provides a complementary view where the publications that form part of the thesis compendium (table horizontal axis) are characterized by the table vertical axis in terms of a) the topic covered, i.e., drifts or partitions, b) the methodological analysis that was applied, i.e. simulation, theoretical[xi] and experimental, and c) the control policies being analyzed among those listed in Tables 1.1 and 1.4. An additional raw is included to characterize the type of contribution[xii].

[xi] The theoretical analysis, as detailed in the thesis objectives in Section 1.3, is divided into closed-loop model (*Th-CLM*), stability analysis (*Th-ST*), and steady-state analysis (*Th-SS*).

[xii] The contribution can be in terms of whether an analysis (A) is developed only, or if new proposals (P) are also presented.

PUBLICATIONS

2

Paper I:

Consensus for Active Power Sharing and Frequency Restoration in Islanded Microgrids Subject to Drifting Clocks

C. X. Rosero, P. Martí, M. Velasco, M. Castilla, J. Miret and A. Camacho, "Consensus for active power sharing and frequency restoration in islanded micro-grids subject to drifting clocks," in *2017 IEEE 26th International Symposium on Industrial Electronics (ISIE)*, pp. 70-75, Edinburgh, June 2017.

ATTENTION¡¡

Pages 38 to 44 of the thesis are available at the editor's web
https://ieeexplore.ieee.org/document/8001225

Summary

3

Paper II:

Impact of Clock Drifts on Active Power Sharing and Frequency Regulation in Distributed-Averaging Secondary Control for Islanded Microgrids

C. X. Rosero, H. Carrasco, M. Velasco and P. Martí, "Impact of clock drifts on active power sharing and frequency regulation in distributed-averaging secondary control for islanded microgrids," in *2017 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, pp. 1-6, Mexico, November 2017.

ATTENTION¡¡

Pages 46 to 52 of the thesis are available at the editor's web

https://ieeexplore.ieee.org/document/8261675

Summary

4

Paper III:

Analysis of the Effect of Clock Drifts on Frequency Regulation and Power Sharing in Inverter-Based Islanded Microgrids

P. Martí, J. Torres-Martínez, C. X. Rosero, M. Velasco, J. Miret and M. Castilla, "Analysis of the Effect of Clock Drifts on Frequency Regulation and Power Sharing in Inverter-Based Islanded Microgrids," in *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10363-10379, December 2018.

ATTENTION¡¡
Pages 54 to 70 of the thesis are available at the editor's web
https://ieeexplore.ieee.org/document/8290685

Summary

5

Paper IV:

Analysis of consensus-based active power sharing with respect to network topology in islanded microgrids

C. X. Rosero, M. Velasco and P. Martí, "Analysis of consensus-based active power sharing with respect to network topology in islanded microgrids," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 115-120, China, November 2017.

ATTENTION¡¡

Pages 72 to 78 of the thesis are available at the editor's web

https://ieeexplore.ieee.org/document/8216024

Summary

6

Paper V:

Analysis of Consensus-Based Islanded Microgrids Subject to Unexpected Electrical and Communication Partitions

C. X. Rosero, M. Velasco, P. Martí, A. Camacho, J. Miret and M. Castilla, "Analysis of Consensus-Based Islanded Microgrids Subject to Unexpected Electrical and Communication Partitions," in *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5125-5135, September 2019.

ATTENTION¡¡

Pages 80 to 92 of the thesis are available at the editor's web
https://ieeexplore.ieee.org/document/8501583

Summary

7

Paper VI:

Active Power Sharing and Frequency Regulation in Droop-Free Control for Islanded Microgrids Under Electrical and Communication Failures

C. X. Rosero, M. Velasco, P. Martí, A. Camacho, J. Miret and M. Castilla, "Active Power Sharing and Frequency Regulation in Droop-Free Control for Islanded Microgrids Under Electrical and Communication Failures," in *IEEE Transactions on Industrial Electronics*, *in press*, 2019.

ATTENTION¡¡

Pages 94 to 104 of the thesis are available at the editor's web

https://ieeexplore.ieee.org/document/8835156

Summary

Analysis and conclusions

8

ANALYSIS OF RESULTS

This chapter summarizes the contributions of the work, analyzes their relation with the objectives of the doctoral thesis and discusses the obtained results.

Summary

8.1 Introduction

As mentioned in Chapter 1, the thesis scope is islanded MGs where the operation of control algorithms for active power sharing and frequency restoration are affected by non-ideal conditions like drifts in processors clocks, and/or failures in transmission lines and communication links.

The thesis main objectives, listed in Section 1.3, included the simulation, theoretical and experimental analysis of the *droop* (1.3), *local integrals* (1.6), *centralized* (1.7), *decentralized* (1.8), *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13) policies subject to drifts and partitions, as well as the design of new proposals aimed at solving those possible problems identified in the analysis part.

8.2 Impact of drifts

All the thesis objectives related to the clock drifts analysis have been covered by publications P1 (IEEE ISIE17), P2 (IEEE ROPEC17) and P3 (IEEE TPEL18) as indicated by Tables 1.4 and 1.5. The main results, corroborated by the simulation, theoretical and experimental analyzes, and reproduced in Figures 1.10 to 1.12, can be summarized as follows:

- All the policies listed in Table 1.1 suffer a small deviation in the steady-state frequency value and this deviation provokes a small deviation in the steady-state active power value. This happens on every inverter for all the policies except for the case of the *local integrals*, where active powers become unstable.

- For all the stable policies, the deviation in frequency and active power values caused by the clock drifts present in the laboratory hardware, can be considered as negligible.

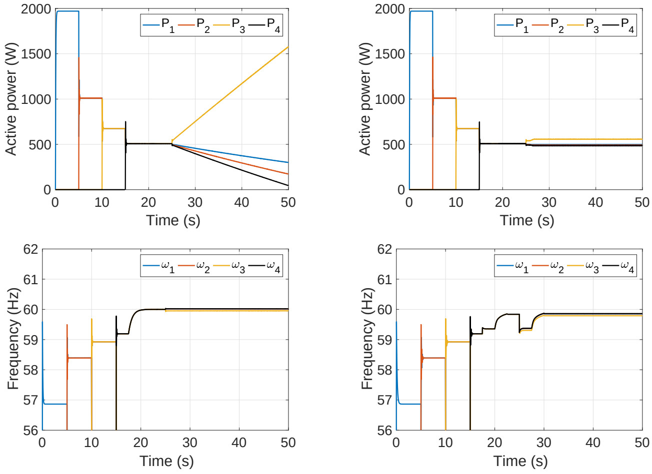
- Clock drifts always alter the counting of time in VSI hardware. Paper P3 (IEEE TPEL18) presents an exact characterization of
    - the closed-loop model accommodating each stable policy derived from the power flow equations (1.14), the drift characterization (1.16) and the particular policy (*droop method* (1.3), *centralized* (1.7), *decentralized* (1.8), *averaging* (1.9), *consensus* (1.10) and *droop-free* (1.13)),
    - the steady-state frequency and active power values for stable policies in terms of the involved control parameters and drift rates,
    - the stability of the equilibrium points of each stable policy as a function of the clock drifts given by the application of multiple-input/multiple-output robust control techniques where the MG is treated as a system with uncertainty given by each drift rate.

- The application of a standard clock synchronization protocol does not remove the identified active power and frequency steady-state deviations. In addition, its application does not solve the instability exhibited by the *local integrals* policy.

