Universidad Tecnológica de Pereira

FACULTY OF ENGINEERING

MASTER THESIS

Secondary control in islanded smart distribution systems considering renewable resources and energy storage: A centralized approach based on convex optimization.

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Abstract

This thesis proposes a receding horizon strategy for the secondary control of islanded microgrids. The proposed control takes into account the action of the primary control as well as the references given by the tertiary control.

A convex optimization model is solved in each time step, based on a linear approximation of the frequency-dependent power flow equations. The main objective of the control is to carry out frequency and voltages to suitable values, taking into account capacity limits of renewable sources and energy-storage devices.

As shown along this document, there are several techniques implemented to deal with the secondary control problem in scientific literature. Neveretheless, the innovation of this proposal lays on the fact that using convex optimization, as a tool for the receding horizon scheme and the hierarchical control structure, allows the algotithm to reach the global best solution that reduces the system frequency deviation around the nominal value.

Numerical experiments on the CIGRE low-voltage benchmark test system were implemented to demonstrate the performance of the proposed control. The algorithm has demonstrated that under different load scenarios the best solution is found.

Acknowledgement

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Chapter 1

Introduction

Concerns about climate change increase around the word with the electrical sector, the most important sectors for the industry and general daily life, as one of the main causes. Thus, it has to contribute to mitigate those problems. One way to contribute to the mitigation of these issues is including different types of generation into the energy mix. The inclusion of new ways of generation brings challenges for the traditional network as they need power electronic devices, new control strategies, new operation modes and different operation controls. Thereby, microgrids appears as a solution for the integration of renewable generation, with the possibility of operating disconnected from the traditional grid. Then, microgrids control requires to be distributed in different layers to guarantee a reliable operation. In this case, hierarchical control strategies including primary, secondary and tertiary layers, have been proposed to stabilize the system after a disturbance, improve set points of power electronic devices to restore electric variables to their rated values and enhance optimal grid operation, respectively. This master thesis deals with secondary control, which takes both local and global control signals in order to improve the power quality and guarantee microgrids stability. In this chapter, the general concepts accompanied by the main contributions of the study made for islanded microgrids with the inclusion of renewable generation and hierarchical control structures, are identified.

1.1 Motivation

Wind and solar energy, integrated to traditional energy networks, are promising solutions to mitigate climate change and CO2 emissions. Nevertheless, these new electric generation resources may induce challenges related to the operation, stability and reliability of distribution grids. Thus, the incorporation of renewable generation and new electronic devices such as energy storage, accompanied by control strategies and mathematical optimization models, may improve economical and operational aspects of the grid. At this point, traditional networks with the inclusion of all mentioned technologies, can be considered as the so-called smart grids.

The main control challenge in smart distribution grids operating in islanded mode is related to the voltage and frequency deviations because of the absence of reference or slack bus, which is able to keep both voltage and frequency constants. Then, several tools such as the load flow requires to be modified to consider frequency variations; a mathematical optimization model that guarantees convergence, feasibility and real time operation becomes necessary in order to implement a centralized secondary control. However, the power flow problem is a nonlinear and nonconvex problem. A linear and convex approximation is required for the strategy to ensure uniqueness in the solution and a proper time for the operation in the microgrid. Therefore, under a similar hierarchical control strategy as for traditional power systems, microgrids includes a secondary control layer which is projected to guarantee reliability, improve power quality and re-establish frequency and voltage deviations. The latter, allows the system to reach a feasible operating point considering all previously mentioned devices and strategies.

The main aim of this master thesis is to generate a centralized secondary control which allows the system to operate in suitable values of voltage and frequency. This can be solved by combining mathematical optimization, renewable generation, energy storage systems and a control strategy as the main characteristics of the proposed method.

A linearized power flow method should be integrated to the secondary control problem since the islanded operation of the system is treated. As previously mentioned, this method may include frequency variations given the lack of a reference bus. Likewise, a mathematical optimization model, capable of guarantee feasibility in the results, convergence and real time operation, must be formulated. In this case, as the system is operating in island mode, the convergence is limited to the system parameters. Finally, the discretization and parametrization of the model must allow real time operation considering the model execution time. The integration of all aforementioned, allows formulate a receding horizon scheme for the centralized secondary control in islanded smart distribution systems under a hierarchical control. This methodology can consider the dynamics of the primary control and also steady state results from tertiary control.

It is worth to mention that creating this secondary control concept infers a computational, theoretical and methodological effort due to the high number of elements considered into the study. Furthermore, the solution of this problem can be obtained using different types of software and also free software such as Python and CVX.

1.2 Microgrids

The integration of non-conventional renewable energy resources into the electric network is imminent due to growing concerns about greenhouse gases emissions, global warming and necessities of customers given the existence of new technologies, such as electric vehicles. These heterogeneous generation systems, including also large communication structures, control and operation strategies are commonly named Smartgrids. Smartgrids and microgrids voltage operating values can be found between the range from 400V to 69kV Hatziargyriou et al. (2007). Their integration is an engineering challenge due to the complex operational changes powered by the inclusion of power electronic elements and the stochastic behavior of solar radiation and wind speed. Figure 1.1 shows an example of a microgrid under the mentioned concept.

Then, storage systems such as battery energy storage systems (BESS) and super-conducting magnetic energy storage (SMES) are technologies that should be considered to serve as assistances for the system reliability. BESS can store energy for long periods of time and can serve as load curve flatteners (Stecca et al., 2020). On the other hand, SMES can provide services as a stabilizer for the system since they can inject high amounts of energy to the system in transitory disturbance. The behavior of both storage elements, show the necessity of creating a coordinated methodology for an optimal operation of the system. At that point, smart grids operating either in connected or islanded mode require a methodology that integrates the properties of BESS and SMES, considering the variability of the primary resource.

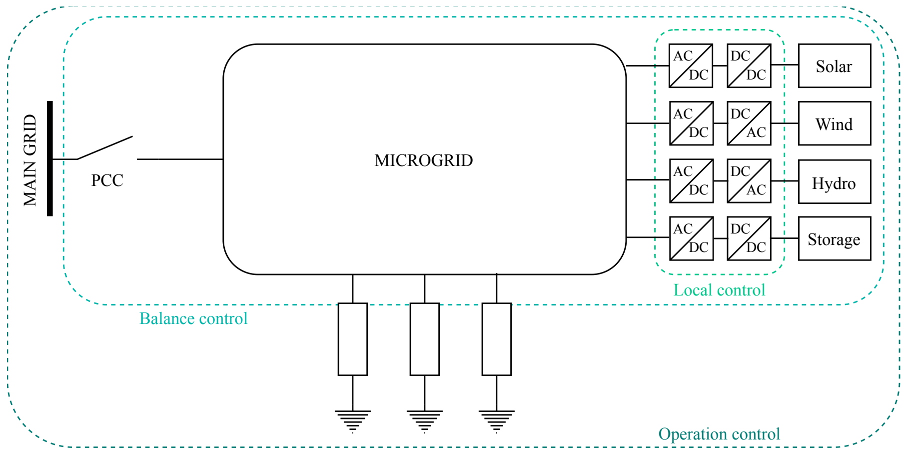


Figure 1.1: Microgrid including heterogeneous generation, communication structures between all control layers, control and operation strategies.

A strong, reliable and secure smart grid must consider a control strategy which integrates all previously mentioned aspects while operating in grid-connected mode or in island mode. Particularly in island mode, several methodologies may be adopted. For example, a centralized approach for the secondary control can be implemented for the system in order to achieve the voltage and frequency references when operating in either connected or island mode. Also, optimal power-sharing must be guaranteed.

A special research work related to an islanded load flow for radial distribution networks must be considered due the absence of slack bus and therefore the missing of frequency and voltage references. Furthermore, it needs to be linearized in order to ensure uniqueness of the solution and a real time operation. Besides, smart transformers enable a local generation of reactive power which can improve the stability of the system and can interconnect a smart distribution system to both the main grid or other smart systems, allowing a re-synchronization in a case where the grid is operating in island mode.

All of these issues could be considered, in the operative point of view, to an optimization problem. In the scientific literature, several algorithms and methodologies have been studied in order to accomplish power balance, establishment of set points for frequency and voltage, among others. However considering that it is a control problem, the system requires a real time operation, uniqueness and global solution which is a challenge from a theoretical perspective. Convex optimization, as a fundamental part of mathematical optimization, includes these variety of properties that can ensure uniqueness on the solution and can also guarantee a global optimum for the problem.

Additionally in practical problems related to electrical systems, convex optimization gives the global optimum in a very small amount of time, e.g, grant a real time operation for a control system in an electrical network.

1.3 State of the art

Microgrids are low voltage systems characterized by a considerable inclusion of distributed energy generation, interconnected loads and energy storage devices. For a system to be considered a microgrid, it may guarantee the correct operation either connected to the main grid or in island mode (Hirsch et al., 2018). Then, studies related to the development of smart-microgrids and their control systems are recently a topic of interest for the scientific community. In grid-connected mode, voltage and frequency are defined by the main grid and a relatively simple synchronization strategy is required in each distributed resource (Rocabert et al., 2012). This differs from island mode, where the references for voltage and frequency are settled by the converters themselves, using a hierarchical scheme of primary, secondary and tertiary controls, just as in the case of power systems (Bidram and Davoudi, 2012) (Guerrero et al., 2013).

Some challenges for the adoption of microgrids are the voltage and frequency regulation, storage planning, active and reactive power exchanges either in connected and islanded mode as well as their optimal operation (Che et al., 2017) (Han et al., 2016a) (Sahoo et al., 2018) (Alam et al., 2019). These challenges, along with the inclusion of heterogeneous distributed resources, distributed energy storage elements and different types of loads, require strong control strategies, under centralized or decentralized approaches, in order to satisfy local objectives to ensure the correct operation of the network in both connection modes. One methodology, as shown by authors in (Bidram and Davoudi, 2012), is a hierarchical time-layered structure mainly used in power systems that includes a primary, secondary and tertiary layers.

The main objective of the primary control is to achieve a stable equilibrium point (Farrokhabadi et al., 2019). This control requires to be fast, simple and reliable. Usually, a droop control is implemented locally in each converter (Chandorkar et al., 1993) which provides the voltage and current reference points at each distributed energy resource (DER) in order to stabilize voltage and frequency. However, frequency deviations can be added even in steady state. Another recent approach, is the use of virtual synchronous generators. Both approaches are equivalent from the small signal perspective, as was demonstrated in (D'Arco and Suul, 2014) and more recently in (Ferreira et al., 2019).

In contradistinction to the primary control, the secondary and tertiary controls are usually centralized and their main objective is to optimize the operation (Agundis-Tinajero et al., 2019). The secondary control, with a centralized approach, reestablish the microgrid frequency and voltage and compensate the deviations caused by the primary control, while the tertiary control optimizes the stationary state operation. Tertiary control is closely related to operative algorithms such as the optimal power flow and the economic dispatch (Capitanescu, 2016). Compared to the secondary control, the tertiary has a slow response and can be considered as a stationary state problem. There is a extensive literature about the primary and the tertiary control (see for example (Yazdanian and Mehrizi-Sani, 2014) and (Capitanescu, 2016) for a complete review of the primary and tertiary controls, respectively).

A wide variety of theoretical development about the secondary control in several approaches can also be found in the scientific literature. Authors in (Khayat et al., 2020) made an extensive literature review around secondary control, its structures and main control strategies; the use of secondary control structures, therefore, becomes a key feature to increase microgrids resilience and deal with the stochastic behavior of distributed generation. In (Delfino et al., 2018a), a study related to the optimal control in secondary level for small sized islanded microgrids was developed . Here, a receding horizon scheme was proposed for secondary and tertiary levels by implementing a multiobjective problem considering a single bus grid with the inclusion of diesel generation.

Shafiee et al. (Shafiee et al., 2014) proposed a secondary control approach that not only restores frequency and voltage of the microgrid but also ensures reactive power sharing under a decentralized strategy (Shafiee

Reference	Main Contribution	Controller type
(Savaghebi et al., 2012) (Savaghebi et al., 2012) (Vovos et al., 2007) (Andishgar et al., 2018) (Han et al., 2016b)	Harmonic cancellation	PI
(Han et al., 2016b) (Savaghebi et al., 2012)	Voltage Unbalance compensation	PI
(Meng et al., 2014)	Voltage Unbalance compensation	Cost function
(Micallef et al., 2014)	Management of reactive power	Cost function
(Liu et al., 2015)	Time delay consideration	Gain schedulling approach
(Yang et al., 2016)	Voltage control	Multi-objetive Optimization

Table 1.1: Main conrtributions of relevant references considering a centralized secondary control for microgrids.

et al., 2014); this strategy allowed a control signal to be locally sent to every primary controller. Authors in (Savaghebi et al., 2012) proposed a hierarchical scheme including the primary and secondary control levels which comprised local controllers for the primary control and a proper design for the central secondary controller, in order to manage the compensation of voltage unbalance at the point of common coupling. In (Yang et al., 2016), an optimal secondary voltage control strategy was proposed with the main objective of keeping the voltage magnitudes of selected nodes within the allowed range and, also, to accomplish accurate reactive power distribution.

The studies made in (Chen and Xiao, 2018) and (Bidram et al., 2013) proposed a cooperative secondary control for islanded microgrids seen as a multiagent systems. For that reason, the communication burden between distributed generators are highly reduced. Nevertheless, authors also conclude that an auxiliary centralized controller was necessary. Similarly, (Manaffam et al., 2018) presented an intelligent pinning-based cooperative secondary control which efficiently synchronizes distributed generation in a microgrid to their nominal voltage and frequency values after disconnecting from the main grid; the selection of pinning nodes depends strictly on the topology of both power and communication systems. Tables 1.1 and 1.2 show the main contributions of relevant references considering both centralized and decentralized secodary control strategies, respectively.

Furthermore, studies related to active power sharing, small-signal analysis and frequency restoration where developed while communication mech-

Ref	Main Contribution	Controller type
(Shafiee et al., 2014)	Proper reactive power sharing	PI-based Multi Agent systems
(Bidram et al., 2013)	Input–output feedback linearisation	PI-based Multi Agent systems
(Chen and Xiao, 2018)	Communication burden reduced	Event-triggered
(Ding et al., 2019)	Active power sharing	Event-triggered
(Manaffam et al., 2018)	Improved transient voltage	Heuristic algorithms
(Coelho et al., 2016)	Small-signal analysis	Consensus algorithm

Table 1.2: Main conrtributions of relevant references considering a decentralized secondary control for micrograms.

anisms, strategies and communication time delays were considered (Ding et al., 2019) (Coelho et al., 2016) (Ahumada et al., 2016); authors states that MPC-based strategies are the main control strategy recommended to be implemented in systems where communication delays are unknown with large variation values. Distributed secondary control for DC Microgrids have also been considered in (Wang et al., 2016) where better dynamic current sharing performance is achieved and enhanced by using an additional average current controller and average droop coefficient controller. As energy storage systems play an important role in microgrids, especially in the secondary control, the study presented in (Ortega and Milano, 2016) proposed a generalized model of energy storage elements considering voltage and angle stability analysis which is useful to compare different control strategies.

