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Hybrid AC/DC Microgrid Mode-Adaptive Controls

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Abstract

The lack of inertial response at microgrids is usually compensated by configuring primary controllers of converter-interfaced devices to contribute in the transient response under power disturbances. The main purpose of this chapter is to study the modes of operation of primary level techniques of generation, storage, loads, and other devices attached to hybrid ac/dc microgrids. Although the chapter includes an analysis of the modes of operation of lower-level regulators, the focus is on upper-level or primary controllers. In this context, we analyze mode-adaptive controls based on voltage and frequency levels and we evaluate their behavior by simulation in the Matlab/Simulink® environment. The results demonstrate that mode-adaptive techniques are adequate for maximizing the energy extracted by distributed generation (DG) systems and limit demand side management actuations while ensuring an adequate regulation of the microgrid.

Keywords: demand-response, demand side management, distributed generation, energy storage systems, inertia emulation, microgrids, mode-adaptive control, primary control

1. Introduction

The electric grid is undergoing various changes in its structure, among other reasons, caused by a high dependence on fossil fuels, a constant increment in the power consumption, and the associated environmental problems. The classical top-down structure of the grid is shifting to a more decentralized topology where generation systems are located near consumption points—also known as distributed generation (DG) systems. This shift brings about several challenges, as the electric grid was not originally designed to handle the distributed and intermittent generating systems. In this context, microgrids are arising as one of the most suitable alternatives [1, 2], as they can efficiently integrate different types of DG systems thanks to the energy storage systems (ESSs) and advanced control strategies they include.

Microgrids are used at a wide variety of applications—distribution grids, electric transportation such as vessels or aircraft, isolated grids, etc.—and therefore can have very different features. However, one of the most common approaches is to classify them depending on the nature of their current [3]: ac, dc, or hybrid ac/dc.

Typically, researchers have focused most part of the research activity related to microgrids on ac systems, as they are the most straightforward solution based on the current infrastructure. The knowledge gained over the years with the electric grid can be directly applied for the development of ac microgrids. Therefore, these systems are characterized by efficient modification of voltage levels with transformers and by advanced fault management capabilities with optimally designed devices.

However, during the last two decades, dc microgrids are arising as an interesting alternative due to the inherent advantages they provide over ac ones. The increment of dc-based systems or devices that require a dc stage to operate, the lack of reactive power circulation or the fact that there is no need for synchronization, among other features, is clearing the path toward dc operated distribution networks. The main drawback resides in the fact that a complete substitution of the ac infrastructure would be unfeasible.

In this context, hybrid ac/dc microgrids are an interesting alternative, as they would enable the integration of dc-based systems through a dc network while maintaining the ac infrastructure [4]. This way the advantages of ac as well as dc grids can be combined, facilitating the shift to a more distributed electric grid composed by DG and ESSs.

As shown in **Figure 1**, hybrid microgrids are composed of ac and dc subgrids, which are linked by one or more interface converter. The integration of these converters not only