The only objective not covered by the set of publications included in this compendium refers to the design of new proposals to minimize or eliminate the negative effects that clock drifts have in active power sharing and frequency regulation. However, the objective has been covered in the sense that a new control proposal has been presented in [45], which is a publication that has not ben included in the compendium but it has been added as Appendix A. The control proposal specifies the corrective term δ_i in (1.5) that should act as an integral-like control of the frequency error, avoiding the integral operator but using a tunable time-varying first-order filter, which can be written in the Laplace domain as

$$\omega_i^*(s) = \omega_{0i}(s) - m_p P_i(s) + \frac{\bar{k}\omega_c}{s+\omega_c}\left(\omega_{0i}(s) - \omega_i^*(s)\right) \tag{8.1}$$

where ω_c is the filter cut-off frequency and $\bar{k}$ its time varying gain. Its operation using both an event-detector and a time-driven protocol specifies that, at every noticeable change in active power, $\bar{k}$ will take first a small value to ensure active power sharing and then a higher value to recover frequency. The replacement of the *local integral* policy for the *local time-varying filter* (8.1) has been shown to be robust to drifts. For example, Figure 8.1 shows its application to be compared with the case of local integrals policy, subject to drifts. In the plotted simulations, droop control is applied at each inverter start-up, which occurs sequentially every 5 s. At time $t = 17.5$ s, the secondary control policy runs, which refers to the local integrals (1.6) in sub-figure 8.1a and to the local time-varying filter (8.1) in sub-figure 8.1b, and at time $t = 25$ s, clock drifts start acting. As previously seen, the active powers in the local integrals policy become unstable, while with the application of the local time-varying filter the instability problem disappears at the expenses of introducing a (negligible) deviation in active power steady-state values and a controllable deviation in frequency. Hence, although the proposal solves the problem for the local control case, its theoretical analysis with emphasis on the drift problem has not been completely addressed.



(a) Local integrals **(b)** Local time-varying filters

Figure 8.1: System dynamics for local control policies in the presence of drifts

8.3 Impact of partitions

The thesis objectives related to the partitions analysis have been covered by publications P4 (IEEE IECON17), P5 (IEEE TSG19) and P6 (IEEE TIE19) as indicated in Tables 1.4 and 1.5. The main results, corroborated by the simulation, theoretical and experimental analyzes, and reproduced in subfigures 1.14b and 1.14c, refer only to the *consensus* (1.10) and *droop-free* (1.13) control policies which are based on communications[i]. Recall that from all policies under study and listed in Table 1.1, the partition analysis does not apply to droop and local integrals methods because they do not use communications. Then, the main contributions can be summarized as follows:

- Electrical partitions constraint the energy flows, and electrical subnetworks reach active power sharing and frequency regulation. The steady-state values of power and frequency depend on both the load at each partition and the communication scheme. If the newly reached active power values are beyond rated powers, VSIs will trip due to the over-current situation that could occur.

- Communication partitions constraint the exchange of information required by the frequency regulation task performed by the secondary control policy. This impairment leads to unstable dynamics that may imply a cascaded failure of VSIs because of the over-current situation.

---

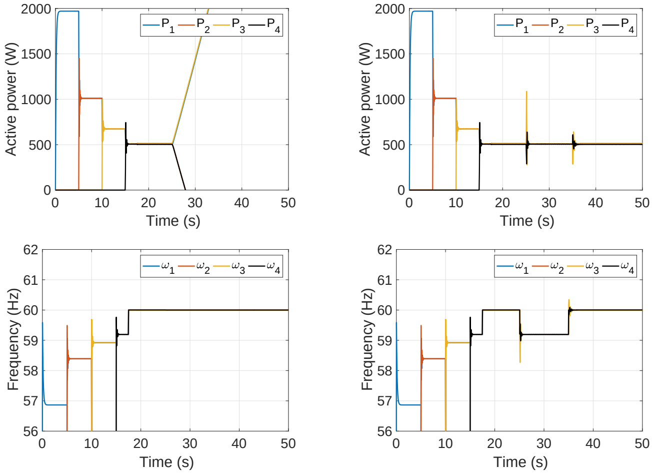
[i] The rest of the policies that also use data exchange such as *centralized* (1.7), *decentralized* (1.8) and *averaging* (1.9), have been covered by the simulation analysis presented in Figures 1.13 and 1.14.

- Papers P5 (IEEE TSG19) and P6 (IEEE TIE19), for the *consensus* and *droop-free* control policies, respectively, present an exact characterization of
  - the closed-loop model derived from the power flow equation (1.15) that also includes the Laplacian matrices of the electrical and communication graphs to characterize the MG electrical and communication connections,
  - the steady-state frequency and active power expressions for stable scenarios in terms of the involved control parameters,
  - the stability study that is based on the zero eigenvalue analysis: system stability under each partition scenario is characterized according to the "role" that each new zero eigenvalue in the Laplacian matrices has in terms of whether it becomes an integrator for each model input/output relation.
- For the *droop-free* method in paper P6 (IEEE TIE19), a new control proposal is presented to avoid the instability problem caused by the communication partition. This is based on a *switched control* policy implemented at each VSI that ensures a graceful degradation of the faulty (partitioned) MG[ii]. The new control policy is based on disabling the application of droop-free control upon detection of a communication failure (leading to a partition) and then switching to frequency droop control. And once the communication is re-established, droop-free control is activated again. This new policy could be applied to all the communication based policies that also become unstable in the occurrence of communication partitions, that is, *decentralized* and *averaging*. This would require a proper analysis extending paper P6 theoretical results and corroborating them with new experimental ones.

For illustrative purposes, Figure 8.2 shows the application of the presented *switched control* policy. In the simulations, droop control applies at each inverter start-up, which occurs sequentially every 5 s with ideal clocks. At time $t = 15$ s, clock drifts start applying. Then, at time $t = 17.5$ s, the secondary control policy applies, which refers to the *droop-free* in sub-figure 8.2a and to the *switched control* policy in sub-figure 8.2b, and at time $t = 25$ s a communication partition occurs. As previously seen, the active powers in the droop-free policy become unstable when the partition occurs, while with the application of the switched control the instability problem disappears at the expenses of introducing a graceful degradation. In particular, when a communication failure occurs at $t = 25$ s, droop-free control is disabled and frequency droop control is activated which guarantees active power sharing while an unavoidable

---

[ii] Otherwise, the application of load shedding techniques may require disconnection of loads.



(a) Droop-free **(b)** Switched control policy

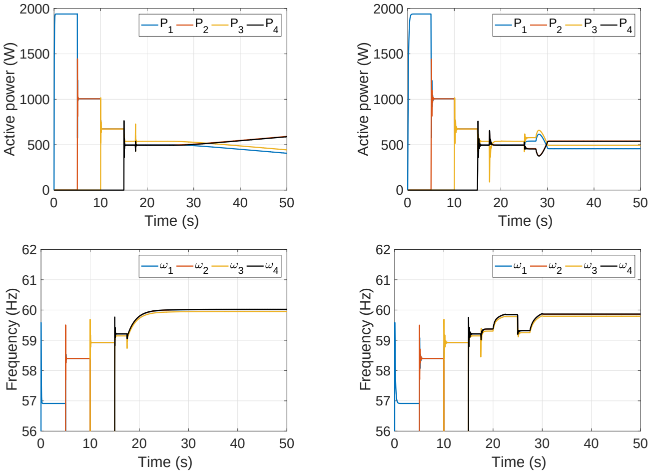
Figure 8.2: System dynamics for droop-free control policy and the proposed switched control policy in the presence of drifts and a communication partition

frequency deviation appears. Whenever the communication is re-established, at $t = 35$ s, frequency droop is disabled and droop-free control is restored to also regulate frequency.

The only objectives not covered by the set of publications included in this compendium refers to the theoretical and experimental analysis of the *centralized* (1.7), *decentralized* (1.8) and *averaging* (1.9) control policies. Simulations have been provided in Figures 1.13 and 1.14 and indicate that apart from the *centralized* that is robust to partitions, the two remaining policies *decentralized* and *averaging*, suffer from the same problems that arise for *consensus* and *droop-free* control policies. That is, when a communication partition occurs, active power dynamics become unstable.