Despite centralized control schemes require large communications infrastructure due to a big amount of data that needs to be transfered, it fits very well with microgrids where DERs are close together (Abedini et al., 2016) (Rocabert et al., 2012) (Chuvychin et al., 2007). Centralized techniques have also been studied for high-voltage transmission systems (Machowski et al., 1997). Event-triggered control was used in (Chen and Xiao, 2018) for the secondary voltage control in islanded microgrids while in (Delfino et al., 2018b) a receding horizon-based control scheme was presented for secondary and tertiary optimal control.

Furthermore, studies related to the SMES and BESS to improve power system dynamics performance have been under study in recent years (Mitani et al., 1988) (Maly and Kwan, 1995). Energy storage devices compensate the power and frequency oscillations powered by the stochastic behavior and intermittent availability of the primary energetic resource as they extract and add power from the network. Energy quality indices amelioration is provoked as well as a flattening on the load curve. However, despite battery energy storage systems (BESS) can store energy for a long time, they can not deal with transient operative problems. Here, super-conducting magnetic energy storage (SMES) and super capacitors can be included since they allow a fast and repetitive charge/discharge cycles preserving the device lifetime (Nomura et al., 2020); nevertheless, they can only store energy in intervals of minutes. Then, a coordination strategy considering different time horizons for all storage devices needs to be included.

Ali et al. (Ali et al., 2010) show a variety of potential applications of SMES where it is clear that these devices with a high return efficiency (up to 95%) also have a fast response time for dynamic change of power flow. Besides, SMES (Abu-Siada and Islam, 2011) and BESS (Li et al., 2013) have the capabilities to ensure the correct operation hybrid AC/DC grids considering the integration of DERs.

This and other problems related to distribution grids such as phase balancing, feeder reconfiguration, among others, can be solved by using metaheuristic techniques. Nevertheless, these type of techniques do not guarantee a global optimum and a unique solution, without mentioning that the execution time could be large. Nevertheless, different techniques as the shown in (Rios et al., 2019) are being developed to reduce drastically the heuristic algorithms execution time. On the other hand, convex optimization, as a mathematical technique that is in constantly growth for electrical systems applications, has a wide group of mathematical properties which can guarantee uniqueness on the solution, a global optimum under certain conditions and a real time operation due to the high efficiency of the algorithms; characteristics that are ideal for smart distribution systems where a real time operation is fundamental for the correct operation of the network.

Being an intermediate layer, the secondary control shares some characteristics from both the primary and the tertiary control. Therefore, a well designed secondary control requires to include the frequency variation and the droops given by the primary control. Moreover, it requires to include capability constraints as the tertiary control. Therefore, optimization-based controls such as model predictive control or receding horizon are ideal for this type of application[1]. The receding horizon strategy is based on a simple idea: to solve an optimization model in each time step. Therefore, the optimization model requires to represent accurately the microgrid and be simple enough to be evaluated on-line with guarantee of convergence. Convex optimization emerges as a suitable alternative in this case.

The study of smart distribution systems also require the integration of methodologies such as a power flow that can solve the problem while the network is opperating in islanded mode. This type of developments need to work optimally in order to give a fast response to the control elements. The study in (Esmaeli et al., 2016) presents a Guaranteed convergence Particle Swarm Optimization with Gaussian Mutation (GPSO-GM) algorithm for solving a power flow for islanded microgrids which considers the system frequency as a load flow variable due to the non-existence of a slack bus. Similar study was realized in (Agundis-Tinajero et al., 2019) without the use of an heuristic algorithm where secondary frequency control fixes the phase angle reference. Additionally, a linearization of the power flow problem as presented in (Ahmadi et al., 2016) and (Garces, 2016) allows to include applications based on convex optimization (Boyd and Vandenberghe, 2004), optimal power flow and distribution system dynamics. Nevertheless, the principal objective of these studies is to apply convex optimization to optimal power flow problems and economic dispatch.

Finally, a variety of methodologies were followed in order to implement an optimal load shedding in islanded microgrids (Bakar et al., 2017). In (Khamis et al., 2018) a backtracking search algorithm was used to implement the a load shedding scheme. However, in (Wu et al., 2017) a sub-gradient-based method for the distributed coordination load shedding, which is demonstrated to have better performance, was proposed. However, this type of methodologies are more a concern of tertiary control.

1.4 Receding horizon-based sequential convex optimization problem

A methodology for the solution of secondary problem issues, including the network parameters, generation capabilities and following the requirements

[1]Although the terms model predictive control and receding horizon are usually considered synonyms, the former is more common for linear models with quadratic functions.

mentioned in Section 1.1, can be presented with a receding horizon approach. Besides, the islanded operation mode characteristics may be taken into account by this methodology as well as the selected tools that are capable of providing feasible results, such as convex optimization

In this case, the proposed methodology for solving the secondary control problem, for a microgrid under the definition shown in Section 1.2, is a receding-horizon-based sequential convex optimization approach. This approach, implemented as a convex optimization problem, allows the inclusion of the system parameters as well as the capability limits of electronic converters and the variation of the frequency provoked by a network disconnection. As shown deeply in Section 5.1, a receding horizon strategy solves an optimization problem in a certain time interval which, at the same time, allows an approach of a hierarchical control architecture (see Chapter 2) including a secondary control strategy that considers the dynamics of the primary control and the steady state operation given by tertiary control. Furthermore, a convex optimization problem guarantees a global optimum for each step and uniqueness in every solution.

1.5 Contributions

A convex optimization approach for the secondary control of microgrids is presented. The main objective is that both, voltage and frequency of the microgrid, can be carried out to their nominal values, taking into account the limits of capacity of distributed resources. The model has to demonstrate to be accurate. The model takes into account the fast dynamics of the primary control and the stationary state set points given by the tertiary control. In each iteration, the power flow as well as the optimization model obtains convergence. The model considers variations of the Y_{BUS} matrix with the frequency. The results, showed in Chapter 6, states that the algorithm reduces successfully the frequency deviation for all the converters around their nominal value. Furthermore, the steady state frequency is the same for all converters.

This thesis proposes a receding horizon strategy based on a convex optimization model for the secondary control in microgrids. The main contributions can be summarized as:

- A power flow method for island operation of microgrids considering variations on the frequency. This model considers a new concept named centroid which is closely related to the center of inertia, commonly used in power systems applications. The centroid allows to define a reference point in system with low inertia using the droop constants of the converters.

- A receding horizon strategy that considers both the effects and constraints of the primary and the tertiary control. In this way, capability of the primary resources is included directly into the model.

- A convex optimization model for the receding horizon scheme that can be solved in every time-step. Because it is a convex model, it guarantees global optimum and convergence of the algorithms in each time step.

The proposed strategy allows a better understanding of the relation among the dynamics of primary/secondary and tertiary controls.

1.6 Structure of the thesis

The rest of the thesis is organized as follows: Chapter 2 describes the main characteristics of the hierarchical control as well as the mathematical models required thereof and a brief introduction to microgrids stability. Chapter 4 presents the model implemented for the secondary control considering heterogeneity in the generation, islanded operation mode, operation control and a control strategy considering variations on the frequency. Next, the proposed centralized secondary control is presented with a receding horizon approach in Chapter 5. Results are presented in Section 6 followed by conclusions in Section 7 and relevant references.

Chapter 2

Control architecture

Electrical systems include several strategies of control for every portion of the system from the generation to the consumption. In the case of smart-grids as they must include connected or islanded operation mode, the control architectures must include local actions in each converter and also actions at system level in order to guarantee a proper performance. A hierarchical control structure is proposed to deal with this challenge as it includes a primary, secondary and tertiary layers that solves different problems as they communicate with each other.

In this chapter a hierarchical control structure for microgrids is presented. In section 2.1 a general view of a hierarchical control structure is shown while in Section 2.2 a sub-layer called Level-0 control is presented. Sections 2.3, 2.4 and 2.5 show the main views of primary, secondary and tertiary control layers, respectively.

2.1 Hierarchical control

In traditional power systems, each generator has several control mechanisms such as the speed governor and the automatic voltage regulator (AVR), excitation, among others, which are in charge of controlling the power generator independently if it is a hydro or thermal generator. Then, despite a primary, secondary and tertiary controls are included to guarantee a stable operation of the main grid the majority of control actions are made locally in every generator. Figure 2.1 shows the traditional time frame on a power systems for a frequency variation.

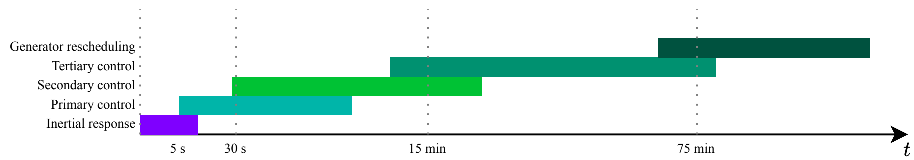


Figure 2.1: Hierarchical control time scale in a traditional power system when a disturbance at $t = 0s$ is presented Milano et al. (2018)

In order to ensure the proper operation of a microgrid, when this is disconnected from the main network, a hierarchical control scheme, based on the traditional control scheme of a power system, is required. A hierarchical control has four levels of control, namely: level-0, primary, secondary and tertiary control.

Level-0 control is the intern control for a electronic converter that can control active, reactive, voltage or frequency, depending on the control variable. It is important to mention that the generation in a microgrid, considering the level-0 control, is heterogeneous since all level-0 controls can be different and for this reason a microgrid can be more versatile, and also more challenging, regarding the traditional system. Primary control is in charge of taking the system to a feasible operation point while secondary control, under a centralized or distributed approach, carries the system to the nominal values of frequency and voltage. On other hand, tertiary control aim is to guarantee the steady state optimal operation of the grid taking into account both market and system constraints. Figure 2.8 shows an example about the interaction between all control layers by measured and control signals. The interaction among all controls layers and their time-frame are important to obtain a suitable model as will be presented later in Section 4.1. Unlike traditional power systems where the main concern of control is the time-frame of each layer, as shown in Figure 2.1, the performance of every control layer in a microgrid considers also the active power injected. This can be seen in Figure 2.2 where a hierarchical control time scale in microgrids is explained.

In this Chapter the definition of each control layer is shown. The definition of Level-0 control can be seen in 2.2, 2.3 for Primary control, 2.4 for secondary control and tertiary control definition can be found in 2.5.

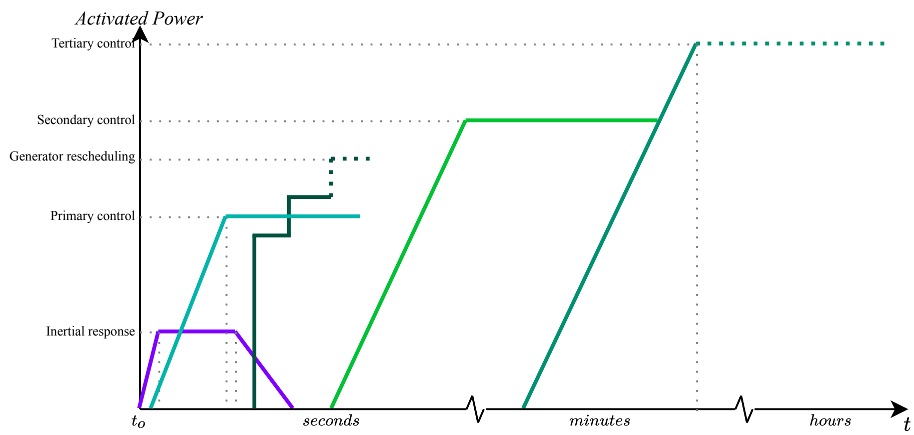


Figure 2.2: Hierarchical control time scale in microgrids with actived power when a disturbance occurs at t_o. Taken from Bevrani and Raisch (2017)

2.2 Level-0 control

Distributed energy resources such as renewable sources and energy storage devices require a voltage source converter to be integrated to the microgrid as depicted in Figure 2.3. These converters in turns, require a level-0 control for the active power, reactive power, voltage or frequency. There are different approaches for this control, two of the most popular are the vector oriented control (Teodorescu et al., 2011) and the PQ theory (Akagi et al., 2011). Furthermore, passivity-based control has been also proposed to integrate distributed energy resources to microgrids (Montoya et al., 2018). The dynamic performance of these controls are fast enough to be neglected in the model of the secondary control. However, the stationary state performance and the control limits require to be analyzed.

Energy storage devices are represented by energy balance equations as follows:

$$E^{\text{min}}_{\text{battery}} \leq E^{k}_{\text{battery}} \leq E^{\text{max}}_{\text{battery}} \tag{2.1}$$

$$P^{\text{min}}_{\text{battery}} \leq P^{k}_{\text{battery}} \leq P^{\text{max}}_{\text{battery}} \tag{2.2}$$

$$E^{k}_{\text{battery}} = E^{\text{k-1}}_{\text{battery}} - P^{k}_{\text{battery}} \Delta t \tag{2.3}$$

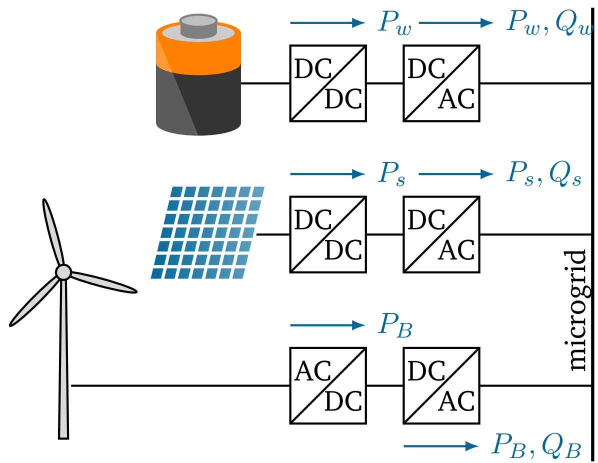


Figure 2.3: Integration of different distributed resources through voltage-source converters.

where E^k_{battery} is the energy stored in the battery and P^k_{battery} the power interchanged with the grid in each time step k. Notice this power can be positive or negative, since the battery can be in charging or discharging. Notice also that this model is general for any energy storage device including superconducting magnetic energy storage, flywheels and supercapacitors.