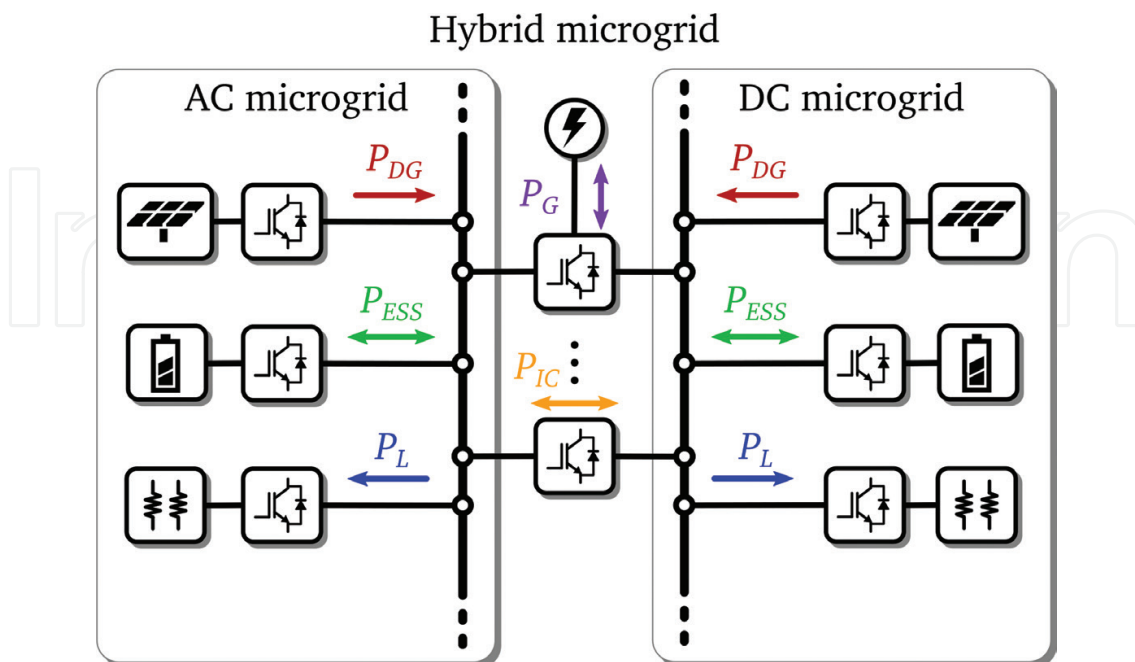


Figure 1. Hybrid ac/dc microgrid.

enables the power exchange between the ac and dc subgrids but they also increase the degrees of freedom regarding the management of the grid, as they can provide other ancillary services [5].

Although these microgrids are gaining a lot of interest especially during the last decades, most of the challenges still reside in their control and management, especially when they operate islanded from the main grid. Even if the control techniques employed at ac, dc, and hybrid ac/dc microgrids can be considerably different, their concept of operation is usually very similar. Inspired by the classical ac grid (**Figure 2**), the management of microgrids is most of the times carried out by employing a hierarchical structure. Each control layer is responsible for certain functions, such as the voltage/frequency control or the management of the islanding/reconnection process.

The main difference is that, at microgrids, conventional synchronous generators are replaced by converter-interfaced generation and storage systems, and therefore, the inertia of the grid is drastically reduced. This is one of the main challenging tasks in the management of microgrids, as lower inertia in the grid means that their voltage and/or frequency is significantly deteriorated under power variations. Consequently, microgrids become more susceptible to failures—especially when operating in the islanded mode—and hence more advanced control strategies need to be adopted to replace the lack of inertial behavior and ensure a stable operation.