Apart from the *switched control* policy suggested in paper P6, the application of a modification of the *local time-varying filter* (8.1) to the communication-based policies is also a promising strategy that has been tested in simulation. As an example, taking the *decentralized* (1.8) policy, the integral operator could be simply replaced by the time-varying filter but keeping the frequency error computation as mandated by the original *decentralized* method, that is, using the frequency sent by the master node. The adaptation could be named *decentralized time-varying filter*.

For illustrative purposes, Figure 8.3 shows the application of the *decentralized time-varying filter* to be compared to the case of the *decentralized* policy, both subject to drifts and communication partitions. In the plotted simulations, droop control applies at each inverter start-up, which occurs sequentially every 5 s, with ideal clocks. At time $t = 15$ s, clock drifts start applying. Then, at



(a) Decentralized **(b)** Dec. time-varying filters

Figure 8.3: System dynamics for decentralized policies in the presence of drifts and a communication partition

time $t = 17.5$ s, the secondary control policy runs, which refers to the decentralized (1.8) in sub-figure 8.3a and to the decentralized local time-varying filter (8.1) in sub-figure 8.3b, and at time $t = 25$ s a communication partition occurs. The active powers in the decentalized policy become unstable when the partition occurs, while with the application of the decentralized time-varying filter the instability problem disappears at the expenses of introducing a (negligible) deviation in active power steady-state values and a controllable deviation in frequency.

Figure 8.3 opens the door to replace the integral operator by the time-varying filter in all the failing communication-based policies, in order to analyze if the instability problem always disappears. Hence, thorough simulation, theoretical and experimental analyzes are required.

8.4 Discussion

Table 8.1 summarizes the thesis objectives and specifies whether they have been published. In the papers column, "thesis" refers to this document. Hence, simulation analysis for several scenarios, or new proposals for the drift problem case have not been published yet. Also, both theoretical and experimental analyzes, as well as new proposals for the partitions problem, have not been published yet.

Table 8.1: Thesis objectives versus published results

Problem	Objective	Objective description	Policies	Papers
Drifts	1a	Simulation	All	P1, P2, thesis
	1b	Theoretical	All	P1, P2, P3
	1c	Experimental	All	P3
	1d	New proposals	All	Thesis
Partitions	1a	Simulation	All	P4, P5, thesis
	1b	Theoretical	Consensus/droop-free	P4, P5, P6
	1c	Experimental	Consensus/droop-free	P6
	1d	New proposals	Droop-free	P6

9

CONCLUSIONS AND FUTURE WORK

This chapter presents the thesis conclusions and identifies open research challenges.

Summary

9.1 Conclusions

The focus of the thesis is the analysis of islanded MGs where the physically distributed VSIs implementing control algorithms to achieve active power sharing and frequency regulation, are faced to non-ideal conditions in both computing platform and electrical configuration. These conditions can be divided into two problems: *clock drifts* and *partitions*. The problem of *clock drifts* is known in distributed computing systems and its consequence is that the progress of the time available to each local algorithm at each hardware, is slightly different. This may have several impacts on the cooperative objective demanded to all local algorithms. The problem of *partitions* has two faces. One refers to the loss of communications among VSIs that impairs the exchange of the control data required for distributed control algorithms. The other one refers to failures in transmission lines that restrict the number of paths available for carrying power flows. The considered communication and electrical failures create partitions that may impact the operation of the control algorithms. In this context, the thesis main conclusions are listed below:

- The existing literature provides a wide range of control policies for VSIs in islanded MGs that have been developed for guaranteeing active power sharing and frequency regulation. In general, all of them consider ideal conditions and only a few of them have been tested or even analyzed in terms of non-ideal conditions. For those control policies using data exchange the most common non-ideal conditions being examined are communication delays and dropouts. In addition, the problem of transmission lines failures has been also covered mainly from the blackouts management point of view, but not specifically for the control goals being considered in this thesis.

- Clock drifts alter the steady-state active power and frequency values achieved by the analyzed policies. In general, all policies attain acceptable equilibrium points except for the local integrals method that becomes unstable and therefore is discarded for real deployment. Looking at the stable policies, the deviation of the frequency with respect to its set-point and the inaccuracy in active power sharing are both negligible. This positive conclusion must be taken carefully because the combination of clock drifts with other non-ideal conditions could make the analyzed policies dangerous for MG stability, as further explained next.

- Electrical and communication partitions provoke large deviations in the steady-state values of active power and frequency. Hence, power sharing is lost and frequency restoration is inaccurate. When electrical partitions occur, electrically isolated MGs co-exist and power flows can not be transferred among them. Cascading failures could take place if each sub-microgrid supply-demand would not be able to reach the equilibrium.

Then, if equilibrium can be achieved (which is the scenario assumed in this thesis), each isolated MG will reach different steady-state equilibrium points depending on the loads, generators, and particular control policy. When communication partitions occur, several control sub-algorithms working in parallel start acting on a single electrical MG. In this scenario two key aspects have been identified thanks to the theoretical analysis:

  - Assuming ideal conditions, the occurrence of a single communication partition implies changing the equilibrium points and therefore loosing active power sharing and exact frequency restoration. Each sub-algorithm drives its part of the MG to specific steady-state equilibrium points for frequency and active power sharing.
  - Removing the assumption of ideal conditions, that is, for example with the presence of clock drifts, the occurrence of a single communication partition drives the MG to instability. Other non-ideal conditions that generate the same problem are measurement errors, measurement noise, or quantization errors. This result is alarming because in the real world, the assumption of ideal conditions does not hold and communication partitions will put the MG into risk. This theoretical result has been corroborated by the simulation analysis, as well as by the experimental results.

- The MG instability caused by drifts and communication partitions can be avoided by designing novel control policies that include this problem within their performance specifications. One of the sources of instability is the use of the integral operator, which is present in many control policies because it has the known appealing property of avoiding steady-state errors. However, when integrators work in parallel, known problems including instability are likely to occur. The local-integrals policy fails due to the unavoidable clock drifts. The secondary control policy based on communications except for the centralized one, also fail because when communication partitions occur, the set of resulting control sub-algorithms working in parallel behave like a set of "local-integrals". And having integrators working in parallel trying to eliminate an error that is different for each of them causes instability. Two control approaches have been suggested to solve this problem:

  - To replace the integral operator by a time-varying first-order filter with the capacity to work like a standard first order filter or like almost an integrator whenever required. This solution has been successfully applied for the communication-less local integrals and for the communication-based decentralized secondary control policies. In both cases, the instability problem is avoided at the expense of introducing small deviations with respect to the desired steady state values of active power and frequency.

  - To design a switched control policy that permits alternating between a particular secondary control policy and the droop method. The MG control is based on a secondary control policy but when a communication partition occurs, the secondary control policy is disabled and only droop control actuates. When communications are restored, the secondary control policy becomes again active. This approach, that has been fully covered for the case of the droop-free method, avoids the instability by accepting a graceful degradation in terms of frequency deviation during the time interval where communications are not available, because during this time only the droop method works.

9.2 Future work

The following research topics deserve future work:

- The analytical and experimental analysis for the case of partitions should be extended to all communication-based secondary control policies. The thesis has only covered *consensus* and *droop-free* control policies, and *centralized*, *decentralized* and *averaging* should be also analyzed. Preliminary results have been already obtained with the simulation analysis presented in this document.

- The case of multiple partitions should be deeply analyzed because the geometry of the partitioned electrical and communication graphs may provide additional results in terms of stability and in terms of characterization of the equilibrium points of both active power and frequency, as long as they exist.

- Considering the design of new proposals, three approaches are identified for future research:

  - To further investigate the replacement of the integral operator by other integrator-like operators.
  - To further investigate the switching strategy and apply different policies according to different scenarios.
  - To design new policies being robust to the non-ideal conditions.