The model of renewable resources such as solar panels and wind turbines, are represented by their capacity as follows:

$$0 \leq p + \Delta p \leq p^{\max} \tag{2.4}$$

where the maximum power $p^{\max}$ is the available power given by the primary resource.

For the reasons previously mentioned, and as a fundamental component to add distributed resources to a microgrid, the electronic converter becomes an important structure for microgrids behavior.

2.3 Primary control

The primary control is the control action carried out by local controllers at the load/grid power converters. This control takes the system to a stable equilibrium point while ensuring that voltage and frequency tracks their set points in a time-frame of 50ms. Since the primary control is faster than secondary and tertiary controls, it includes islanded detection, power sharing and output control (Yazdanian and Mehrizi-Sani, 2014).

There are a few strategies for the primary control depending if the network is operating in grid-connected mode or islanded from it. First, the centralized primary control operation is based on a master-slave strategy where a converter operates in voltage control mode as a master and all the other converters operate in PQ mode as slaves current source converters. Here, by using droop control, the master converter addresses the references of frequency and voltage. Then, all of the slave convertes inject active and reactive power taking into account the reference points given by the central controller. It is important to mention that in grid-connected mode it exist the possibility that a lot of converters are able to operate in PQ mode since the main grid determines the frequency and voltage.

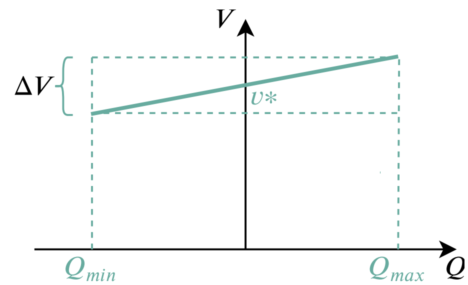
On the other hand, $P-f$ and $Q-V$ represent the classical droop method which is in charge of the frequency and voltage regulation when the network is operating in islanded mode. The relation of active power and frequency and reactive power and voltage can be seen in Figure 2.4. The droop method imitates the inertial behavior of a synchronous machine in order to balance the difference between generation and demand while the frequency is stabilized. So, the $P-f$ control reduces the frequency to increase the injected active power while the $Q-V$ reduces the voltage magnitude in order to allow the increasing of reactive power.

Droop controls for voltage and frequency are considered, by Equations (2.5) and (2.6), below:

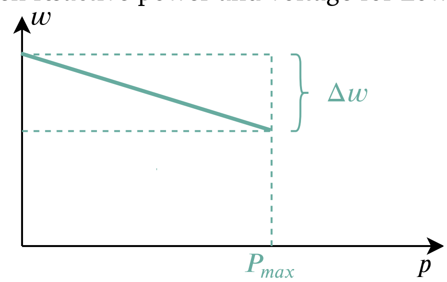
$$\xi_k(p_k - \bar{p}_k) + \omega_0 = \omega_k \tag{2.5}$$

$$\zeta_k(q_k - \bar{q}_k) + \bar{v}_k = v_k \tag{2.6}$$

where $\bar{p}_k, \bar{q}_k, \bar{v}_k$ are reference values given by the tertiary control and ξ_k, ζ_k are the droop constants given by the primary control. ω_0 is the nominal frequency and p_k, q_k, v_k, ω_k are variables in the model (i.e active power, reactive power, voltage and frequency).



(a) Relation between Reactive power and voltage for Low-voltage microgrids



(b) Relation between Active power and frequency for Low-voltage microgrids

Figure 2.4: Relation for $P - f$ and $Q - V$ droop control in low-voltage microgrids. 2.4a shows the $Q - V$ droop control relation. 2.4b indicates that for a reduction or increase of the system frequency the active power injected to the microgrid system increases or decreases, respectively. It is worth to highlight that, in islanded operation, the active power is limited for the generation capabilities of each distributed energy resource.

2.4 Secondary control

Microgrids are systems that, different from the traditional power system, are more susceptible to voltage and frequency variations since they operate even in islanded mode. Therefore, the system response to a disturbance is more challenging due to the lack of inertia if distributed energy resources are considered. Furthermore, a microgrid includes power electronic devices that are not included in traditional power systems.

As seen in Section 2.3, primary control carries frequency and voltage variables to a stable point which is necessarily not the nominal values. The main objective of secondary control is to restore frequency and voltages from stable to nominal values after a change of load and/or generation and even if the microgrid is disconnected from the main grid. Secondary control is the intermediate control layer between primary and tertiary control. It takes measured signals from primary control and give them to the tertiary control. The latter, that is in charge of guarantee a proper steady state operation (see Section 2.5), gives a range of possibilities to secondary control for it to generate new set points, as a control signal, for primary control.

Secondary control, as a slower dynamic control in respect to primary control, is responsible for power quality improvement since it provides the new set points for the primary control while taking into account the frequency and voltage variations provoked when the grid starts operating in islanded mode. The power injections of every distributed resource must be established taking into account, also, limits of capability from the primary resources as well as grid codes. Besides, the secondary control requires to take into account the droop constant and the frequency of the primary control and, also, the set points given by the tertiary control which is an stationary state optimal power flow (see Section 2.5). Therefore, some general aspects of the primary and the tertiary control require to be represented in the model.

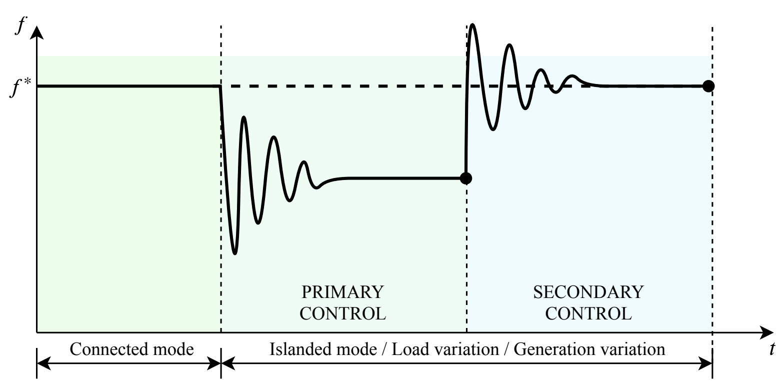


Figure 2.5: Microgrids frequency behavior considering primary and secondary control under a frequency variation.

Figure 2.5 shows the behavior of the frequency, considering primary and secondary control, when it is disconnected from the main grid or, a generation or load variation, is presented. When a frequency variation appears primary control stabilizes it, whether or not in the nominal value f^*. Then, secondary control, considering the reached stable point and the operation capabilities, granted by tertiary control, gives a new series of set points in order to increase or decrease power generation and, in that way, carry the system frequency to f^*.

Despite the inclusion of power electronic devices, a microgrid has low inertia properties and its generation capacity is limited. Thus, a small change on the microgrid load has a powerful impact on the systems frequency.

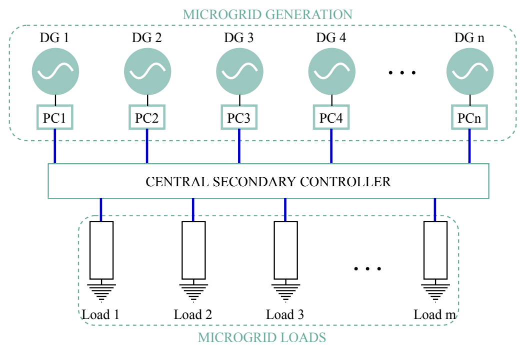
Depending in the nature of its operation the secondary control can be centralized or decentralized (Sahoo et al., 2018). The decentralized strategy allows a communication between all of the DG units in a microgrid when they are distributed in a wide area without the necessity of a central controller. Decentralized controllers reduce the economical impact of a large scale communications system and allow some ”plug and play” properties. Nevertheless, a decentralized control strategy can have complications when it is implemented in large-scale networks considering that every distributed generator, connected to the grid by a power converter, can only stabilize its own power injection, voltage and frequency (Xin et al., 2014) (Xin et al., 2011). In that way, for a non-coordinated stabilization of the grid, power balance can not be guaranteed. Some contributions in decentralized secondary control can be seen listed in Table 1.2

On the other hand, a centralized approach for the secondary control, coordinates all DG units preserving the same frequency for all of them. The key features of a centralized approach for the secondary control are active power management, voltage control, reactive power management, frequency restoration and harmonic cancellation. Important contributions in a centralized approach for the secondary control can be seen in Table 1.1 in Section 1.3.

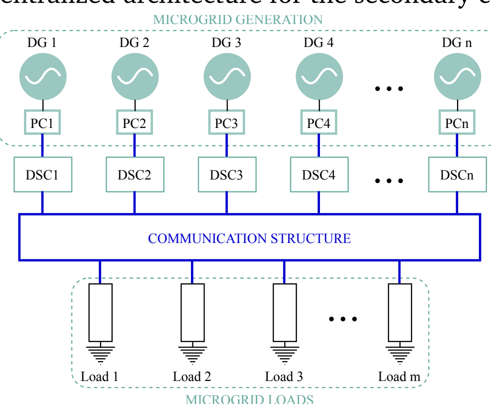
Figures 2.6a and 2.6b shows the two main secondary control strategies architectures. In both, 2.6a and 2.6b, figures a set of n distributed generators are in charge to supply electricity to m loads.

For both strategies, the central controller in the case of a centralized approach and every decentralized secondary controller (DSC), have to analyze data from the generation, energy storage and loads in order to manage the energy and give control signals to every primary controller (PC) for them to take the system to its nominal values of frequency and voltage.

In both cases a communication structure is required but for decentralized approaches each DSC has to communicate with the others to avoid that



(a) Centralized architecture for the secondary control



(b) Decentralized architecture for secondary control

Figure 2.6: Secondary control main architectures. 2.6a shows the centralized architecture and 2.6b shows the decentralized architecture.

everyone stabilizes separately. The control models implemented may also guarantee a real time operation. Then, the time frames including the time delays of communication structures must be considered. Figure 2.7 shows the objectives and time-frame of each of these control layers.

2.5 Tertiary control

The tertiary control is a widely studied aspect of electrical systems (Ilic et al., 1995), which is the slowest control layer that can be summarized as an optimization problem related to the steady operation of the network. This optimization problem deals with economic related problems such as optimal dispatching, operation scheduling, unit commitment and optimization

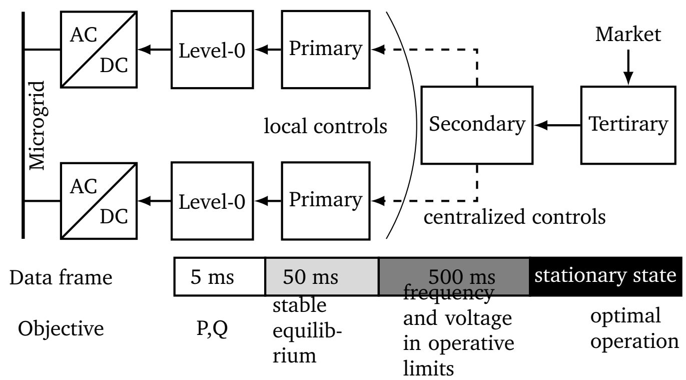


Figure 2.7: Schematic representation of the hierarchical control for island operation of microgrids.

for different objectives. Tertiary control is in charge of managing the active power exchange between de microgrid and the main grid when the microgrid is operating in connected mode. On the other hand, for islanded mode, tertiary control is in charge of the management of the available resources. Then, the tertiary control is considered, in many cases, as an optimal power flow problem that can be defined as follows by considering minimization of operation costs or power losses reduction, namely:

$$
\begin{aligned}
\textbf{minimize} \quad & \text{Costs or Power Losses} && (2.7)\\
\textbf{subject to} \quad & \text{Grid constraints} && (2.8)\\
& \text{Energy Balance} && (2.9)\\
& \text{Energy storage systems constraints} && (2.10)\\
& \text{Voltage Regulation} && (2.11)\\
& \text{Generation capabilities} && (2.12)
\end{aligned}
$$

The objective equation (2.7) can be established in two ways: costs reduction or power losses reduction. For the costs reduction, the information of energy costs given by the network operator is required while for the power losses reduction, it is enough to consider the physical and electrical characteristics of the grid. Network constraints (2.8) addresses the line capacities and physical characteristics of the grid and (2.9) guarantees the energy bal-

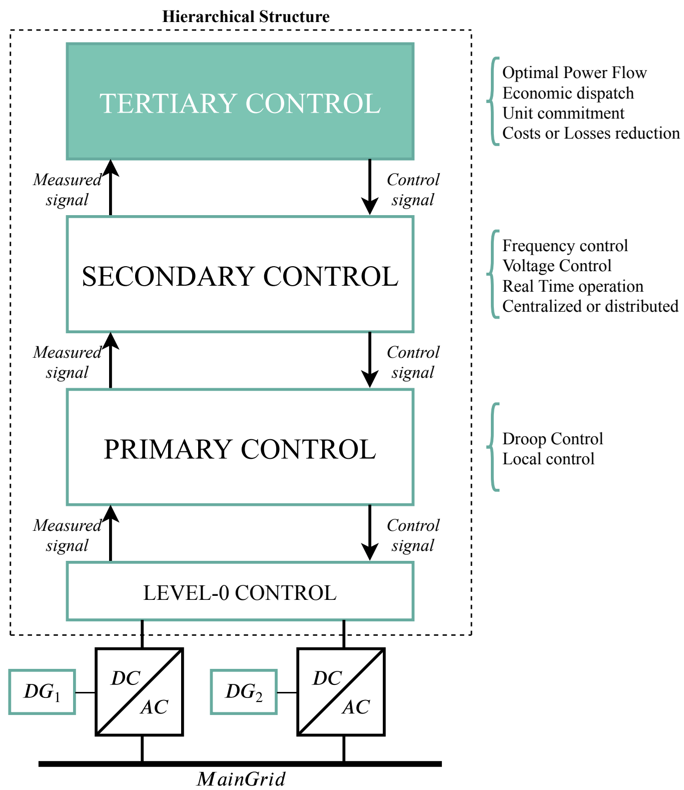


Figure 2.8: Signals flow between a hierarchical control scheme

ance in all nodes. When storage systems are considered, several constraints (2.10) related to the state of charge, storage capacities and life time, must be included. Voltage regulation constraint (2.11) forces the voltages in all buses to be in an allowed range usually between 0.95 and 1.05 times the nominal voltage while constraint (2.12) limits the power generation taking into account the capabilities of the generators.