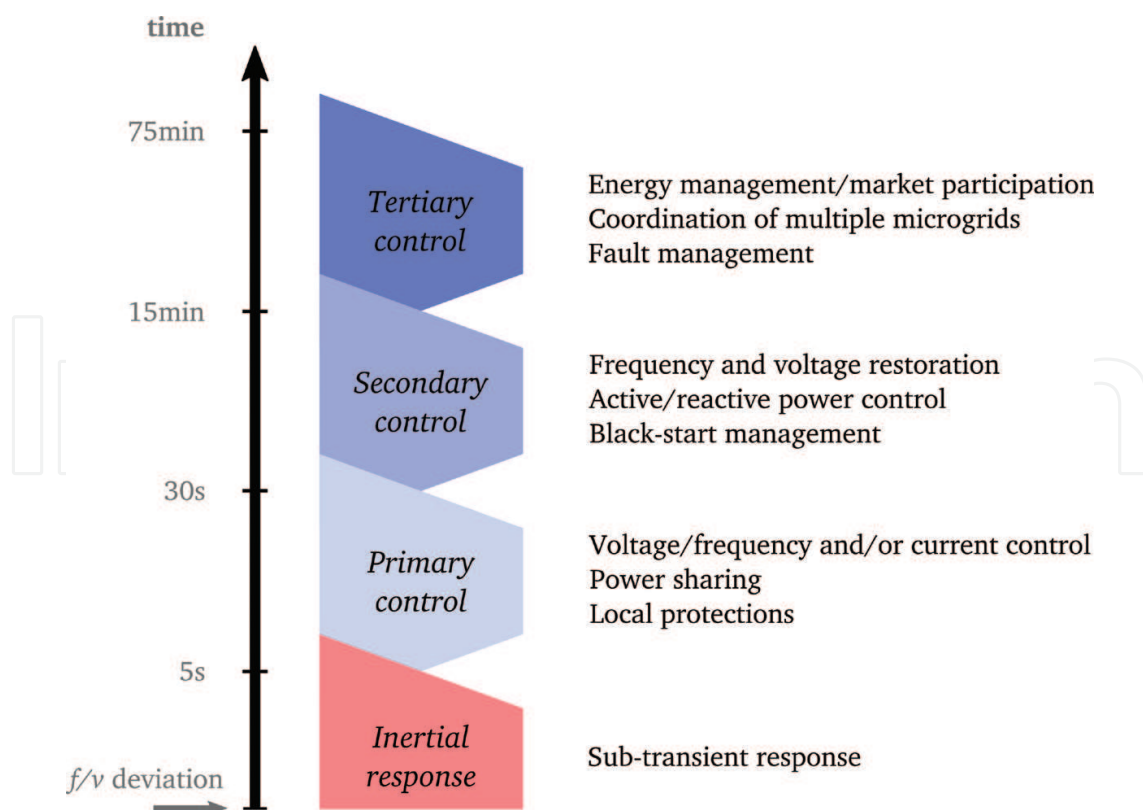


Figure 2. Main ac grid hierarchical control layer functions [6].

One of the most common solutions is to configure the converters associated to DG, ESSs, and even loads to contribute in the voltage and frequency regulation of microgrids. This is usually carried out by primary controllers, which are most of the times integrated locally in each device. **Figure 3** shows the dynamics of each control layer in a microgrid after a power variation.

As shown in the figure, the lack of inertial response is partially replaced by the primary control of converter-interfaced devices connected to the microgrid. In the literature, there is a wide collection of this type of primary techniques that can be integrated at ac, dc, and hybrid microgrids. A review of some of the most relevant strategies can be seen for instance in Refs. [3, 7].

Primary control techniques employed at microgrids are usually composed of two main stages (**Figure 4**): the lower-level stage usually contains the faster regulation loops, which are responsible for the current and/or voltage regulation of converters; similarly, the upper level of the primary control, which is slower than the previous one, determines the reference value where the converter should be controlled, e.g., the active or reactive power.

When there is a variation in the grid, the lower-level control stage primarily defines the transient response of the converter. In addition, the upper-level stage determines the steady-state operation point of the converter. However, depending on how are these stages designed, their effect in the transient as well as steady state response is coupled.

The aim of this chapter is to analyze the operation modes of primary control strategies employed at hybrid ac/dc microgrids, focusing on their lower- and upper-level (primary)