  The goal for all of them would be to avoid the instability problems while providing different degrees of performance improvement.

- The thesis has focused on drifts and partitions. Additional non-ideal conditions could be included in the analysis.

BIBLIOGRAPHY

[1] R.H. Lasseter, "MicroGrids," in IEEE Power Engineering Society Winter Meeting, vol.1, pp.305-308 vol.1, 2002.

[2] N. Hatziargyriou, H. Asano, R. Iravani and C. Marnay, "Microgrids," in *IEEE Power and Energy Magazine*, vol.5, no.4, pp.78-94, July-Aug. 2007.

[3] H. Farhangi, "The path of the smart grid," in *IEEE Power and Energy Magazine*, vol.8, no.1, pp.18-28, Jan.-Feb. 2010.

[4] R.H. Lasseter, "Smart distribution: coupled microgrids," in *Proceedings of the IEEE*, vol.99, no.6, pp.1074-1082, June 2011.

[5] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, "State of the art in research on microgrids: a review," in *IEEE Access*, vol.3, pp.890-925, 2015.

[6] F. Katiraei, M. R. Iravani, and P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," in *IEEE Transactions on Power Delivery*, vol.20, no.1, pp.248-257, Jan 2005.

[7] D.E. Olivares, A. Mehrizi-Sani, A.H. Etemadi, C.A. Canizares, R. Iravani, M. Kazerani, A.H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G.A. Jimenez-Estevez and N.D. Hatziargyriou, "Trends in microgrid control," in *IEEE Transactions on Smart Grid*, vol.5, no.4, pp.1905-1919, July 2014.

[8] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," in *IEEE Power and Energy Magazine* , vol.6, no.3, pp.54-65, May-June 2008.

[9] J. Rocabert, A. Luna, F. Blaabjerg and P. Rodríguez, "Control of power converters in AC microgrids," in *IEEE Trans. on Power Electronics*, vol.27, no.11, pp.4734-4749, Nov. 2012.

[10] Y. Han, H. Li, P. Shen, E. A. A. Coelho and J. M. Guerrero, "Review of active and reactive power sharing strategies in hierarchical controlled microgrids," in *IEEE Transactions on Power Electronics*, vol.32, no.3, pp.2427-2451, Mar. 2017.

[11] J.M. Guerrero, J.C. Vasquez, J. Matas, J.; L.G. de Vicuña, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids: a general approach toward standardization," in *IEEE Transactions on Industrial Electronics*, vol.58, no.1, pp.158-172, Jan. 2011.

[12] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," in *IEEE Transactions on Smart Grid*, vol.3, no.4, pp.1963-1976, Dec. 2012.

[13] S. M. Rinaldi, J. P. Peerenboom and T. K. Kelly, "Identifying, understanding, and analyzing critical infrastructure interdependencies," in *IEEE Control Systems*, vol.21, no.6, pp.11-25, Dec 2001.

[14] I. A. Tøndel, J. Foros, S. S. Kilskar, P. Hokstad, M. G. Jaatun, "Interdependencies and reliability in the combined ICT and power system: An overview of current research," in *Applied Computing and Informatics*, vol.14, no.1, pp.17-27, 2018.

[15] Y. Cai, Y. Cao, Y. Li, and T. Huang, "Cascading failure analysis considering interaction between power grids and communication networks," in *IEEE Trans. Smart Grid*, vol.7, no.1, pp.1-9, 2015.

[16] G. Andersson, P. Donalek., R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A. Stankovic, C. Taylor, and V. Vittal, "Causes of the 2003 major grid blackouts in North America and Europe and recommended means to improve system dynamic performance," in *IEEE Trans. Power Syst.*, vol.20, no.4, pp.1922-1928, Nov. 2005.

[17] M.C. Pulcherio, A.A. Renjit, M.S. Illindala, A.S. Khalsa, J.H. Eto, D.A. Klapp and R.H. Lasseter, "Evaluation of control methods to prevent collapse of a mixed-source microgrid," in *IEEE Transactions on Industry Applications*, vol.52, no.6, pp.4566-4576, Nov.-Dec. 2016.

[18] M. Khederzadeh and A. Beiranvand, "Identification and prevention of cascading failures in autonomous microgrid," in *IEEE Systems Journal*, vol.12, no.1, pp.308-315, Mar. 2018.

[19] A. Gholami, F. Aminifar, and M. Shahidehpour, "Front lines against the darkness: enhancing the resilience of the electricity grid through microgrid facilities," in *IEEE Electrific. Mag.*, vol.4, no.1, pp.18-24, 2016.

[20] S. Poudel and A. Dubey, "Critical load restoration using distributed energy resources for resilient power distribution system," in *IEEE Trans. Power Systems*, vol.34, no.1, pp.52-63, Jan. 2019.

[21] G. Delille, B. Franois, and G. Malarange, "Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia," in *IEEE Trans. Sustain. Energy*, vol.3, no.4, pp.931-939, Nov. 2012.

[22] C.Yuen, A. Oudalov, and A. Timbus, "The provision of frequency control reserves from multiple microgrids," in *IEEE Trans. Ind. Electron.*, vol.58, no.1, pp.173-183, Jan. 2011.

[23] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for microgrids islanded operation," in *IEEE Transactions on Power Systems*, vol.21, no.2, pp.916-924, May 2006.

[24] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," in *IEEE Transactions on Industrial Electronics*, vol.53, no.5, pp.1398-1409, Oct. 2006.

[25] A. Mohd, E. Ortjohann, D. Morton, and O. Omari, "Review of control techniques for inverters parallel operation", in *Electric Power Systems Research*, vol.80, n. 12, pp.1477-1487, Dec. 2010.

[26] E. Rokrok, M. Shafie-khah, and J.P.S. Catalão, "Review of primary voltage and frequency control methods for inverter-based islanded microgrids with distributed generation", in *Renewable and Sustainable Energy Reviews*, vol.82, part 3, pp.3225-3235, Feb. 2018.

[27] Z. Cheng, J. Duan, and M. Chow, "To centralize or to distribute: that is the question. A comparison of advanced microgrid management systems," in *IEEE Industrial Electronics Magazine*, vol.12, no.1, pp.6-24, Mar. 2018.

[28] S. K. Sahoo, A. K. Sinha, and N. K. Kishore, "Control techniques in AC, DC, and hybrid AC/DC microgrid: A review," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol.6, no.2, pp.738-759, June 2018.

[29] M.C. Chandorkar, D.M. Divan, and R. Adapa, R., "Control of parallel connected inverters in standalone AC supply systems," in *EEE Transactions on Industry Applications*, vol.29, no.1, pp.136-143, Jan./Feb. 1993.

[30] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed AC power systems with consideration offline impedance," in *IEEE Transactions on Industry Applications*, vol.36, no.1, pp.131-138, Jan./Feb. 2000.

[31] U. Borup, F. Blaabjerg, and P. N. Enjeti, "Sharing of nonlinear load in parallel-connected three-phase converters," in *IEEE Transactions on Industry Applications*, vol.37, no.6, pp.1817-1823, Nov. 2001.

[32] J. M. Guerrero, L. G. de Vicuña, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," in *IEEE Transactions on Power Electronics*, vol.19, no.5, pp.1205-1213, Sept. 2004.

[33] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," in *IEEE Transactions on Power Electronics*, vol.22, no.4, pp.1107-1115, July 2007.

[34] N. Ainsworth and S. Grijalva, "A structure-preserving model and sufficient condition for frequency synchronization of lossless droop inverter-based AC

networks," in *IEEE Transactions on Power Systems*, vol.28, no.4, pp.4310-4319, 2013.

[35] J.C. Vasquez, J.M. Guerrero, M. Savaghebi, J. Eloy-Garcia, and R. Teodorescu, "Modeling, analysis, and design of stationary-reference-frame droop-controlled parallel three-phase voltage source inverters," in *IEEE Transactions on Industrial Electronics*, vol.60, no.4, pp.1271-1280, Apr. 2013.