On the other hand, Figure 2.8 shows the information flow between all control layers where tertiary control sets the path of control signals for secondary, primary and level-0 controllers.

Tertiary control, as an optimal power flow with different objectives alongside a hierarchical control structure, has been used for several issues in traditional power systems operation, standalone microgrids (Zhao et al., 2013) and also for DC networks (Mohamed et al., 2017). It also contributes to global power quality optimization when a hierarchical control structure is implemented to realize optimal voltage unbalance compensation in islanded microgrids (Meng et al., 2014). Furthermore, tertiary control can be considered as an stochastic optimization problem due to the variability in the load and the primary resource when renewable distributed generation is included (Vergara et al., 2020) (Olivares et al., 2015) (Silani and Yazdanpanah, 2019) (Lara et al., 2019).

2.6 Microgrids Stability under a hierarchical control structure

As presented in Section 1.2, microgrids have become a widely studied subject for nowadays and future development of electric grids. However, due to their complexity, many analysis involving control, operation and stability are very challenging specially when islanded operation mode is considered. Then, many approaches to these problems are considered emulating the behavior of traditional power systems.

Section 2.1 shows the main operating properties of a hierarchical control in islanded microgrids which is similar to electric power systems. However, the stability problem is considerably different for microgrids since the system size is smaller than conventional power systems, the feeders are shorter and, thus, lower reactance to resistance ratio which provokes a different dynamic performance in comparison to electric power systems. Stability analysis in microgrids, differently from power systems, can be seen as a variation in all of the system variables especially when islanded operation mode is considered. This, as a result of the strong bond, especially, between voltage and frequency. Here, the characteristics of both voltage and frequency stability are discussed.

2.6.1 Voltage stability

Due to the small size of microgrids compared to power systems, the voltage drops between nodes is considerable smaller since larger transmission lines limits the power transfer between generation and loads (Farrokhabadi et al., 2017). Nevertheless, principally in older grids evolving into smartgrids voltage drops may cause several issues. Therefore, control designs must consider this problem in order to preserve voltage regulation also considering that a change of voltage in terminals of energy sources are rapidly reproduced in all of the system and, thus, properly configured voltage-reactive power (QV) droop, as shown in Section 2.3. Thereby, as an emulation of multiple generators in traditional power systems, the voltage in the terminals of a energy resource decreases linearly while reactive power increases the reactive power control; this is linked directly to the energy resource instead of FACTS, OLTCS which are not tipically considered in microgrids.

2.6.2 Frequency stability

Differently from bulk power systems where voltage stability analysis are more relevant, frequency stability in microgrids is a major challenge. This is given by the lack of inertia in the system, low quantity if generation and the stochastic behavior of the primary source in every distributed energy resource. Here, a small modification of either load or generation may result in large stability issues. Moreover, even in the present of sufficient generation reserve, traditional techniques for frequency control are not fast enough to deal with frequency stability problems (Hajimiragha et al., 2015).

The strong coupling between voltage and frequency, the variation of the reactance to resistance ratio and small size of the network the voltage varies in all of the grid, including load nodes, when reactive power is modified in the generation terminals which may result in frequency instabilities due to the low inertia of the system (Farrokhabadi et al., 2019). In this case, the absence of generation reserve may cause the frequency to be outside the feasible ranges. For this reason, coordinated control schemes that preserves frequency stability inside feasible ranges while guaranteeing a proper voltage regulation in the system have to be proposed.

2.6.3 Defintion of stability in microgrids

Despite the behavior of microgrids components are modeled similarly to electric power systems, the stability analysis is different since there are many differences between microgrids and conventional power systems. The main contrast lays in the low reactance to resistance ratio given by the radically smaller size of microgrids compared to power systems. Even more, microgrids include renewable energy sources that depend on the stochastic behavior of the primary resource. Also, the fitful behavior of renewable energy sources and reduced load numbers, considering also that the power injections are made by electronic power converters with small inertia, makes the stability analysis even more challenging. As microgrids must also operate in islanded mode, a small configuration modification in the grid may result in larges voltage and frequency deviations. Then, control and operation strategies not only have to take voltage and frequency near to their nominal value but also have to guarantee frequency and voltage stability in microgrids especially in islanded operation.

A microgrid, as the one shown in Figure 1.1 is considered stable following the previous mentioned concepts if, after a disturbance, all of the steady state variables are preserved. Also, new steady state variables can be achieved as long as they are kept in the operational constraints. A disturbance can be considered as any external input which can be load modifications, component breakdown or even operational set-point adjustments for the power converters (Farrokhabadi et al., 2019). However, due to the particular characteristics of microgrids, stability can be analyzed under different approaches. In traditional power systems voltage stability issues happen more frequently, as shown previously, than frequency stability issues. However, in islanded microgrids is harder to maintain the frequency due to the absence of inertia in the system and the high penetration of renewable generation.

Despite stability is mainly dominated by primary control in electric systems, as the control with fastest response for a disturbance in the system, secondary control must be designed in order to generate feasible set points to primary control which also guarantees stability of all variables, in particularly for microgrids.

Chapter 3

Microgrids Stability

As presented in Section 1.2, microgrids have become a widely studied subject for nowadays and future development of electric grids. However, due to their complexity, many analysis involving control, operation and stability are very challenging specially when islanded operation mode is considered. Then, many approaches to these problems are considered emulating the behavior of traditional power systems.

Chapter 2 shows the performance of a hierarchical control in islanded microgrids which is similar to electric power systems. However, the stability problem is considerably different for microgrids since the system size is smaller than conventional power systems, the feeders are shorter and, then, lower reactance to resistance ratio which provokes a different dynamic performance in comparison to electric power systems. In this chapter, a brief introduction to stability analysis for islanded microgrids is presented. Section 3.1 shows two main approaches for stability in microgrids comparing them to power systems stability. Section 3.2 shows the main definition of stability given by authors in microgrids.

3.1 Stability

Stability analysis in microgrids, differently from power systems, can be seen as a variation in all of the system variables especially when islanded operation mode is considered. This, as a result of the strong bond, especially, between voltage and frequency. Here, the characteristics of both voltage and frequency stability are discussed.

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Chapter 4

Dynamic model of the grid

In previous chapters, a general overview a microgrids including 4 main features, for it to be considered a microgrid, is presented. Those features, heterogeneity, islanded operation mode, control strategies and operation control, must be included for a study of secondary control in islanded microgrids. Also, a hierarchical control architecture was presented.

In this chapter, the model implemented for the secondary control considering heterogeneity in the generation, islanded operation mode, operation control and a control strategy, is presented as a dynamic model of the grid, considering that the latters parameters varies with the change of the frequency. In Section 4.1 the grid model is introduced while in Section 4.2 a methodology for the implementation of an islanded power flow is presented.

4.1 Grid model

The grid is represented as a connected graph where every node k is connected to, at least, other node; i,e, an isle inside the microgrid is not considered. Figure 4.1 shows the analysis made in one node.

Also, with admittance matrix $[y_{km}] = [g_{km} + jb_{km}] \in \mathbb{C}^{n\times n}$ where n is the number of nodes considering the PI line model of Figure 4.2. A PI model is considered in distribution systems because the capacitive effects of cables and converter filters may became important and, thus, must be included in the grid model. Loads and step nodes are eliminated by a Kron's reduction in order to obtain a system that only include nodes with controllable resources. When the connected mode is considered the frequency is imposed by the main grid. However, in islanded mode, every controllable resource must find

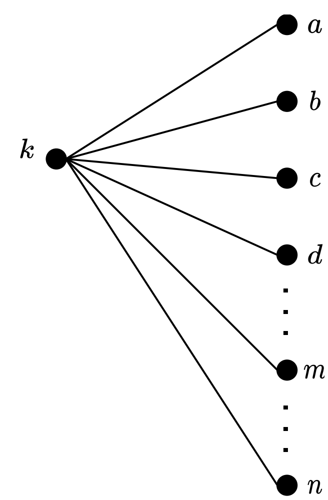

Figure 4.1: Connected graph example

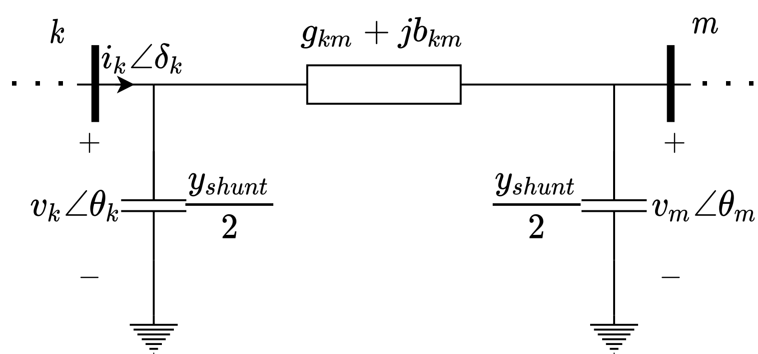

Figure 4.2: PI line model considered for the distribution system,

their own frequency; in this case the frequency for all controllable resources must be the same to guarantee the precise operation of the network. The nodal current for every node k is given by (4.1).

$$i_k e^{\delta_k} = \sum_{m=1}^{n} (g_{km} + jb_{km}) v_m e^{j\theta_m},\ \forall k \in \{1, 2, \ldots, n\} \tag{4.1}$$

Droop controls for voltage and frequency are considered by Equations (2.5) and (2.6). It is important to remark that the microgrid is operated in island model and hence, the admittance matrix depends on the frequency.

There is not slack node and therefore, the center of inertia of the system is considered in Equation (4.2) for the angle and in Equation (4.3) for angular frequency.

$$\theta_{CI} = \frac{\sum_{k=1}^{n} \xi_k^{-1}\theta_k}{\sum_{k=1}^{n} \xi_k^{-1}} \tag{4.2}$$

$$\omega_{CI} = \frac{\sum_{k=1}^{n} \xi_k^{-1}\omega_k}{\sum_{k=1}^{n} \xi_k^{-1}} \tag{4.3}$$

Considering Equations (2.5) and (2.6) and the Equation (4.1) of nodal currents, the active and reactive power injected at each node is obtained in terms of the droop constants, as follows:

$$\bar{p}_k + \frac{1}{\xi_k}(\omega_0 - \omega_{CI}) = \sum_{m=1}^{n} g_{km} v_k v_m \cos(\theta_{km}) \tag{4.4}$$

$$+ \sum_{m\in\mathcal{N}} b_{km} v_k v_m \operatorname{sen}(\theta_{km}) \tag{4.5}$$

$$\bar{q}_k + \frac{1}{\zeta_k}(\bar{v}_k - v_k) = \sum_{m=1}^{n} g_{km} v_k v_m \operatorname{sen}(\theta_{km})$$

$$- \sum_{m=1}^{n} b_{km} v_k v_m \cos(\theta_{km}) \tag{4.6}$$

$$\theta_{CI} = 0 \tag{4.7}$$

$$\omega_{CI} = \frac{\sum_{k=1}^{n} \bar{p}_k - p_k}{\sum_{k=1}^{n} \xi_k^{-1}} + \omega_0 \tag{4.8}$$

This set of non-linear equations constitutes the model of the grid including the effect of the primary control. $\bar{p}_k$ and $\bar{q}_k$ are the active and reactive power references, respectively, for every k node of the system. ω_0 is the frequency reference while ω_{CI} is the center of inertia for angular frequency from Equation (4.3) which can be also considered as in Equation (4.8).

4.2 Islanded Load flow

Traditional power flow considers the relation between the variations of active power and reactive power with angle and voltage variations taking into account the Jacobian matrix. Equation (4.9) shows this relation were ΔP and ΔQ represent the variation of active and reactive power, respectively, and $\Delta\theta$ and ΔV the variation of angles and voltages while J concern to the Jacobian matrix.

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = J \begin{pmatrix} \Delta\theta \\ \Delta V \end{pmatrix} \tag{4.9}$$

where,

$$J = \begin{pmatrix} D^{p\theta} & D^{pv} \\ D^{q\theta} & D^{qv} \end{pmatrix} \tag{4.10}$$

It is important to mention that Equation (4.9), considering the Jacobian structure shown in Equation (4.10), is the traditional power flow equation when the microgrid is in connected mode.

For the secondary control approach, considered for islanded microgrids in this document, two new variations must be included since smart distribution systems require to assure the proper performance of the network even in island mode. The main characteristics to consider in a microgrid operating under this mode are the absence of a slack bus that maintains fixed voltage and frequency and the inclusion of renewable generation connected to the microgrid by a electronic converters. A frequency-dependent load flow is then required to determine the operation point including frequency variations (Bravo et al., 2019). A Newton's method is proposed with a linearization given by (4.11).

$$\begin{pmatrix} \Delta p \\ \Delta q \\ \Delta\theta_{CI} \end{pmatrix} = J \begin{pmatrix} \Delta\theta \\ \Delta v \\ \Delta\omega_{CI} \end{pmatrix} \tag{4.11}$$

Here, two new variables are added to the problem. $\Delta\theta_{CI}$ represents the variation of the voltage angles respect to the center of inertia of Equation 4.7 and $\Delta\omega_{CI}$ considers the variation of angular frequency of Equation 4.8 for all of the nodes with an associated electronic converter.