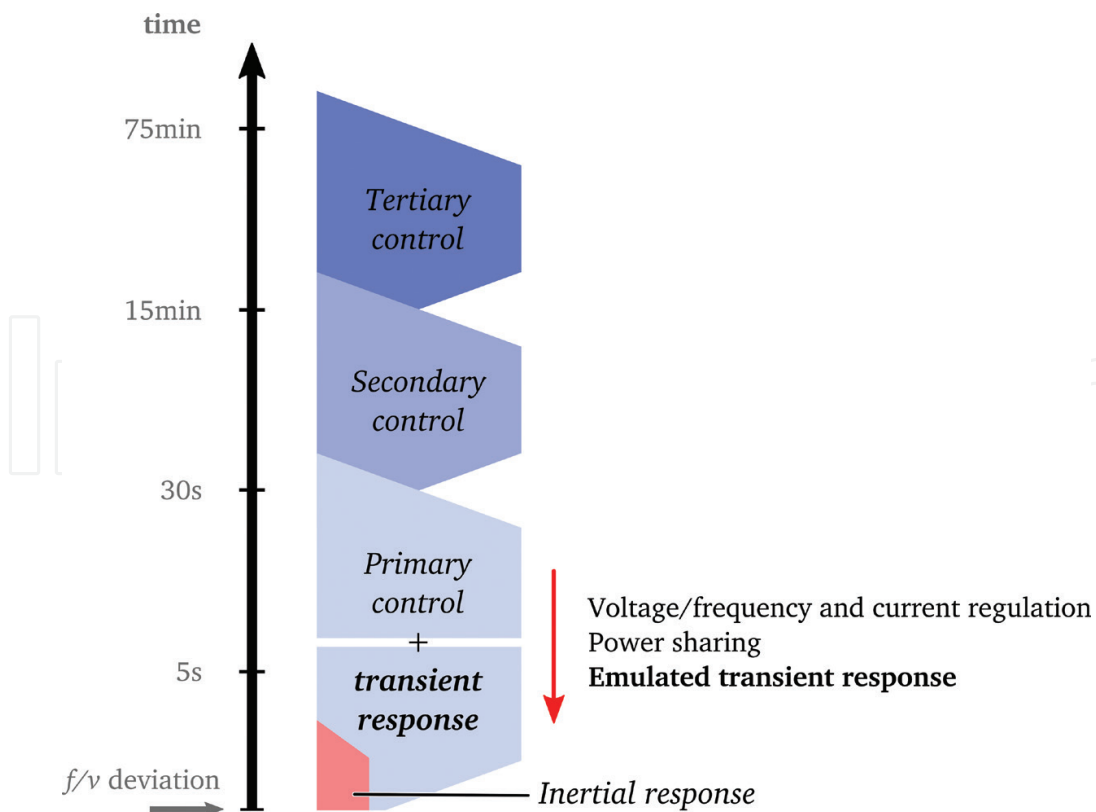


Figure 3. Microgrid hierarchical control layer functions.

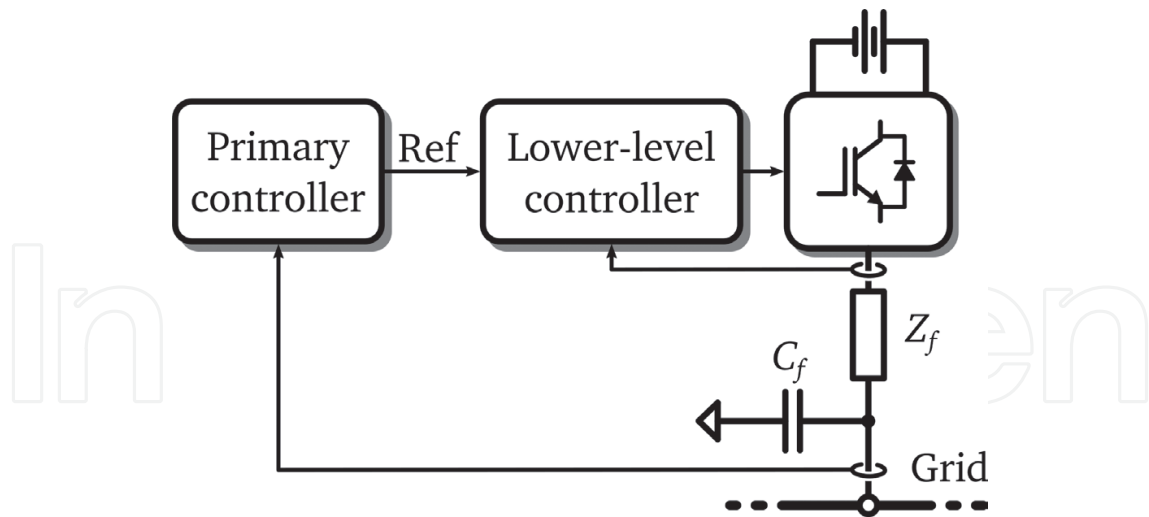


Figure 4. Primary controller configuration.

control stages. Taking into account that ac and dc microgrids are a particular case of hybrid microgrids, the study carried out in this chapter is also appropriate for these systems.

2. Lower-level control operation modes

When designing the lower-level control stages of primary regulators, we can usually follow two main approaches.

In the classical approach, this control stage is composed by one or more cascaded PI regulators that are tuned to follow the reference value provided by upper-level controllers, e.g., a voltage or a power reference. In this case, the regulators do not provide any inherent response over variations in the grid and are mainly designed to control the system so that it reaches the reference value as fast as possible.

On the other hand, in the last decades, a different approach has been proposed where the lower-level regulators are designed to participate in the transient regulation of the voltage and frequency of the network. These regulators are designed to emulate the behavior of classical synchronous generators with power converters associated to DG, ESSs, and loads connected to microgrids. In the literature, these techniques have been widely employed for different applications and are also known as virtual synchronous machines (VSMs) or synchronverters [8–15]. Following the main ac grid configuration—where synchronous generators are directly connected—most of these techniques are usually employed for devices connected to ac microgrids. However, recently, similar approaches have been developed to reproduce an analogous behavior at dc systems. For instance, the study carried out in Ref. [16] shows that a similar response can be emulated at dc systems by employing virtual-impedances in the control strategy, for example, as virtual-capacitors. In this case, instead of controlling the frequency as in VSMs, the variable controlled is the bus voltage.