[36] J. Schiffer, R. Ortega, A. Astolfi, J. Raisch, and T. Sezi, "Conditions for stability of droop-controlled inverter-based microgrids," in *Automatica*, vol.50, no.10, pp.2457-2469, 2014.

[37] T. Kawabata, S. Higashino, "Parallel operation of voltage source inverters," in *IEEE Transactions on Industry Applications*, vol.24, no.2, pp.281-287, Mar/Apr 1988.

[38] W. Yao, M. Chen, J. Matas, J. M. Guerrero and Z. Qian, "Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing," in *IEEE Transactions on Industrial Electronics*, vol.58, no.2, pp.576-588, Feb. 2011.

[39] J. Matas, M. Castilla, L. García de Vicuña, J. Miret and J.C. Vasquez, "Virtual impedance loop for droop-controlled single-phase parallel inverters using a second-order general-integrator scheme", in *IEEE Trans. Power Electronics,* vol.25, no.12, pp.2993-3002, Dec. 2010.

[40] M. Hua, H. Hu, Y. Xing, and J.M. Guerrero, "Multilayer control for inverters in parallel operation without intercommunications," in *IEEE Transactions on Power Electronics*, vol.27, no.8, pp.3651-3663, Aug. 2012.

[41] H. Xin, L. Zhang, Z. Wang, D. Gan, and K. P. Wong, "Control of island AC microgrids using a fully distributed approach," in *IEEE Transactions on Smart Grid*, vol.6, no.2, pp.943-945, Mar. 2015.

[42] H. Xin, R. Zhao, L. Zhang, Z. Wang, K. P. Wong, and W. Wei, "A decentralized hierarchical control structure and self-optimizing control strategy for f-p type DGs in islanded microgrids," in *IEEE Transactions on Smart Grid*, vol.7, no.1, pp.3-5, Jan. 2016.

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

[44] M. Castilla, A. Camacho, J. Miret, M. Velasco and P. Martí, "Local Secondary Control for Inverter-Based Islanded Microgrids With Accurate Active Power Sharing Under High-Load Conditions," in *IEEE Transactions on Industrial Electronics*, vol.66, no.4, pp.2529-2539, Apr. 2019.

[45] J. M. Rey, C. X. Rosero, M. Velasco, P. Martí, J. Miret and M. Castilla, "Local Frequency Restoration for Droop-Controlled Parallel Inverters in Islanded Microgrids," in *IEEE Transactions on Energy Conversion*, vol.34, no.3, pp.1232-1241, Sept. 2019.

[46] E.A.A. Coelho, P. Cabaleiro, and P.F. Donoso, "Small-signal stability for parallel-connected inverters in stand-alone ac supply systems," in *IEEE Transactions on Industry Applications*, vol.38, no.2, pp.533-542, Mar./Apr. 2002.

[47] P. Lopes, J.A. Moreira, C.L. Madureira, "Defining control strategies for MicroGrids islanded operation," in *IEEE Transactions on Power Systems*, vol.21, no.2, pp.916-924, May 2006.

[48] M. Prodanovic and T.C. Green, "High-quality power generation through distributed control of a power park microgrid," in *IEEE Transactions on Industrial Electronics*, vol.53, no.5, pp.1471-1482, Oct. 2006.

[49] A. Mehrizi-Sani and R. Iravani, "Potential-function based control of a microgrid in islanded and grid-connected modes," in *IEEE Transactions on Power Systems*, vol.25, no.4, pp.1883-1891, Nov. 2010.

[50] Q. Shafiee, J.M. Guerrero, and J.C. Vasquez, “Distributed secondary control for islanded microgrids - A novel approach,” in *IEEE Transactions on Power Electronics*, vol.29, no.2, pp.1018-1031, Feb. 2014.

[51] I. Serban, "Frequency restoration in microgrids by means of distributed control with minimum communication requirements," in *2014 IEEE 23rd International Symposium onIndustrial Electronics (ISIE)*, June 2014.

[52] A. Bidram, A. Davoudi, F.L. Lewis, S. Sam Ge, "Distributed adaptive voltage control of inverter-based microgrids," in *IEEE Transactions on Energy Conversion*, vol.29, no.4, pp.862-872, Dec. 2014.

[53] F. Dörfler, J.W. Simpson-Porco, and F. Bullo, "Plug-and-play control and optimization in microgrids," in *IEEE Conf. on Decision and Control*, Los Angeles, CA, USA, Dec. 2014.

[54] W. Liu, W. Gu, W. Sheng, X. Meng, Z. Wu, W. Chen, "Decentralized multi-agent system-based cooperative frequency control for autonomous microgrids with communication constraints," in *IEEE Transactions on Sustainable Energy*, vol.5, no.2, pp.446-456, Apr. 2014.

[55] O. Palizban and K. Kauhaniemi, "Secondary control in AC microgrids: challenges and solutions," in *2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)*, Lisbon, Portugal, 2015.

[56] C. Gavriluta, I. Candela, A. Luna, A. Gomez-Exposito, and P. Rodriguez, "Hierarchical control of HV-MTDC systems with droop-based primary and OPF-based secondary," in *IEEE Transactions on Smart Grid*, vol.6, no.3, pp.1502-1510, May 2015.

[57] P. H. Huang, P. C. Liu, W. Xiao and M. S. El Moursi, "A Novel Droop-Based Average Voltage Sharing Control Strategy for DC Microgrids," in *IEEE Transactions on Smart Grid*, vol.6, no.3, pp.1096-1106, May 2015.

[58] F. Guo, C. Wen, J. Mao, and Y.-D. Song, "Distributed secondary voltage and frequency restoration control of droop-controlled inverter-based microgrids," in *IEEE Transactions on Industrial Electronics*, vol.62, no.7, pp.4355-4364, July 2015.

[59] L.-Y. Lu and C.-C. Chu, "Consensus-based secondary frequency and voltage droop control of virtual synchronous generators for isolated AC micro-grids", in *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol.5, no.3, pp.443-455, Sept. 2015.

[60] F. Guo, C. Wen, J. Mao, J. Chen, and Y.-D. Song, "Distributed Cooperative Secondary Control for Voltage Unbalance Compensation in an Islanded Microgrid," in *IEEE Transactions on Industrial Informatics*, vol.11, no.5, pp.1078-1088, Oct. 2015.

[61] J.W. Simpson-Porco, Q. Shafiee, F. Dorfler, J.C. Vasquez, J.M. Guerrero, and F. Bullo, "Secondary frequency and voltage control of islanded microgrids via distributed averaging," in *IEEE Transactions on Industrial Electronics*, vol.62, no.11, pp.7025-7038, Nov. 2015.

[62] J. Schiffer, T. Seel, J. Raisch and T. Sezi, "Voltage stability and reactive power sharing in inverter-based microgrids with consensus-based distributed voltage control," in *IEEE Trans. on Control Systems Technology*, vol.24, no.1, pp.96-109, Jan. 2016.

[63] J. Schiffer, F. Dorfler, and E. Fridmann, "Robustness of distributed averaging control in power systems: time delays & dynamic communication topology", in *Automatica*, vol.80, pp.261-271, 2017.

[64] X. Lu, X. Yu, J. Lai, J. M. Guerrero and H. Zhou, "Distributed secondary voltage and frequency control for islanded microgrids with uncertain communication links," in *IEEE Trans. on Industrial Informatics*, vol.13, no.2, pp.448-460, Apr. 2017.

[65] N. M. Dehkordi, N. Sadati and M. Hamzeh, "Fully distributed cooperative secondary frequency and voltage control of islanded microgrids," in *IEEE Trans. Energy Conversion*, vol.32, no.2, pp.675-685, June 2017.