Also, for the proposed seconday control approach, the effects of primary and tertiary controls must be contemplated. Equation (4.11) can be expressed as shown as in Equation (4.12) where the droop control is considered by the inclusion of ξ and ζ by Equations (2.5) and (2.6).

$$\begin{pmatrix} \bar{p}_k + \frac{1}{\xi_k}(\omega_0 - \omega_{CI}) \\ \bar{q}_k + \frac{1}{\zeta_k}(\bar{v}_k - v_k) \\ \Delta\theta_{CI} \end{pmatrix} = J \begin{pmatrix} \Delta\theta \\ \Delta v \\ \Delta\omega_{CI} \end{pmatrix} \tag{4.12}$$

Furthermore, considering the definition given in Section 2.4 for the secondary control, a modification in the set points for every electronic converter associated to a renewable generation unit, is required. Then, two variables are added to Equation (4.12) as presented in Equation (4.13).

$$\begin{pmatrix} \bar{p}_k + \frac{1}{\xi_k}(\omega_0 - \omega_{CI}) + \Delta p_{\text{sec}} \\ \bar{q}_k + \frac{1}{\zeta_k}(\bar{v}_k - v_k) + \Delta q_{\text{sec}} \\ \Delta\theta_{CI} \end{pmatrix} = J \begin{pmatrix} \Delta\theta \\ \Delta v \\ \Delta\omega_{CI} \end{pmatrix} \tag{4.13}$$

Variables ΔP_{SEC} and ΔQ_{SEC} are the ones that the optimization problem shown in Section 5.2 requires to find in order to reduce frequency deviation to its minimum. J corresponds to the Jacobian matrix associated to the set of non-linear Equations (4.4) to (4.8). This matrix given by (4.14).

$$J = \begin{pmatrix} D^{p\theta} & D^{pv} & \operatorname{diag}(1/\xi) + D^{p\omega} \\ D^{q\theta} & D^{qv} + \operatorname{diag}(1/\zeta) & D^{q\omega} \\ -\operatorname{diag}(1/\xi) & 0 & 0 \end{pmatrix} \tag{4.14}$$

The elements $D^{p\theta}$, D^{pv} and $D^{q\theta}$ are calculated as the usual load flow problem, taking into account the variation of the Y_{BUS} in terms of the frequency. Terms D^{qv}, $D^{q\omega}$ and $D^{p\omega}$ correspond to the variation of active and reactive power as function to voltages and frequency. Matrices $\operatorname{diag}(1/\zeta)$ and $\operatorname{diag}(1/\xi)$ represent the droop constants.

Equations for active and reactive power in every node for an electric network connected to an infinite bus can be represented with Equations (4.15) and (4.16) below:

$$P_N = fp\,(V, \theta, Y_{bus}) \tag{4.15}$$

$$Q_N = fq\,(v, \theta, Y_{bus}) \tag{4.16}$$

Hence, the Jacobian matrix that relates active and reactive power with voltages and anlges is given by Equation (4.17):

$$J = \begin{pmatrix} \frac{\partial f_P}{\partial \theta} & \frac{\partial f_P}{\partial v} \\ \frac{\partial f_Q}{\partial \theta} & \frac{\partial f_Q}{\partial v} \end{pmatrix} \tag{4.17}$$

When islanded microgrids are considered, a primary control, as presented in Section 2.3, may be considered. Accordingly, variables P_N and Q_N are modified. Equations (4.18) and (4.19), listed as follows, includes classical droop control constants for primary control:

$$P_{ref} + \frac{1}{\xi}(\omega - \omega_o) - fp\,(v, \theta, Y_{bus}(\omega)) = f_1 \tag{4.18}$$

$$Q_{ref} + \frac{1}{\zeta}(\bar{V} - V_{ref}) - fq\,(v, \theta, Y_{bus}(\omega)) = f_2 \tag{4.19}$$

$$\sum \frac{1}{\xi_i}\theta_i = \frac{1}{\xi}^T \theta = f3 \tag{4.20}$$

Variables P_{ref} and Q_{ref} of Equations (4.18) and (4.19), respectively, vary with every loop of the optimization algorithm showed in Section 5.2. As the optimization algorithm finds the optimal modification of the set points in every DER converter, i.e ΔP_{SEC} and ΔQ_{SEC}, in order to improve frequency and voltage profiles, then, the P_{ref} and Q_{ref} values are given by Equations (4.21) and (4.22), below:

$$P_{ref(k)} = P_{ref(k-1)} + \Delta P_{SEC(k)} \tag{4.21}$$

$$Q_{ref(k)} = Q_{ref(k-1)} + \Delta Q_{SEC(k)} \tag{4.22}$$

Hence, as a new variable ω is added to the problem, the Jacobian matrix considering frequency variations is show in the form of (4.23):

$$J = \begin{pmatrix} \frac{\partial f_1}{\partial \theta} & \frac{\partial f_1}{\partial v} & \frac{\partial f_1}{\partial \omega} \\ \frac{\partial f_2}{\partial \theta} & \frac{\partial f_2}{\partial v} & \frac{\partial f_2}{\partial \omega} \\ \frac{\partial f_3}{\partial \theta} & \frac{\partial f_3}{\partial v} & \frac{\partial f_3}{\partial \omega} \end{pmatrix} \tag{4.23}$$

Therms $\frac{\partial f_1}{\partial \theta}$, $\frac{\partial f_1}{\partial v}$ and $\frac{\partial f_2}{\partial \theta}$ are calculated as the traditional Newton's power flow method while the rest are calculated as follows:

$$\frac{\partial f_1}{\partial \omega} = \frac{1}{\xi} - \frac{\partial f_p}{\partial \omega} \tag{4.24}$$

$$\frac{\partial f_2}{\partial v} = \frac{1}{\zeta} - \frac{\partial f_q}{\partial v} \tag{4.25}$$

$$\frac{\partial f_2}{\partial \omega} = -\frac{\partial f_q}{\partial \omega} \tag{4.26}$$

$$\frac{\partial f_3}{\partial \theta} = (\frac{1}{\xi}) \tag{4.27}$$

$$\frac{\partial f_3}{\partial v} = 0 \tag{4.28}$$

$$\frac{\partial f_3}{\partial \omega} = 0 \tag{4.29}$$

In order to find the terms $\frac{\partial f_p}{\partial \omega}$ and $\frac{\partial f_q}{\partial \omega}$, the term $\frac{\partial Y_{bus}(\omega}{\partial \omega}$ must be computed. Here, consider that $Y_{bus}(\omega)$ is given by (4.30):

$$Y_{bus}(\omega) = A(j\omega L + R)^{-1}A^T + j\omega C \tag{4.30}$$

Also, renaming the term $(j\omega L + R)^{-1}$, Equation (4.31) is proposed:

$$Y_o(\omega) = (j\omega L + R)^{-1} \tag{4.31}$$

Therefore, the derivative of the Y_{bus} matrix respect to ω can be found by deriving the latter equation as presented in Equation (4.32):

$$\frac{\partial Y_{bus}(\omega)}{\partial \omega} = A\frac{\partial Y_o(\omega)}{\partial \omega}A^T + jC \tag{4.32}$$

From Equation (4.32), Equation (4.33) is obtained where 1_N represents the identity matrix:

$$(j\omega L + R)Y_o(\omega) = 1_N \tag{4.33}$$

Hence, $\frac{\partial Y_o}{\partial \omega}$ can be calculated easily as follows:

$$0 = (j\omega L + R)\frac{\partial Y_o(\omega)}{\partial \omega} + jLY_o \tag{4.34}$$

$$\frac{\partial Y_o(\omega)}{\partial \omega} = -(j\omega L + R)^{-1}jLY_o \tag{4.35}$$

$$\frac{\partial Y_o(\omega)}{\partial \omega} = -Y_o jLY_o \tag{4.36}$$

by substituting Equation (4.36) in (4.32), the expression (4.37) can easily help to calculate expressions $\frac{\partial f_p}{\partial \omega}$ and $\frac{\partial f_q}{\partial \omega}$ from the modified Jacobian matrix:

$$\frac{\partial Y_{bus}(\omega)}{\partial \omega} = -AY_o jLY_o A^T + jC \tag{4.37}$$

Finally, several advantages can be extracted from the islanded power flow. The variation of the Y_bus matrix, modified by a variation on the frequency, followed by the inclusion of the primary control dynamics allow several advantages. Then, the proposed power flow can be seen as a block, as shown in Figure 4.3, that takes data from the grid and release signals that can be processed by many applications; in this way, it can result on being a fundamental part of a control strategy.

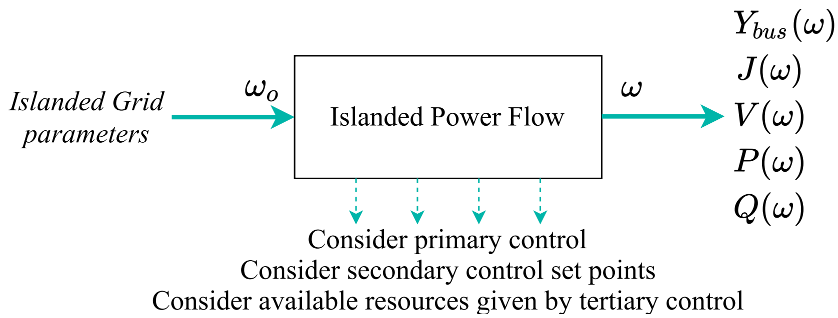

Figure 4.3: Islanded power flow.

On one hand, considering the absence of slack nodes this power flow algorithm can determine electric variables considering the nature of islanded grids. On the other hand, for microgrids, strategies for the control of the frequency, as a challenging issue, can be contemplated as it can deals with the absence of inertia by including the primary control. Then as the power flow may consider the influence of primary, secondary and tertiary controls a frequency control strategy can be proposed.

Chapter 5

Centralized secondary control

As previously shown in Section 2.4 secondary control can be executed under different control approaches: centralized control or distributed control. Each one has its own advantages and disadvantages compared to the other. However, one difficulty in a decentralized approach is that all distributed generation units can reach different stable point.

It is important to highlight, in the case of the frequency, that it is not enough that all units reach a stable point but that this stable point is the same for all units. Hence, even for a decentralized strategy, a central controller is required for synchronization issues. Also, centralized approaches have demonstrated to be efficient for smart distribution systems or microgrids with generation units close to each other. In this chapter a centralized secondary control based on a receding horizon strategy is proposed.

5.1 Receding horizon

Receding horizon approaches are a classical control techniques that have been used for electric powers system (Thomas, 1975). This control technique is an optimization-based control that solves an optimization problem in a certain time interval. Thus, the optimization techniques used for a receding horizon strategy must be fast and reliable. There are many ways to use a receding horizon strategy for electrical power systems as the shown in (Tielens and Van Hertem, 2017) which provides frequency regulation taking into account future load and wind variations. Also, it has been used for optimal placement of batteries (Fortenbacher et al., 2018) and, even, it has been reformulated as an stochastic receding horizon control in (Jiang et al., 2019).

For the secondary control problem (see 2.4 for a secondary control explanation), and considering that the power converters have a limited capacity of suddenly modify the injected power, a proposed approach based on the concept of receding horizon considering the primary control effect is depicted in Figure 5.1. Notice that unlike the ideal behavior of frequency shown in Figure 2.5, the secondary control improves, step by step, considering the network limitations, not only the frequency but also voltages and injected power.

The objective of the control is to carry out the frequency and the grid voltage to suitable values. In each time step, a frequency-dependent load flow, as the presented in Section 4.1, is calculated in order to determine the operative point and the corresponding linearization. Then, an optimization model is solved in order to determine the control actions required to carry out the frequency and voltages to their nominal values. This optimization model requires to be solved in real time. Therefore, it must to be convex in order to guarantee global optimum and convergence of the algorithm. Next, the control action is executed and the resulting operative point is calculated again by a frequency-dependent power flow. The process continues until the control objective is achieved.

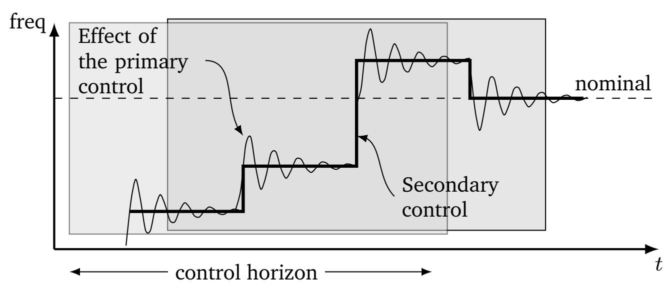

Figure 5.1: Receding horizon strategy for the secondary control of islanded microgrids

In each step, the primary control achieves an stationary state due to the difference in the time-frame between the primary and the secondary control. However, the effect of the frequency from the primary is clearly considered in the secondary control.

5.2 Optimization model

The secondary control is performed by convex optimization approach which is based on the linearization given by the frequency-dependent power flow of Section 4.1. Two new variables, Δp_{sec} and Δq_{sec}, are included in the model. These are the adjustments in the set point of active and reactive power, respectively, for every distributed resource. Then, the equation (4.12) can be rewritten as (4.13), as previously shown. This model allows the implementation of an optimization model in order to find the presented variations with the objective of minimizing the frequency deviation from its nominal value.

Then, while the frequency deviation from its nominal value is greater than a given tolerance, an optimization problem is solved as the frequency approaches its nominal value. This is shown in Section 5.3.

The optimization model is shown below:

$$\text{minimize } \|\Delta\omega\| \tag{5.1}$$

$$\text{subject to} v^{\min} \leq v + \Delta v \leq v^{\max} \tag{5.2}$$

$$p^{\min} \leq p + \Delta p_{\text{sec}} \leq p^{\max} \tag{5.3}$$

$$\|\Delta p_{\text{sec}}\| \leq \Delta p_{\text{sec}}^{\max} \tag{5.4}$$

$$\|\Delta q_{\text{sec}}\| \leq \Delta q_{\text{sec}}^{\max} \tag{5.5}$$

$$E_{\text{battery}}^{\min} \leq E_{\text{battery}}^{k} \leq E_{\text{battery}}^{\max} \tag{5.6}$$

$$P_{\text{battery}}^{\min} \leq P_{\text{battery}} \leq P_{\text{battery}}^{\max} \tag{5.7}$$

$$E_{\text{battery}}^{k} = E_{\text{battery}}^{\text{k-1}} - P_{\text{battery}}^{k}\Delta t \tag{5.8}$$

$$\begin{pmatrix} \bar{p} + \Delta p_{\text{sec}} + (1/\xi)\Delta\omega \\ \bar{q} + \Delta q_{\text{sec}} + (1/\zeta)\Delta v \\ \Delta\theta_{CI} \end{pmatrix} = J \begin{pmatrix} \Delta\theta \\ \Delta v \\ \Delta\omega_{CI} \end{pmatrix} \tag{5.9}$$

Here, the objective function (5.1) is to minimize the deviation of the frequency from its nominal value in order to found the optimal modification for the set points in every converter. Equation (5.2) limits the voltages to a value between an allowed range (for example ± 0.1pu) and Equation (5.3) limits the power injected by each converters. In Equations (5.4) and (5.5) the adjustment on the set points of active and reactive power, respectively, are restricted in order to avoid changes that overcomes the converter capacity. Constraints (5.6) and (5.7) restricts the energy and power injected by the battery energy storage systems in each time step k while constraint (5.8) shows the remaining energy on every storage unit where Δt refers to the time where a new set point is established.