3. Upper-level (primary) control operation modes

Due to the dispersed nature of microgrids, primary controllers are usually autonomous and operate based on local measurements of the device they are controlling. Whether the device contributes in the frequency/voltage regulation or not, their upper-level regulator is responsible for defining the steady-state point of operation of the converter.

Similar to lower-level regulators, upper-level ones are mainly classified into two different types.

On the one hand, there are certain devices that do not contribute in the frequency/voltage regulation of the microgrid and operate based on the reference provided by another control level (e.g., the secondary) or based on a reference internally calculated to, for example, extract as much energy as possible from the energy source they are connected to—a maximum power point tracking (MPPT) technique. These units are also named grid-following devices, as they do not regulate the bus but rather they “follow” their frequency and/or voltage [5, 7].

On the other hand, systems that contribute in the regulation of the bus are known as grid-forming or grid-supporting systems. These devices share the power variations occurring in the microgrid to decrease the variations of the bus frequency/voltage [5, 7].

We can design generation, storage systems, and loads connected via a power converter to operate differently for example depending on the bus voltage or frequency level. These systems usually include both types of upper-level controllers, and change their mode of operation based on some external condition. This approach is also known as mode-adaptive control, and one of the most interesting methods is to adapt the behavior of each controller based on the level of the bus frequency or voltage.

The authors in Refs. [17–22], for example, propose different types of mode adaptive control strategies for microgrids inspired by this concept, where the devices connected to the microgrid adapt their characteristics based on the frequency or voltage of the grid.

Figure 5 shows a possible configuration for the primary upper-level control of generation, storage systems, and loads connected to a hybrid microgrid. In addition, we have also depicted the connection to the mains grid, in case the microgrid is attached to it.

As we can observe, the primary control of each type of device is configured to behave differently depending on the value of the voltage or frequency. The solid thick lines illustrate an example of these and the shades show that the curves can be modified depending on the requirements. In a

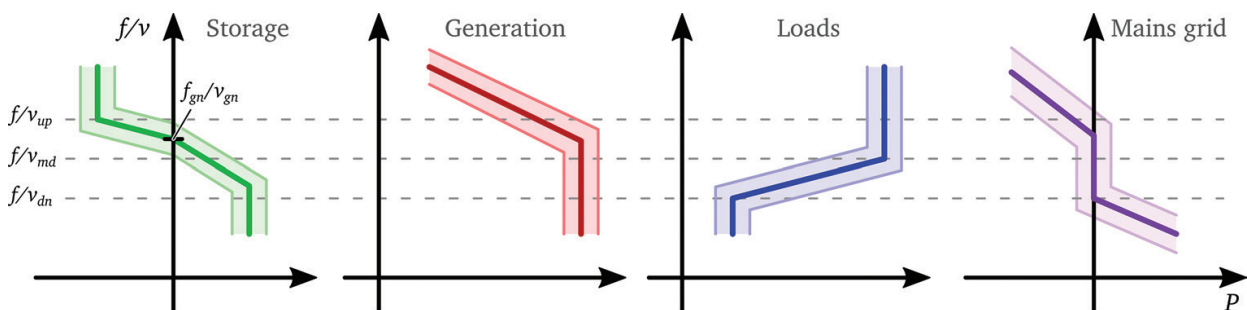


Figure 5. Example of adaptive primary controllers for systems connected to a microgrid.

real application, the ideal approach would be to configure all converter-interfaced devices to contribute in the power regulation. Each system could be designed to participate more or less for certain conditions, but the system would become more robust and stable because power variations would be handled by a higher number of devices with different characteristics and dynamics.

In the following sections, we describe more details of the modes of each type of system.

3.1. Energy storage systems

ESSs are one of the most important agents in the microgrid regulation because they serve as an energy “buffer” to compensate generation and demand deviations during normal operation. We must design and size these systems in order to cope with the most severe conditions of the system; otherwise, a poor regulation would cause the malfunction or disconnection of devices.

Figure 6 shows the most important modes of operation of energy storage systems connected to a microgrid. Under a balanced operation (mode 1), the ESS does not exchange any power with the microgrid. This hysteresis range must be carefully determined in order to avoid an excessive cycling and therefore ageing of the ESS but also to prevent the system from entering into an unstable point of operation.