[66] A. Pilloni, A. Pisano and E. Usai, "Robust finite-time frequency and voltage restoration of inverter-based microgrids via sliding-mode cooperative control," in *IEEE Trans. on Industrial Electronics*, vol.65, no.1, pp.907-917, Jan. 2018.

[67] M. Chen, X. Xiao and J. M. Guerrero, "Secondary restoration control of islanded microgrids with a decentralized event-triggered strategy," in *IEEE Transactions on Industrial Informatics*, vol.14, no.9, pp.3870-3880, Sept. 2018.

[68] B. Abdolmaleki, Q. Shafiee, M. M. Arefi and T. Dragicević, "An instantaneous event-triggered Hz-Watt control for microgrids," in *IEEE Transactions on Power Systems*, vol.34, no.5, pp.3616-3625, Sept. 2019.

[69] M. A. Shahab, B. Mozafari, S. Soleymani, N. M. Dehkordi, H. M. Shourkaei and J. M. Guerrero, "Stochastic consensus-based control of μGs with communication delays and noises," in *IEEE Transactions on Power Systems*, vol.34, no.5, pp.3573-3581, Sept. 2019.

[70] J. Fang, Z. Shuai, X. Zhang, X. Shen and Z. J. Shen, "Secondary power sharing regulation strategy for a DC microgrid via maximum loading factor," in *IEEE Transactions on Power Electronics*, vol.34, no.12, pp.11856-11867, Dec. 2019.

[71] F. Garcia-Torres and C. Bordons, "Optimal economical schedule of hydrogen-based microgrids with hybrid storage using model predictive control," in *IEEE Transactions on Industrial Electronics*, vol.62, no.8, pp.5195-5207, Aug. 2015.

[72] T. A. Nguyen and M. L. Crow, "Stochastic optimization of renewable-based microgrid operation incorporating battery operating cost," in *IEEE Transactions on Power Systems*, vol.31, no.3, pp.2289-2296, May 2016.

[73] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Network topology independent multi-agent dynamic optimal power flow for microgrids with distributed energy storage systems," in *IEEE Transactions on Smart Grid*, vol.9, no.4, pp.3419-3429, July 2018.

[74] X. Hou, Y. Sun, J. Lu, X. Zhang, L.H. Koh, M. Su and J.M. Guerrero, "Distributed hierarchical control of AC microgrid operating in grid-connected, islanded and their transition modes," in *IEEE Access*, vol.6, pp.77388-77401, 2018.

[75] P. P. Vergara, J. C. López, M. J. Rider, and L. C. P. da Silva, "Optimal operation of unbalanced three-phase islanded droop-based microgrids," in *IEEE Transactions on Smart Grid*, vol.10, no.1, pp.928-940, Jan. 2019.

[76] J. Duan, Z. Yi, D. Shi, C. Lin, X. Lu and Z. Wang, "Reinforcement-learning-based optimal control of hybrid energy storage systems in hybrid AC-DC microgrids," in *IEEE Transactions on Industrial Informatics*, vol.15, no.9, pp.5355-5364, Sept. 2019.

[77] V. Nasirian, Q. Shafiee, J.M. Guerrero, F.L. Lewis and A. Davoudi, "Droop-Free Distributed Control for AC Microgrids," in *IEEE Transactions on Power Electronics*, vol.31, no.2, pp.1600-1617, Feb. 2016.

[78] F. Dörfler, J.W. Simpson-Porco, and F. Bullo, "Breaking the hierarchy: distributed control & economic optimality in microgrids," in *IEEE Transactions on Control of Network Systems*, vol.3, no.3, pp.241-253, Sept. 2016.

[79] J.W. Simpson-Porco, F. Dörfler and F. Bullo, "Voltage Stabilization in Microgrids via Quadratic Droop Control," in *IEEE Transactions on Automatic Control*, vol.62, no.3, pp.1239-1253, 2017.

[80] S. T. Cady, M. Zholbaryssov, A. D. Domínguez-García and C. N. Hadjicostis, "A distributed frequency regulation architecture for islanded inertialess AC microgrids," in *IEEE Transactions on Control Systems Technology*, vol.25, no.6, pp.1961-1977, Nov. 2017.

[81] S. Trip and C. De Persis, "Distributed optimal load frequency control with non-passive dynamics," in *IEEE Transactions on Control of Network Systems*, vol.5, no.3, pp.1232-1244, Sept. 2018.

[82] M. Babakmehr, F. Harirchi, A. Al-Durra, S. M. Muyeen and M. G. Simões, "Compressive system identification for multiple line outage detection in smart grids," in *IEEE Transactions on Industry Applications*, vol.55, no.5, pp.4462-4473, Sept./Oct. 2019.

[83] Y. Zhao, A. Goldsmith and H. Vincent Poor, "Minimum Sparsity of Unobservable Power Network Attacks," in *IEEE Transactions on Automatic Control*, vol.62, no.7, pp.3354-3368, July 2017.

[84] R. Yao and K. Sun, "Toward simulation and risk assessment of weather-related outages," in *IEEE Transactions on Smart Grid*, vol.10, no.4, pp.4391-4400, July 2019.

[85] B. Moussa, P. Akaber, M. Debbabi and C. Assi, "Critical links identification for selective outages in interdependent power-communication networks," in *IEEE Transactions on Industrial Informatics*, vol.14, no.2, pp.472-483, Feb. 2018.

[86] H. F. Habib, C. R. Lashway and O. A. Mohammed, "A review of communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency," in *IEEE Transactions on Industry Applications*, vol.54, no.2, pp.1194-1207, Mar./Apr. 2018.

[87] L. Lamport, "Time, clocks, and the ordering of events in a distributed system," in *Communications of the ACM*, vol.2, no.7, pp.558-565, July 1978.

[88] N. M. Freris, S. R. Graham and P. R. Kumar, "Fundamental Limits on Synchronizing Clocks Over Networks," in *IEEE Transactions on Automatic Control*, vol.56, no.6, pp.1352-1364, June 2011.

[89] C. Lenzen, T. Locher, and R. Wattenhofer, "Tight bounds for clock synchronization," in *Journal of ACM*, vol.57, num. 2, Article 8, Feb. 2010.

[90] R.A. Gupta, and M.-Y. Chow, "Networked control system: overview and research trends," in *IEEE Transactions on Industrial Electronics*, vol.57, no.7, pp.2527-2535, July 2010.

[91] W.P.M.H. Heemels, A.R. Teel, N. Ivan de Wouw, D. Nesic, "Networked control systems with communication constraints: tradeoffs between transmission intervals, delays and performance," in *IEEE Transactions on Automatic Control*, vol.55, no.8, pp.1781-1796, Aug. 2010.

[92] Z. Lixian, G. Huijun and O. Kaynak, "Network-induced constraints in networked control systems: a survey," in *EEE Transactions on Industrial Informatics*, vol.9, no.1, pp.403-416, Feb. 2013.

[93] P. Martí, C. Lin, S. A. Brandt, M. Velasco and J. M. Fuertes, "Draco: efficient resource management for resource-constrained control tasks," in *IEEE Transactions on Computers*, vol.58, no.1, pp.90-105, Jan. 2009.

[94] Y. Wu, G. Buttazzo, E. Bini, A. Cervin, "Parameter selection for real-time controllers in resource-constrained systems," in *IEEE Transactions on Industrial Informatics*, vol.6, no.4, pp.610-620, 2010.

[95] N. R. Chaudhuri, D. Chakraborty, and B. Chaudhuri, "An architecture for facts controllers to deal with bandwidth-constrained communication," in *IEEE Transactions on Power Delivery*, vol.26, pp.188-196, Mar. 2011.

[96] S. Wang, X. Meng, and T. Chen, "Wide-area control of power systems through delayed network communication," in *IEEE Transactions on Control Systems Technology*, vol.20, pp.495-503, Mar. 2012.