This optimization model is convex since the objective function is convex and the set of constraints are linear/affine. Therefore, global optimum and convergence of the interior point algorithm are guaranteed.

5.3 Integrating optimization model and power flow

The entire process required for each step of the receding horizon strategy is presented in Algorithm 1. This algorithm takes all of the the system parameters and measures of voltage and frequency, and performs an frequency dependent power flow in order to find the steady state parameters of the system, considering the effect of the primary control. At this point is important to recall that the absence of a slack bus delimits the problem solutions since its feasibility depends on the load that, in some cases, can be greater than the generation and storage capability.

Algorithm 1 Receding horizon

```
Receive ← measures(v, ω, p, q) and references(p̄, q̄, v̄, ω_0)
(v, θ, ω) ← initialization(v, ω)measured
ϵ → error
while ϵ ≤ 1 × 10^-8 do
    Calculate Y_BUS and ∂Y_BUS/∂ω
    Calculate Jacobian with (4.14)
    Calculate new values of PowerFlow(v, θ, ω)
    ϵ → error
Solve Convex Optimization Model (5.1) to (5.9)
returns: Control actions (p + Δp, q + Δq)
```

After that, the optimization problem described in Section 5.2 is solved. It takes the results from the power flow such as the power injected by the converters, voltages, frequency and the the Jacobian matrix. The main required results are Δp_{sec} and Δq_{sec} which establish new set points that minimizes the frequency deviation $\Delta\omega$. This algorithm is solved in each time step of the receding horizon strategy. Figure 5.2 presents how the proposed centralized secondary control strategy reduces frequency and voltage deviations using the load flow presented in Section 4.2 while taking data from both primary and tertiary control.

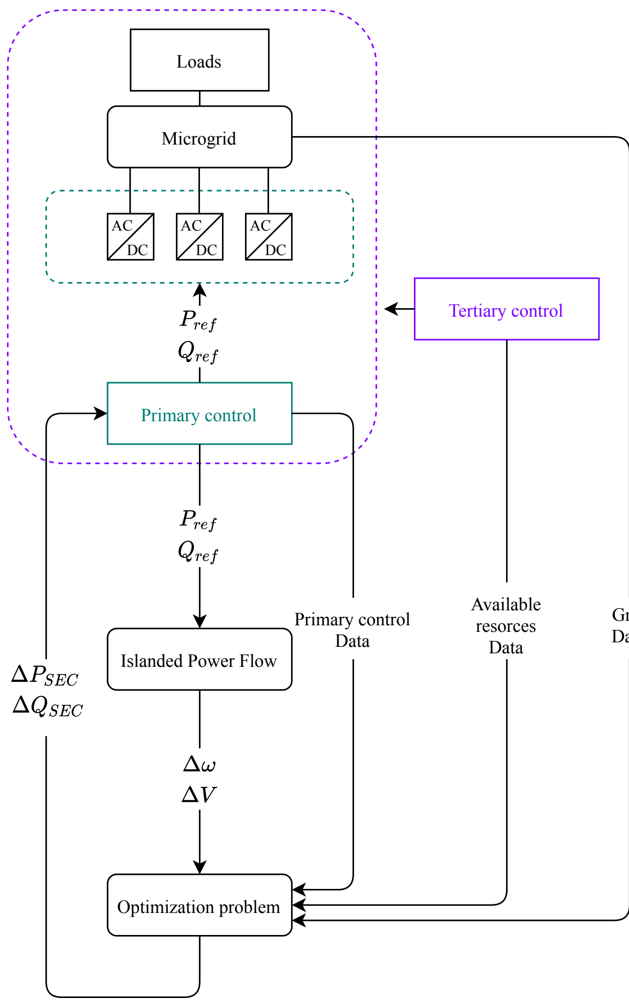

Figure 5.2: Schematic representation of secondary control model taking into account primary and tertiary control effect

Three main issues must to be considered in order to use the strategy: i) convergence of the power flow, ii) convergence of the optimization model and iii) feasibility of the optimization model. The first issue was analyzed in (Bravo et al., 2019) where convergence of the proposed power flow algorithm was demonstrated using Kantarovich Theorem. The convergence of the optimization model is guaranteed since the problem is convex (in fact, it is strongly convex).

Finally, feasibility depends on the demand value when the microgrid is islanded. This is because when the demand exceeds the generation and storage capabilities the problem became unfeasible. One way to mitigate this problem is to implement a load shedding scheme. From the operational point of view the load shedding problem must be solved by the tertiary control.

Chapter 6

Results

As mentioned along this document, the main objective of the secondary control strategy presented is to carry the system frequency to the nominal value while preserving several electrical characteristics of the network such as voltage stability, voltage regulation and electronic devices capacities. For that reason, simulations must be carried out in order to guarantee that, effectively, the strategy proposed fulfils the requirements to be considered a feasible control architecture under different scenarios. The default parameters of the modified test system are shown in Appendix A.1.

In this chapter a variety of results after implementing the sequential secondary control algorithm, in a modified low-voltage CIGRE benchmark microgrid, are presented. Under different load scenarios the modified 19 nodes microgrid presents different dynamic responses since a system operating in islanded mode is highly sensitive to load changes and perturbations. For this reason, and following the discussion carried out in Section 3, the stability of the voltage and frequency after every new set point is analyzed.

6.1 Highly loaded scenario

In order to show the behavior of the grid, under the sequential secondary control strategy, the loads in every nodes were increased. Then, the loads for the system are shown in Table 6.1.

Figure 6.1 shows the modification on the set points for active power (ΔP_{SEC}) for a total time of 0.25 seconds where the frequency deviation is

Table 6.1: Load values

Highly loaded scenario	
Node	Load [W]
11	37000
13	60000
14	50000
18	12000
19	12000

minimized with a 1×10^{-4} error around its nominal value i.e. 60Hz. Every ΔP_{SEC} is smaller than the previous one as the algorithm is reducing the deviation from the frequency as a main objective.

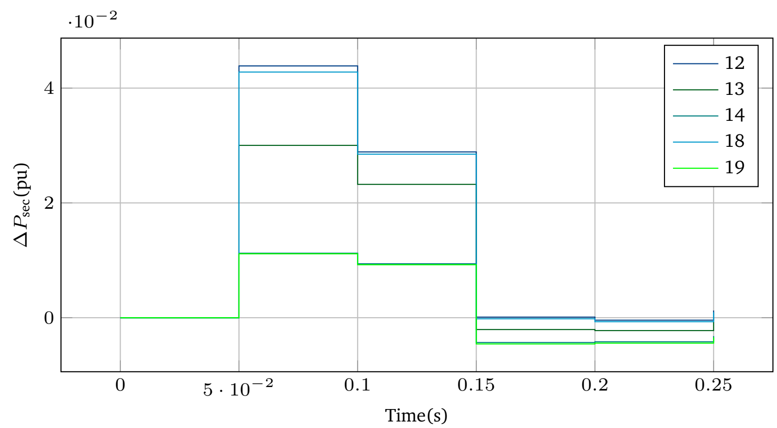

Figure 6.1: Variation of set points of active power provided by the secondary control - highly loaded case

Equally, for reactive power the modifications in the set points (corresponding to ΔQ_{sec}) are shown in Figure 6.2. Here, every variation of the reactive power set point is made in order to maintain the voltages in the terminals of every power converter between the feasible boundaries defined by Equation 5.2. Furthermore, notice that, in both Figure 6.1 and 6.2, the set points do not exceed 1.2 times the nominal set point which means that the change on the set points do not exceed the value of $\Delta P_{sec_{max}}$ and $\Delta Q_{sec_{max}}$ from equations (5.4) and (5.5), respectively, which is 0.1pu for this case. This value, considering that phisycally, the electronic converters are not capable to increase or decrease their power injection to the network; this may also increase the number of the algorithm iterations until the optimal set points are settled.

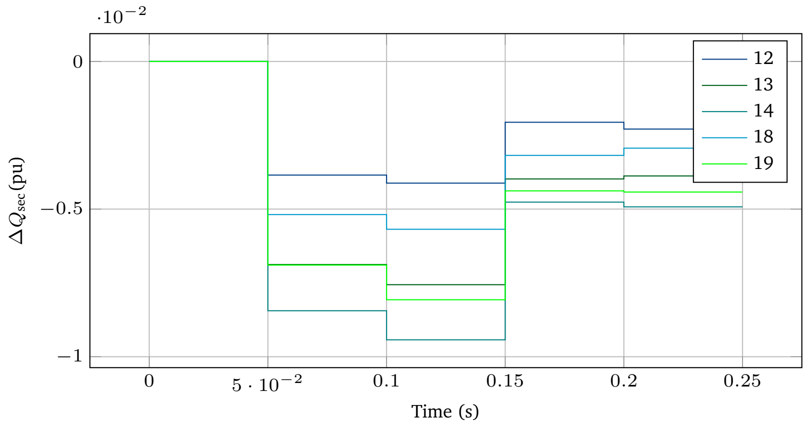

Figure 6.2: Variation of set points of reactive power provided by the secondary control - highly loaded case

As every modification on the set point is considered a disturbance in the case of microgrids, the verification that after every disturbance the frequency remains stable might be made. Also, frequency control and stability is more challenging as long as the lack of inertia in microgrids different from power systems where voltage stability is a main issue to be solved. Considering this, Figure 6.3 shows the dynamic response of the system frequency for the set points, of active and reactive power shown in Figures 6.1 and 6.2, established by the secondary control algorithm. Here, the frequency returns to his nominal value after 0.2 seconds for every DER converter after the algorithm is implemented when the disconnection from the main grid occurs. It is important to recall that despite the frequency varies in every converter in different ways, the steady state frequency is the same for each one.

On the other hand, Figures 6.4 and 6.5 evidences the secondary response and dynamic behavior from primary control voltages. It is also clear that the dynamic response of the voltages reaches a stable point while its regulation stays inside the values of 0.95 and 1.05 pu corresponding to V_{min} and V_{max} of equation (5.2) respectively. This is made by the variation of reactive power injected by every electronic converter which is reproduced almost instantaneously in all of the nodes due to the small size of the microgrid;

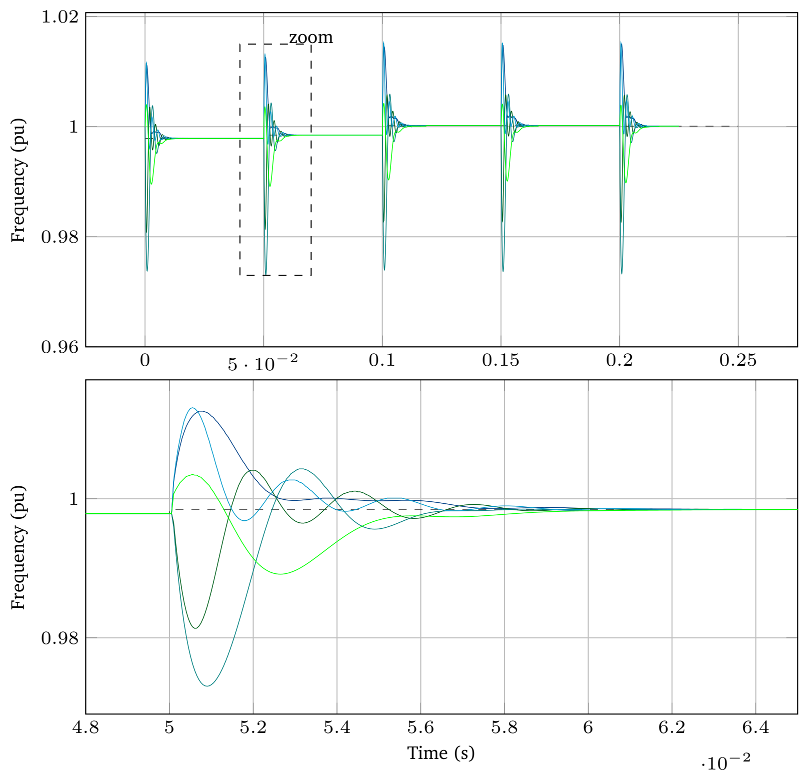

Figure 6.3: Frequency dynamic response for the optimal set points - highly load case.

different from power system where the voltage drop in transmission lines are considerably larger. Besides, note that the secondary control voltage values are the same of the dynamic response given by primary control.

Furthermore, Figures 6.6 and 6.7 shows the power injected by every DER converter for both secondary and primary control, respectively. Here, non of them exceeds the 20% of its nominal capacity and the dynamic response of every converter remains stable. The injection of active power is made to guarantee the equilibrium between generation and load and the injection of reactive power is made to maintain voltages inside feasible limits. Additionally, notice that the power injected by every converter differs from the set points of active and reactive power of Figure 6.1; this situation is given because the effect of primary control modifies the real power injected since it is the sum of the set point plus the effect of primary control.

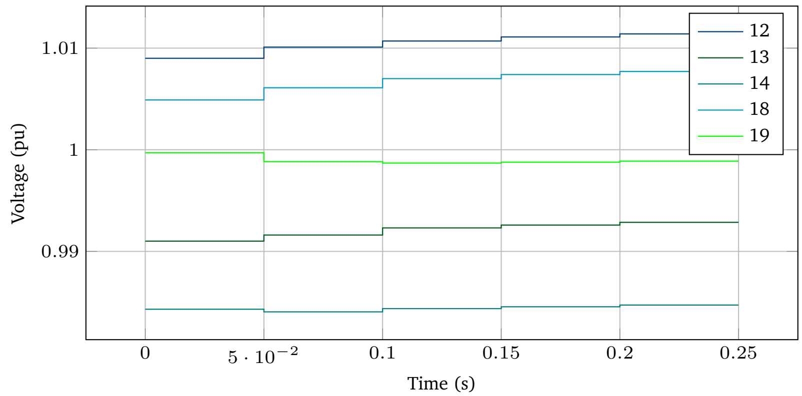

Figure 6.4: Secondary control voltage response.