When the generated power is higher than the demanded one the voltage or frequency of the microgrid increases over the hysteresis upper value and therefore the ESS absorbs power according to the charging droop slope (mode 2). This slope depends not only on the charging capabilities of the ESS but also on the sizing of its power converter.

When the voltage/frequency of the microgrid increases above the preestablished value or the state of charge (SOC) of the ESS is too high, the device turns to mode 3, where the power absorbed from the microgrid is kept constant although the v/f deviation keeps increasing. As shown in **Figure 6**, if the SOC of the ESS continues to increase while in mode 3, the maximum power level value is decreased. The limit of this saturation would be when the SOC is on its upper limit and hence the ESS would not absorb power anymore.

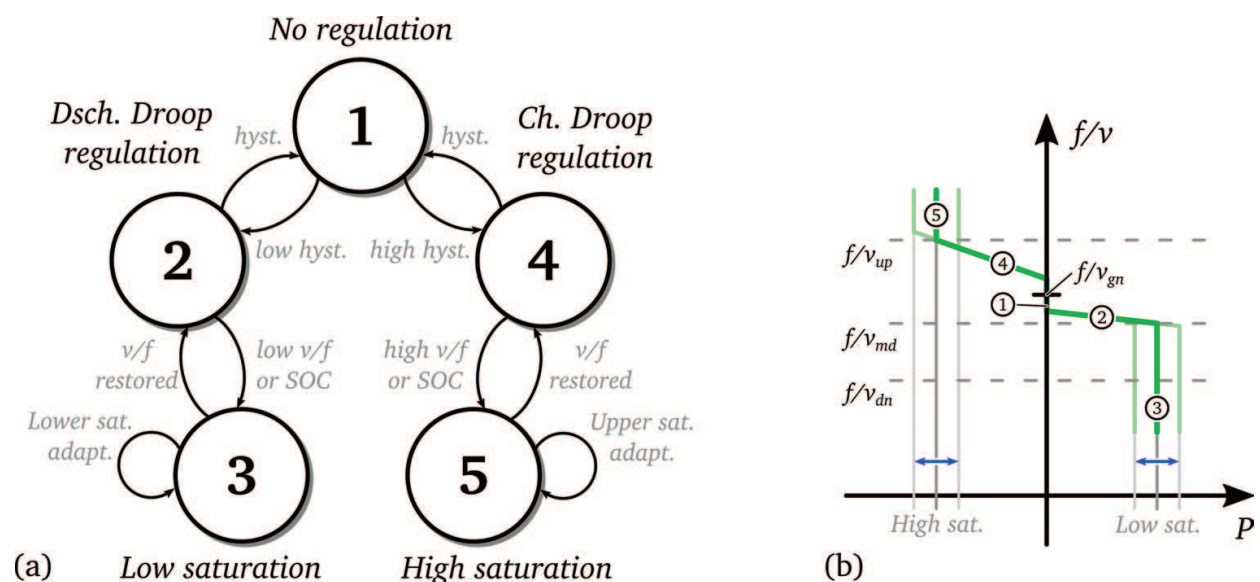


Figure 6. ESS primary controller operation modes.

A similar behavior is reproduced when there is an excessive demand in the microgrid and the voltage or frequency decrease below the hysteresis lower value (mode 4). At this point, the ESS supplies power to the microgrid according to its discharging droop slope. We must note that we could design the droop slopes differently for the ESS charging or discharging process, which means they do not have to be symmetric.

The ESS remains in mode 4 until the voltage or frequency reach their minimum value or the SOC of the ESS is too low. When any of these conditions takes place, the ESS jumps to mode 5 and supplies a constant power regardless of the v/f negative deviation. As in mode 3, the maximum power provided by the ESS will be decreased if the SOC decreases below the pre-defined levels. At some point, when the minimum SOC is reached, the ESS will not supply more power to the microgrid.

3.2. Generation systems

Generation systems mainly operate in two different modes (**Figure 7**): maximum energy extraction/constant power operation and droop regulation. During normal operation in mode 1, as most DG systems are based on renewable energy sources (RESs), the converters attached to generation systems are controlled to absorb as much energy as possible from energy sources. In the case of other types of DG systems such as diesel generators, secondary level controllers determine their constant power reference.