[97] A. Usman and S.H. Shami, "Evolution of communication technologies for smart grid applications," in *Renewable and Sustainable Energy Reviews*, vol.19, pp.191-199, Mar. 2013.

[98] C.-H. Lo and N. Ansari, "Decentralized controls and communications for autonomous distribution networks in smart grid," in *IEEE Transactions on Smart Grid* , vol.4, no.1, pp.66-77, Mar. 2013.

[99] G. Pasini, L. Peretto, and R. Tinarelli, "Study of the accuracy requirements of the instrumentation for efficiency measurements in power conversion systems," in *IEEE Trans. Instrum. Meas.*, vol.62, no.8, pp.2154-2160, Aug. 2013.

[100] A.K. Singh, R. Singh, and B.C. Pal, "Stability analysis of networked control in smart grids," in *IEEE Transactions on Smart Grid*, vol.6, no.1, pp.381-390, Jan. 2015.

[101] A. Kahrobaeian, Y.A.-R. Ibrahim Mohamed, "Networked-based hybrid distributed power sharing and control for islanded microgrid systems," in *IEEE Transactions on Power Electronics*, vol.30, no.2, pp.603-617, Feb. 2015.

[102] L. Shichao, X. Wang, and P.X. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid," in *IEEE Transactions on Industrial Electronics*, pp.2021-2031, vol.62, num.4, Apr. 2015.

[103] V. Kounev, D. Tipper, A.A. Yavuz, B.M. Grainger, G.F. Reed, "A secure communication architecture for distributed microgrid control," in *IEEE Transactions on Smart Grid*, vol.6, no.5, pp.2484-2492, Sept. 2015.

[104] C. Ahumada, R. Cárdenas, D. Sáez, J.M. Guerrero, "Secondary control strategies for frequency restoration in islanded microgrids with consideration of communication delays," in *IEEE Transactions on Smart Grid*, vol.7, no.3, pp.1430-1441, May 2016.

[105] J. Schiffer, C. A. Hans, T. Kral, R. Ortega and J. Raisch, "Modeling, analysis, and experimental validation of clock drift effects in low-inertia power systems," in *IEEE Transactions on Industrial Electronics*, vol.64, no.7, pp.5942-5951, July 2017.

[106] P. Martí, M. Velasco, E. X. Martín, L. García de Vicuña, J. Miret and M. Castilla, "Performance evaluation of secondary control policies with respect to digital communications properties in inverter-based islanded microgrids," in *EEE Transactions on Smart Grid*, vol.9, no.3, pp.2192-2202, May 2018.

[107] P. Danzi, M. Angjelichinoski, C. Stefanović, T. Dragicević and P. Popovski, "Software-defined microgrid control for resilience against denial-of-service attacks," in *IEEE Trans. Smart Grid*, *in press*, Nov. 2018.

[108] M. Chlela, D. Mascarella, G. Joós and M. Kassouf, "Fallback control for isochronous energy storage systems in autonomous microgrids under denial-of-service cyber-attacks," in *IEEE Trans. Smart Grid*, vol.9, no.5, pp.4702-4711, Sept. 2018.

[109] J. Schiffer, R. Ortega, C. A. Hans and J. Raisch, "Droop-controlled inverter-based microgrids are robust to clock drifts," in *2015 American Control Conference (ACC)*, pp.2341-2346, Chicago, IL, 2015.

[110] M. Velasco, P. Martí, A. Camacho, J. Miret, M. Castilla, "Synchronization of local integral controllers for frequency restoration in islanded microgrids", in *42nd Annual Conference of IEEE Industrial Electronics Society*, Oct. 2016.

[111] A. Krishna, C. A. Hans, J. Schiffer, J. Raisch and T. Kral, "Steady state evaluation of distributed secondary frequency control strategies for microgrids in the presence of clock drifts," in *25th Mediterranean Conference on Control and Automation (MED)*, 2017.

[112] R. R. Kolluri, I. Mareels, T. Alpcan, M. Brazil, J. de Hoog and D. A. Thomas, "Power Sharing in Angle Droop Controlled Microgrids," in *IEEE Transactions on Power Systems*, vol.32, no.6, pp.4743-4751, Nov. 2017.

[113] M. Castilla, A. Camacho, P. Martí, M. Velasco and M. Moradi Ghahderijani, "Impact of Clock Drifts on Communication-free Secondary Control Schemes for Inverter-based Islanded Microgrids," in *IEEE Transactions on Industrial Electronics*, vol.65, no.6, pp.4739-4749, June 2018.

[114] S. Bolognani and S. Zampieri, "A Distributed Control Strategy for Reactive Power Compensation in Smart Microgrids," in *IEEE Transactions on Automatic Control*, vol.58, no.11, pp.2818-2833, Nov. 2013.

[115] J. W. Simpson-Porco, F. Dorfler, F. Bullo, "Synchronization and power sharing for droop-controlled inverters in islanded microgrids," in *Automatica*, vol.49, no.9, pp.2603-2611, 2013.

[116] E. Tegling, B. Bamieh and D. F. Gayme, "The Price of Synchrony: Evaluating the Resistive Losses in Synchronizing Power Networks," in *IEEE Transactions on Control of Network Systems*, vol.2, no.3, pp.254-266, Sept. 2015.

[117] J. W. Simpson-Porco, "A Theory of Solvability for Lossless Power Flow Equations - Part I: Fixed-Point Power Flow," in *IEEE Transactions on Control of Network Systems*, vol.5, no.3, pp.1361-1372, Sept. 2018.

[118] Z. Zhang and M. Y. Chow, "Convergence Analysis of the Incremental Cost Consensus Algorithm Under Different Communication Network Topologies in a Smart Grid," in *IEEE Transactions on Power Systems*, vol.27, no.4, pp.1761-1768, Nov. 2012.

[119] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," in *IEEE Transactions on Automatic Control*, vol.49, no.9, pp.1520-1533, Sept. 2004.

[120] W. Liu, W. Gu, W. Sheng, X. Meng, S. Xue and M. Chen, "Pinning-Based Distributed Cooperative Control for Autonomous Microgrids Under Uncertain Communication Topologies," in *IEEE Transactions on Power Systems*, vol.31, no.2, pp.1320-1329, Mar. 2016.

[121] R. M. Imran, S. Wang and F. M. F. Flaih, "DQ-voltage droop control and robust secondary restoration with eligibility to operate during communication failure in autonomous microgrid," in *IEEE Access*, vol.7, pp.6353-6361, 2019.

[122] F. Katiraei and M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," in *IEEE Transactions on Power Systems*, vol.21, no.4, pp.1821-1831, Nov. 2006.

[123] N. Pogaku, M. Prodanovic and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," in *IEEE Transactions on Power Electronics*, vol.22, no.2, pp.613-625, Mar. 2007.

[124] J. Schiffer, D. Zonetti, R. Ortega, A.M. Stanković, T. Sezi, and J. Raisch, "A survey on modeling of microgrids - From fundamental physics to phasors and voltage sources," in *Automatica*, vol.74, pp.135-150, 2016.

[125] J. Belikov and Y. Levron, "Uses and misuses of quasi-static time-varying phasor models in power systems," in *IEEE Transactions on Power Delivery*, vol.33, no.6, pp.3263-3266, Dec. 2018.

[126] S. Sen and V. Kumar, "Microgrid modelling: A comprehensive survey," in *Annual Reviews in Control*, vol.46, pp.216-250, 2018.

[127] F. Dorfler and F. Bullo, "Kron reduction of graphs with applications to electrical networks," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol.60, no.1, pp.150-163, Jan. 2013.

[128] S.Y. Caliskan and P. Tabuada, "Towards Kron reduction of generalized electrical networks", *Automatica*, vol.50, no.10, pp.2586-2590, 2014.