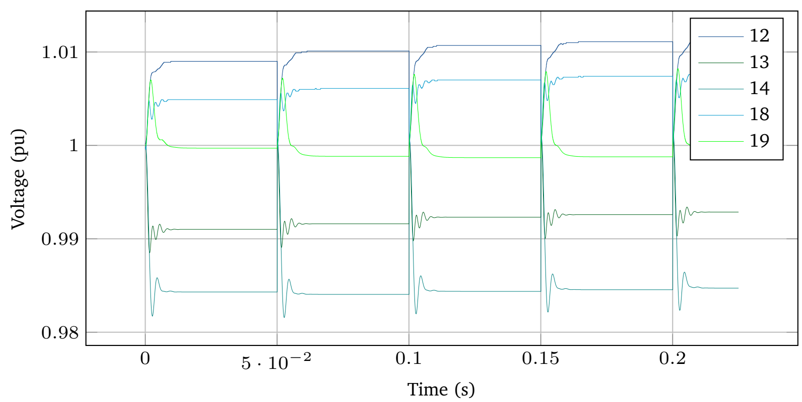

Figure 6.5: Voltages dynamic response to optimal set point in a highly loaded scenario.

Figures 6.8 and 6.9 show the behavior of the power injected by every energy storage unit and his energy respectively; the storage unit placed on node 12 has an initial energy of 1 pu while the units placed on nodes 14 and 18 have an initial energy of 0.8 and 0.1 pu, respectively. Since the value of $E_{Battery_{min}}$ from equation (5.6) is 0.1 the unit placed on node 18 start charging.

The active power injected by the converters and the batteries fulfills the demand at every time step. Besides, since the grid is operating in islanded mode and the model minimizes the frequency deviation, the storage

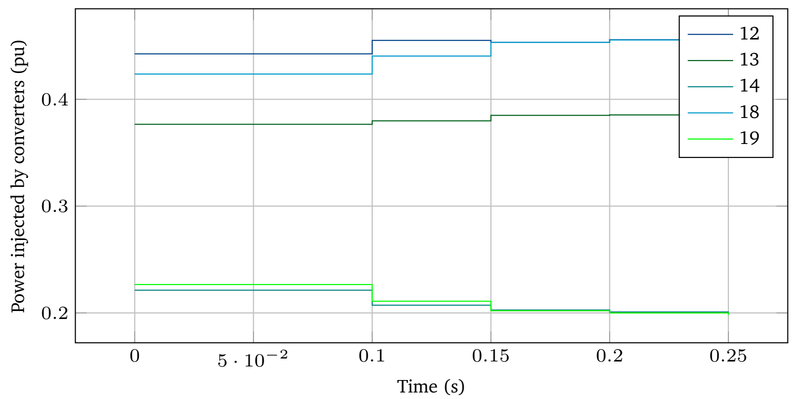

Figure 6.6: Secondary control Active power injected response.

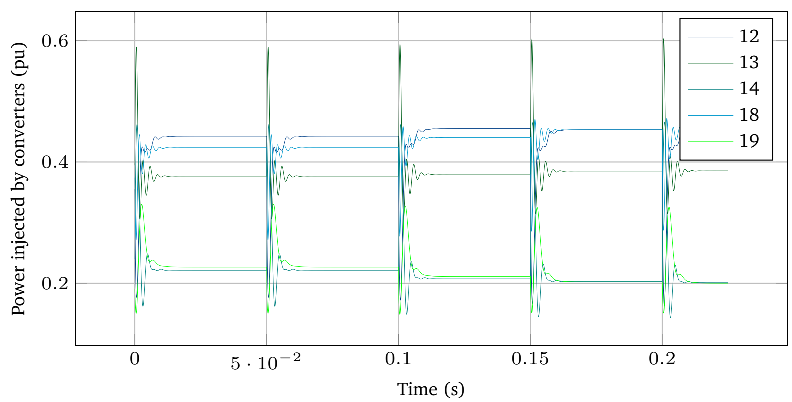

Figure 6.7: Injected active power dynamic response in every DER converter for the optimal set points in highly loaded scenario.

units provides the power that the DER converters cannot supply. This means that the secondary layer, being a fast control compared to the tertiary control, needs to guarantee that both frequency and voltage reach the nominal value. In order to do that, energy storage systems supply the energy needed for the secondary control to fulfill balance constraints of the optimization problem. On the other hand, tertiary control, as the layer in charge of the system optimal operation, is in charge to study the state of state of charge of energy storage systems in a longer time scale.

Also, the batteries are modeled as a tool that only operates in the case where the grid is in islanded mode.

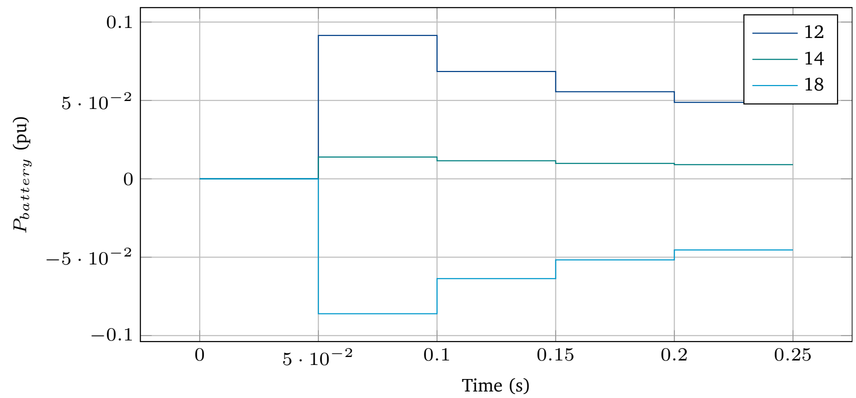

Figure 6.8: Injected power behavior by every storage device due to the optimal set points - Highly loaded scenario.

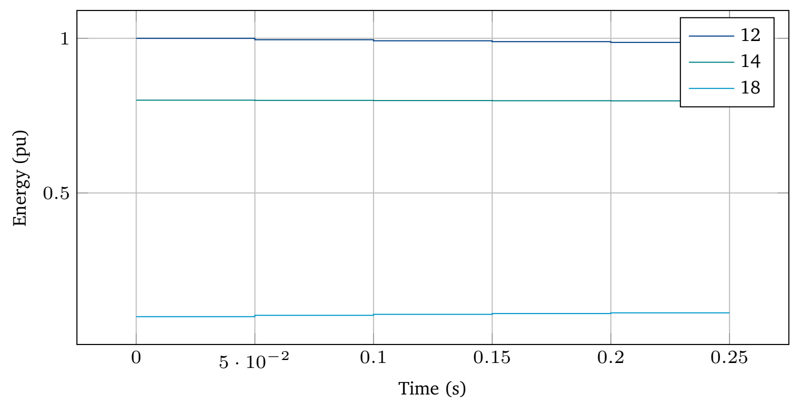

Figure 6.9: Energy behavior in every storage device due to the optimal set points - Highly loaded scenario.

6.2 Low charged scenario

A new modification to the loads of the modified CIGRE low-voltage benchmark microgrid was considered. Then, the modified loads are shown in Table 6.2. Figures 6.12 - 6.18 show the dynamic response of the system to the reference values of active and reactive power of Figures 6.10 and 6.11 when frequency overcomes his nominal value due to a low charged network when a disconnection from the main network occurs.

Table 6.2: Load vaues

Low charged scenario	
Node	Load
11	7000
13	40000
14	18000
18	12000
19	1000

For this scenario, the optimization model presents as a result the set points modifications Δp_{sec} and Δq_{sec} for active and reactive power of Figure 6.10 and 6.11, respectively. For the active power, and different from the results for the highly loaded scenario in Figure 6.1, the optimization problem reduces the set points in every electronic converter separately. This is given by a higher value of generation in comparison to the load values.

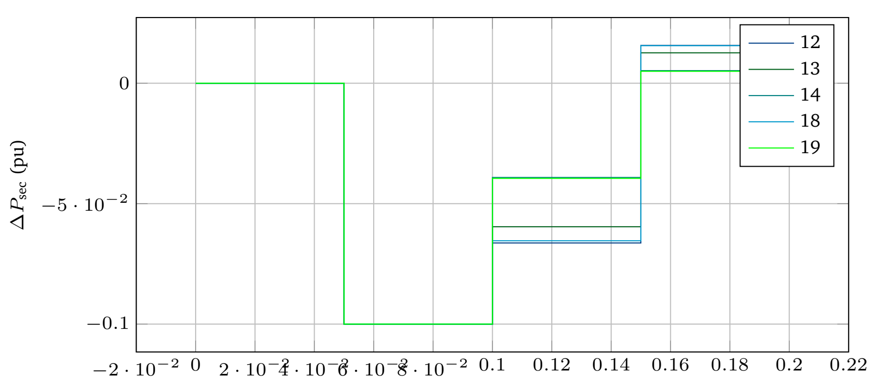

Figure 6.10: Secondary active set points variation - Low charged scenario.

This imbalance provokes, also, a different behavior of the reactive power set point for every converter. Figure 6.11 shows that in first iterations reactive power set points are increases to maintain feasible voltages while satisfying voltage limit constraints. In power systems, the voltage control can be made even externally from the electric generators. In microgrids, considering also his small size and the immediately reproduction of a voltage variation in the electronic convertes in all of the microgrids nodes, the voltage control and regulation is made locally in every converter.

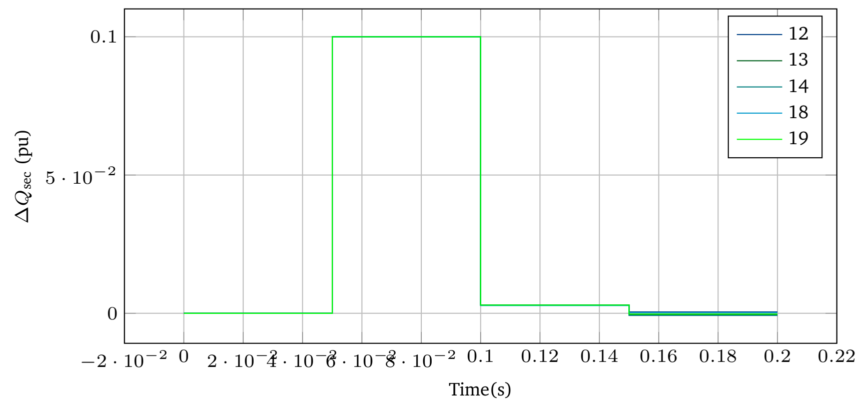

Figure 6.11: Secondary reactive set points variation - Low charged scenario.

The frequency dynamic response is shown in Figure 6.12. Here, despite the frequency overcomes the nominal value, the optimization algorithm manages the DER converters in order to relocate the frequency of every unit to the nominal value. As a major challenge for microgrids considering the absence of inertia in the system, the results show that under the secondary control strategy and the complementarity with primary and tertiary control layers frequency stability and steady frequency value is achieved. This, also considering that despite the dynamic behavior of every converter is different, the steady state frequency is the same for every one of them.

Voltages dynamics for the primary control, depicted in Figure 6.13, show that voltage profiles are improved as they are approached to their nominal value while they are kept within the established limits following the reactive power modifications from Figure 6.11.

Similarly, Figure 6.14 shows the secondary control voltage signals. As expected, they are the same signals of the stable values of primary control voltages.

Figure 6.15, as similarly shown in Figure 6.7, shows the active power injected by every DER converter due to the optimal set points variation. Again, the constraints related to the capabilities of every converter are met at the time the behavior of the power injected by every converter reaches a steady point. Also, non of them exceeds the 20% of their nominal capacity in all

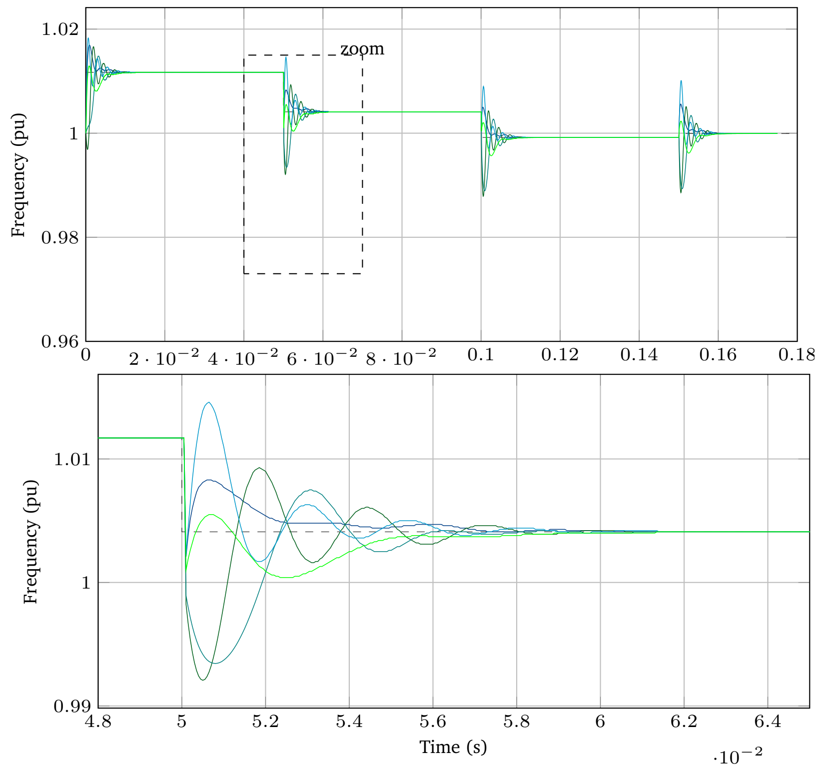

Figure 6.12: Frequency dynamic response to optimal set points - Low charged scenario.

iterations. Equally, the secondary control, as seen in Figure 6.16, reaches the same values making sense of the results. In the case of active power it is modified to reach the active power balance which is fundamental for the operation of the system and to reach the nominal frequency due to the relation $f - P$ shown in Section 2.1.

Reactive power, on the other hand, varies following the relation $V - Q$ shown in Section 2.1. The voltage regulation and control is made locally in each power converter as the voltage is reproduced in all of the nodes without a considerable drop in the lines.

Finally, Figures 6.17 and 6.18 exposes the power injected for every storage device as well as the remain energy for them, respectively. Also, the behavior of every storage device as a support for the power injected by the converters is evidenced. The energy in the last time step in all of the stor-

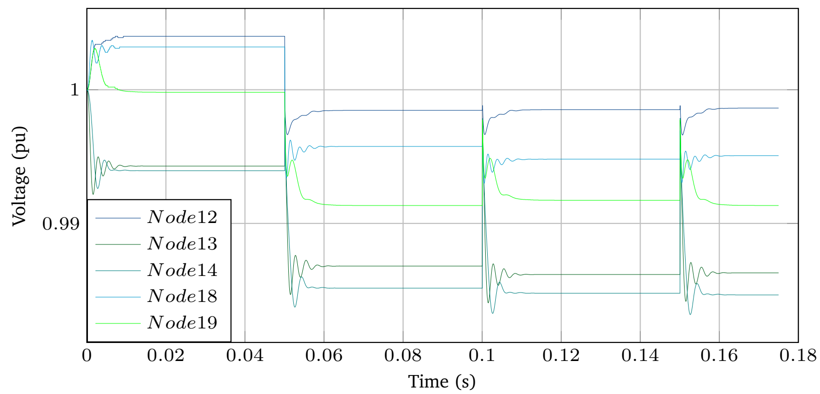

Figure 6.13: Dynamic response of primary control voltages to the optimal set points - Low charged scenario.