[129] L. Luo and S. V. Dhople, "Spatiotemporal model reduction of inverter-based islanded microgrids," in *IEEE Transactions on Energy Conversion*, vol.29, no.4, pp.823-832, Dec. 2014.

[130] A. Floriduz, M. Tucci, S. Riverso and G. Ferrari-Trecate, "Approximate kron reduction methods for electrical networks with applications to plug-and-play control of AC islanded Microgrids," in *IEEE Transactions on Control Systems Technology*, pp.1-14, 2018.

[131] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.

[132] X. Guo, Z. Lu, B. Wang, X. Sun, L. Wang and J. M. Guerrero, "Dynamic phasors-based modeling and stability analysis of droop-controlled inverters for microgrid applications," in *IEEE Transactions on Smart Grid*, vol.5, no.6, pp.2980-2987, Nov. 2014.

[133] F. Dörfler, J. W. Simpson-Porco and F. Bullo, "Electrical networks and algebraic graph theory: models, properties, and applications," in *Proceedings of the IEEE*, vol.106, no.5, pp.977-1005, May 2018.

[134] J. Miret, J. García de Vicuña, R. Guzmán, A. Camacho, and M. Moradi Ghahderijani, "A flexible experimental laboratory for distributed generation networks based on power inverters," in *Energies*, vol.10, no.10, pp.1589, 2017.

[135] R. H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, and J. Roy, "CERTS microgrid laboratory test bed," in *IEEE Transactions on Power Delivery*, vol.26, no.1, pp.325-332, Jan. 2011.

[136] L. Widanagama Arachchige and A. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," in *Renewable and Sustainable Energy Reviews*, vol.15, pp.186-202, Jan. 2011.

[137] V. Salehi, A. Mohamed, A. Mazloomzadeh and O. A. Mohammed, "Laboratory-Based Smart Power System, Part I: Design and System Development," in *IEEE Transactions on Smart Grid*, vol.3, no.3, pp.1394-1404, Sept. 2012.

[138] V. Salehi, A. Mohamed, A. Mazloomzadeh and O. A. Mohammed, "Laboratory-Based Smart Power System, Part II: Control, Monitoring, and Protection," in *IEEE Transactions on Smart Grid*, vol.3, no.3, pp.1405-1417, Sept. 2012.

[139] B. Zhao, X. Zhang, and J. Chen, "Integrated microgrid laboratory system," in *IEEE Transactions on Power Systems*, vol.27, no.4, pp.2175-2185, Nov. 2012.

[140] M. Rasheduzzaman, B. H. Chowdhury and S. Bhaskara, "Converting an Old Machines Lab Into a Functioning Power Network With a Microgrid for Education," in *IEEE Transactions on Power Systems*, vol.29, no.4, pp.1952-1962, July 2014.

[141] L. Meng, A. Luna, E.R. Díaz, B. Sun, T. Dragicevic, M. Savaghebi, J.C. Vasquez, J.M. Guerrero, M. Graells, and F. Andrade, "Flexible system integration and advanced hierarchical control architectures in the microgrid research laboratory of Aalborg university," in *IEEE Transactions on Industry Applications*, vol.52, no.2, pp.1736-1749, Mar. 2016.

[142] L. Mariam, M. Basu, and M. F. Conlon, "Microgrid: architecture, policy and future trends," in *Renewable and Sustainable Energy Reviews*, vol.64, pp.477-489, Oct. 2016.

[143] N. S. Coleman, K. L. Ogawa, J. Hill, and K. N. Miu, "Reconfigurable distribution automation and control laboratory: Solar microgrid experiments," in *IEEE Transactions on Power Systems*, vol.33, no.6, pp.6379-6386, Nov. 2018.

[144] Schematics F28M36x controlCARD, Texas Instruments INC, Notes 2012, ftp://ftp.ti.com/pub/dml/DMLrequest/Christy FTP-10-30-12/ controlSUITE/development kits/?controlCARDs/TMDSCNCD28M36 v1 0/R1 1/F28M36x 180controlCARD R1.1 SCH.pdf

[145] O. Abrishambaf, P. Faria, L. Gomes, J. Spínola, Z. Vale, J.M. Corchado, "Implementation of a real-time microgrid simulation platform based on centralized and distributed management", in *Energies*, vol.10, pp.806, 2017.

[146] J. Meng, Y. Wang, C. Wang and H. Wang, "Design and implementation of hardware-in-the-loop simulation system for testing control and operation of DC microgrid with multiple distributed generation units," in *IET Generation, Transmission & Distribution*, vol.11, no.12, pp.3065-3072, 2017.

[147] A. S. Vijay, S. Doolla and M. C. Chandorkar, "Real-time testing approaches for microgrids," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol.5, no.3, pp.1356-1376, Sept. 2017.

[148] S. Tan, W. Song, D. Huang, Q. Dong and L. Tong, "Distributed software emulator for cyber-physical analysis in smart grid," in *IEEE Transactions on Emerging Topics in Computing*, vol.5, no.4, pp.506-517, Oct.-Dec. 2017.

[149] X. Zhou, X. Gou, T. Huang and S. Yang, "Review on testing of cyber physical systems: methods and testbeds," in *IEEE Access*, vol.6, pp.52179-52194, 2018.

[150] G. Cao et al., "Real-time cyber-physical system co-simulation testbed for microgrids control," in *IET Cyber-Physical Systems: Theory & Applications*, vol.4, no.1, pp.38-45, Mar. 2019.

[151] Y. Huo and G. Gruosso, "Hardware-in-the-Loop Framework for Validation of Ancillary Service in Microgrids: Feasibility, Problems and Improvement," in *IEEE Access*, vol.7, pp.58104-58112, 2019.

[152] Simscape Power Systems, https://www.mathworks.com/products/simscape-electrical.html, 2019.

[153] A. Cervin, D. Henriksson, B. Lincoln, J. Eker and K-E. Arzen, "How does control timing affect performance? Analysis and simulation of timing using Jitterbug and TrueTime," in *IEEE Control Systems Magazine*, vol.23, no.3, pp.16-30, June 2003.

[154] F. S. Gazijahani and J. Salehi, "Robust design of microgrids with reconfigurable topology under severe uncertainty," in *IEEE Transactions on Sustainable Energy*, vol.9, no.2, pp.559-569, Apr. 2018.

[155] F. Samadi Gazijahani and J. Salehi, "Optimal bilevel model for stochastic risk-based planning of microgrids under uncertainty," in *IEEE Transactions on Industrial Informatics*, vol.14, no.7, pp.3054-3064, July 2018.

[156] Y.-S. Kim, E.-S. Kim, S.-I. Moon, "Distributed generation control method for active power sharing and self-frequency recovery in an islanded microgrid", *IEEE Transactions on Power Systems*, vol.32, pp.544-551, 2017.

[157] X. Wu, S. Shi, X. Wang, C. Duan, T. Ding and F. Li, "Optimal black start strategy for microgrids considering the uncertainty using a data-driven chance constrained approach," in *IET Generation, Transmission & Distribution*, vol.13, no.11, pp.2236-2248, 2019.

[158] G. Chen and Z. Guo, "Distributed secondary and optimal active power sharing control for islanded microgrids with communication delays," in *IEEE Transactions on Smart Grid*, vol.10, no.2, pp.2002-2014, Mar. 2019.

A

Appendix: Publication not included in the thesis

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

J. M. Rey, C. X. Rosero, M. Velasco, P. Martí, J. Miret and M. Castilla, "Local frequency restoration for droop-controlled parallel inverters in islanded microgrids," in *IEEE Transactions on Energy Conversion*, vol. 34, no. 3, pp. 1232-1241, September 2019.

ATTENTION¡¡

Pages 140 to 150 of the thesis are available at the editor's web
https://ieeexplore.ieee.org/document/8572796