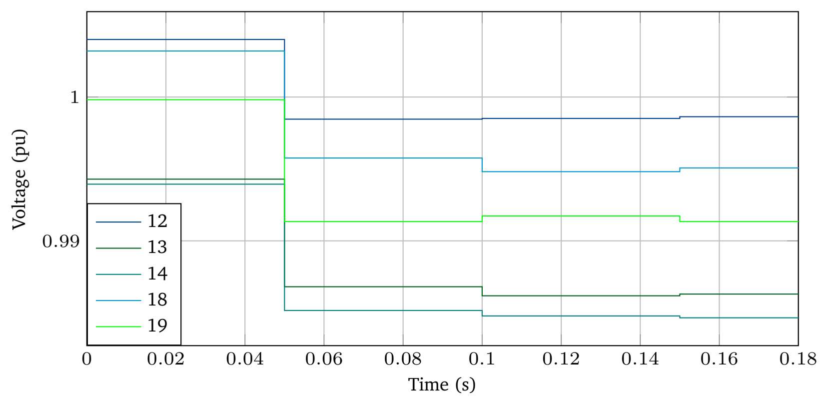

Figure 6.14: Secondary control voltages response to the optimal set points - Low charged scenario.

age devices allows to identify that the storage devices can support the grid for a more extended time period since the energy consumption is low when the secondary control carries the voltages and frequency to their nominal values. Tertiary control strategies must consider the requirements by the secondary control for the energy storage systems to guarantee the required amount of energy to guarantee the power balance.

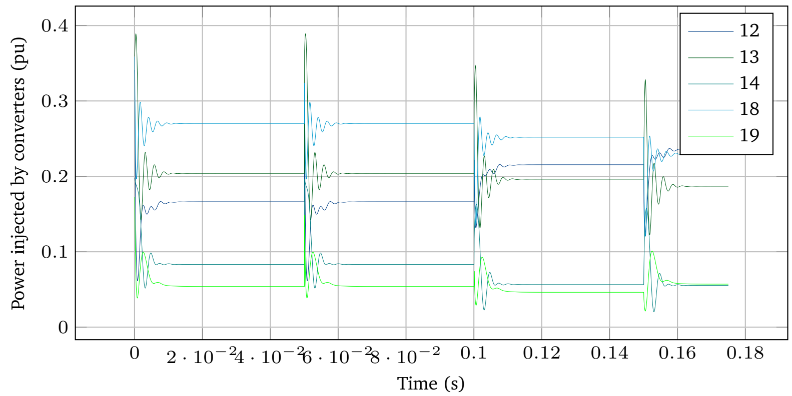

Figure 6.15: Secondary injected power behavior by every DER converter due to the optimal set points - Low charged scenario.

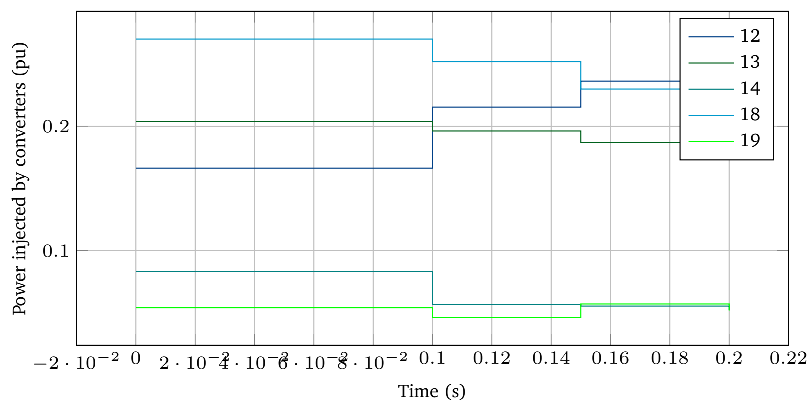

Figure 6.16: Injected power behavior by every DER converter due to the optimal set points - Low charged sceario.

6.3 Impact of the proposed secondary control in the voltage stability

As presented in Chapter 3, stability in microgrids have to be also considered when a new control scheme is presented. Although primary control is the main control layer that takes charge of the system stability, secondary control should guarantee feasible set points for primary control for it to preserve system stability. In this case, the secondary control algorithm finds out the optimal set point for the primary control.

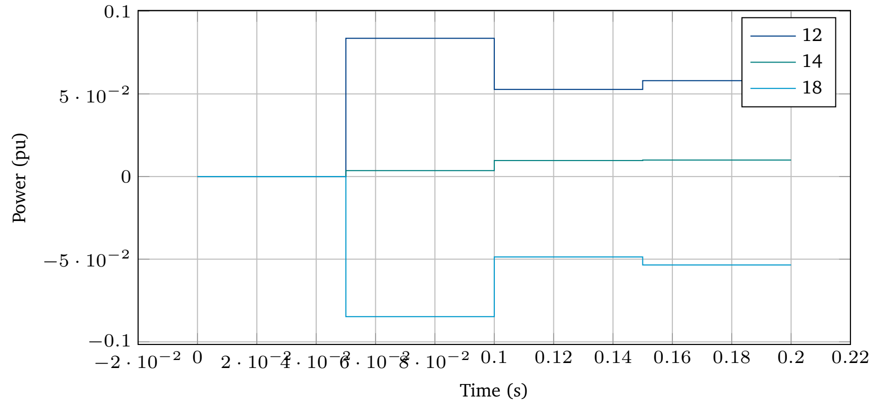

Figure 6.17: Injected power behavior by every storage device due to the optimal set points - Low charged scenario.

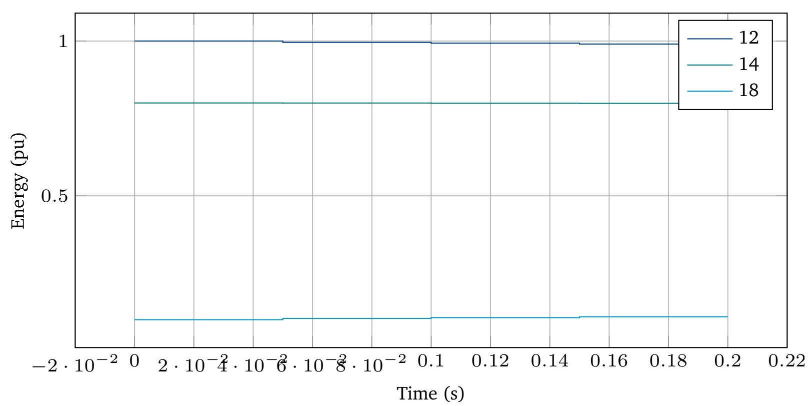

Figure 6.18: Energy behavior in every storage device due to the optimal set points - Low charged scenario.

In Section 3.2, it is established that a modification on load or even new set points for the electronic converters is considered a disturbance in the case of microgrids in islanded mode (Farrokhabadi et al., 2019). Sections 6.1 and 6.2 show the response of the secondary control under two scenarios and it shows that for every modification of the set points, a steady state variable was reached. This means that both, primary, take the system to a feasible steady state operation point (different from the first one) and then secondary control takes the system to the nominal value while preserving voltage and frequency stability. This stability in power injected, voltage and frequency can be seen in the representation of the dynamic behavior of all system variables after each disturbance. After every disturbance a feasible and stable operation point is guaranteed.

Chapter 7

Conclusions

A convex optimization approach for the secondary control of microgrids was developed. The frequency of the grid was carried out to its nominal value, taking into account the limits of capacity of distributed resources. The model demonstrated to be accurate and the accuracy was improved as the frequency returned to its nominal value. The model took into account the fast dynamics of the primary control and the stationary state set points given by the tertiary control.

A power flow method for islanded microgrids considering frequency changes was also presented. Then, the model considered variations of the Y_{BUS} with the frequency. In each iteration, the power flow as well as the optimization model obtained convergence as the frequency varies. The results showed that, under different load scenarios, the algorithm reduced successfully the frequency deviation for all the converters around their nominal value. Furthermore, the steady state frequency was the same for all converters.

Secondary control has become a required concept to be considered for incoming developments not only for microgrids but for traditional power systems and control structures since a wide variety of non-conventional energy generation devices are included. Besides, in order to improve power quality especially when islanded mode is considered secondary control becomes fundamental for the network operation.

It can be also concluded that mathematical techniques, such as convex optimization in this document, despite not having been completely studied for secondary control in islanded microgrids, they can be used to improve the behavior of control algorithms and their execution times giving extra capacity to include grid restrictions or generation capacities.

7.1 Future work

A secondary control approach based on the presented document an be implemented in an unbalanced microgrid. This will require additional tools as a phase balancing algorithm in order to give equilibrium to the network. Also, despite the variation of the primary resource is studied by tertiary control, different variables as a chance constraint inclusion can be added to the optimization problem to look for the impact of the consumption in the near future.

A distributed-based secondary control can be also implemented by using convex optimization taking into account the communication networks required for this aim. Since, the optimization model presented gives different signals to all of the DER converters the implementation for a distributed approach will require to solve several optimization models depending on the areas or controllers considered.

Finally, an implementation of the secondary control in a centralized or distributed approach can be made. This implementation is feasible since there are devices that allow the inlusion of cvx in order to solve optimization problems in real time.

Apendix A

Test system

A modified CIGRE low voltage microgrid test system was the system selected for the implementation of the secondary control algorithm. The main reason was that this is a well known system that is composed for 19 nodes with a distance between them which makes the structure similar to a traditional distribution system but with the inclusion of non-conventional generation structures, distributed loads and energy storage units.

This Appendix shows the parameters of the test system and the topological distribution of every element. All parameters given in per unit are calculated with voltage base of 400V, power base of 100kW and with a base frequency of 60Hz.

A.1 Parameters

Figure A.1 shows the topology of the CIGRE 19 nodes test system. There, all nodes can be classified taking into account the residential consumer, storage units, solar generation and wind generation .

Also, the characteristics of 4 line types are shown in Table A.1 where the values are given in Ω/km for resistance and reactance and $\mu F/km$ for capacitance.

Table A.2 presents the connection between every node with their longitude and line type.

Table A.3 shows the main characteristics of the 5 converters for their corresponding nodes. The capacity in Watts is also presented along with the constants ξ and ζ which corresponds to the droop constants for primary

Table A.1: Line types

Type	Rph	Xph	Ro	Xo	Cap	Description
1	0.284	0.083	1.136	0.417	0.38	OL $-4x120mm^2$ Al
2	3.690	0.094	13.64	0.472	0.05	SC - $4x6mm^2$ Cu
3	1.380	0.082	5.520	0.418	0.18	SC - $4x16mm^2$ Cu
4	0.871	0.081	3.480	0.409	0.22	SC - $4x25mm^2$ Cu

control. τ corresponds to the time constants for each converter. Finally, the form and scale constants for each type of renewable resource is shown.

Furthermore, storage units following the model of (A.1) were considered in nodes 12, 14 and 18 following main parameters of Table A.4.

$$E_B(k+1) = E_B(k) - P_B(k)\Delta t \tag{A.1}$$

Table A.2: Nodes connection

CIGRE System lines			
Nodes		Longitude	Line type
$N_{s]}$	N_r	[m]	Type
1	2	35	1
2	3	35	1
3	4	35	1
4	5	35	1
5	6	35	1
6	7	35	1
7	8	35	1
8	9	35	1
9	10	35	1
3	11	30	2
4	12	30	3
6	13	30	4
10	14	30	3
4	15	35	1
15	16	35	1
16	17	35	1
17	18	30	1
9	19	30	2

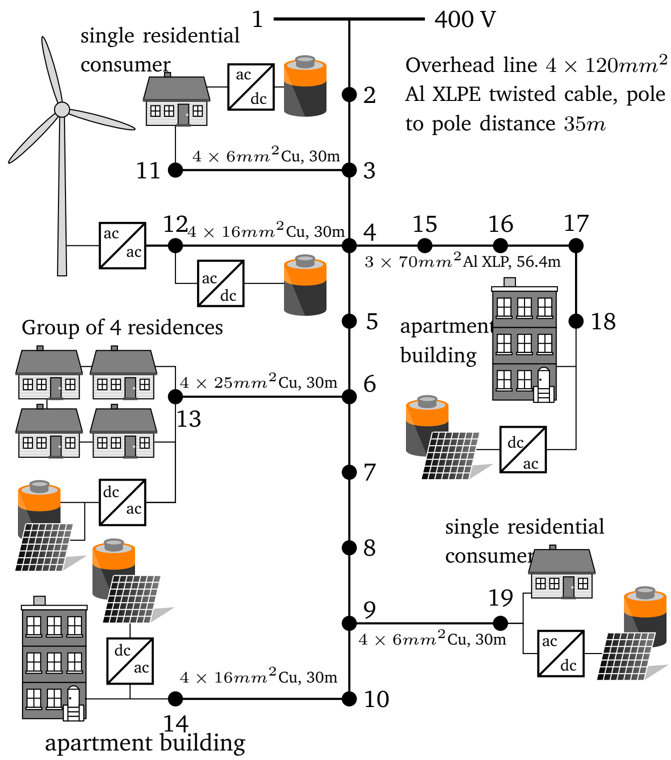

Figure A.1: The CIGRE low voltage benchmark test system

Table A.3: Converters Data

Node	**Capacity**	ξ	ζ	**Tau**	**Type**	**Form**	**Scale**
12	40000	0.05	0.04	0.32E-3	wind	1.5	10
13	35000	0.08	0.09	0.38E-3	solar	200	700
14	20000	0.10	0.09	0.41E-3	solar	200	700
18	40000	0.09	0.10	0.31E-3	solar	200	700
19	20000	0.08	0.08	0.34E-3	solar	200	700

Table A.4

Storage units characteristics				
Node	E_{min}	E_{max}	$P_{max\}}$	$E_{initial}$
12	0.1	1	1	1
14	0.1	1	1	0.8
18	0.1	1	1	0.1

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