When the voltage or frequency of the microgrid increases above the preestablished level, DG systems shift out of their MPP to reduce the power amount they supply to the system. In this mode 2, DG systems contribute in the v/f regulation of the microgrid through a droop slope (**Figure 7**). As we can see in **Figure 7b**, the droop slope and saturation point depend not only on the value of the voltage or frequency, but also on the maximum power point (MPP) of the DG system. This means that depending on the available power that can be absorbed from the RES, the controllers will have to adapt their operation characteristics to meet the grid codes predefined by the system operator.

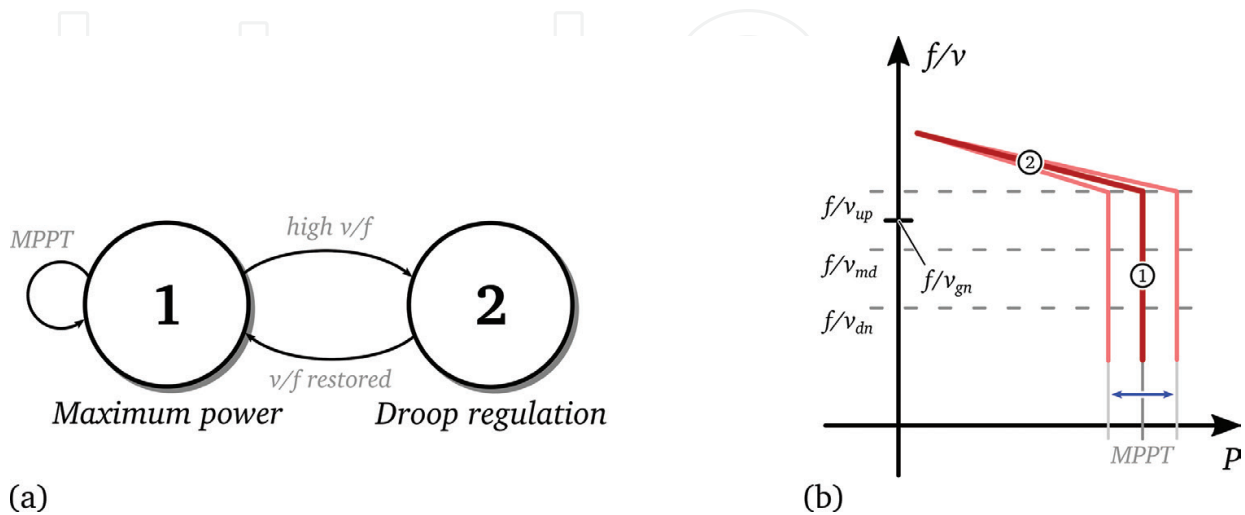


Figure 7. DG primary controller operation modes.

Classically, most converters associated to DG systems have been configured to exclusively operate on the MPP. However, the transition toward a more decentralized electrical system requires the participation of these generators in the regulation of the grid [13].

3.3. Demand-response

Similar to DG systems, loads operate normally in mode 1, absorbing the power required by the attached device. When generation systems are producing all the power they can, no power can be absorbed from the main grid, and energy storage systems are not able to provide more power, the voltage or frequency decreases below the predefined level and the power consumed by loads is consequently decreased (mode 2). In this case, as with DG systems, the droop slopes as well as saturation values are dependent on the instantaneous load (**Figure 8b**).

In the literature, this type of operation is a part of the so-called demand side management, as the loads actively participate in the regulation of the microgrid by reducing their consumed power when required. A high research activity has been carried out in the last years highlighting the importance of the participation of loads in the management of different types of electric systems [23].

3.4. Connection to the main grid

Depending on the topology and type of microgrid, we can follow different approaches with respect to the connection to the main grid. On a classical approach, the connection to the main grid can be employed to contribute in the regulation of the microgrid for the entire voltage range [3]. Another solution would be to use the link to the main grid at specific cases where the voltage or frequency levels are above the maximum or below minimum levels, avoiding the malfunction or disconnection of other devices.

Figure 9 shows the three main operation states of this last approach; as it can be seen, this link only operates when the v/f levels are out of some predefined levels. If the voltage or frequency goes above or below boundaries, we employ the link to the main grid to support the regulation

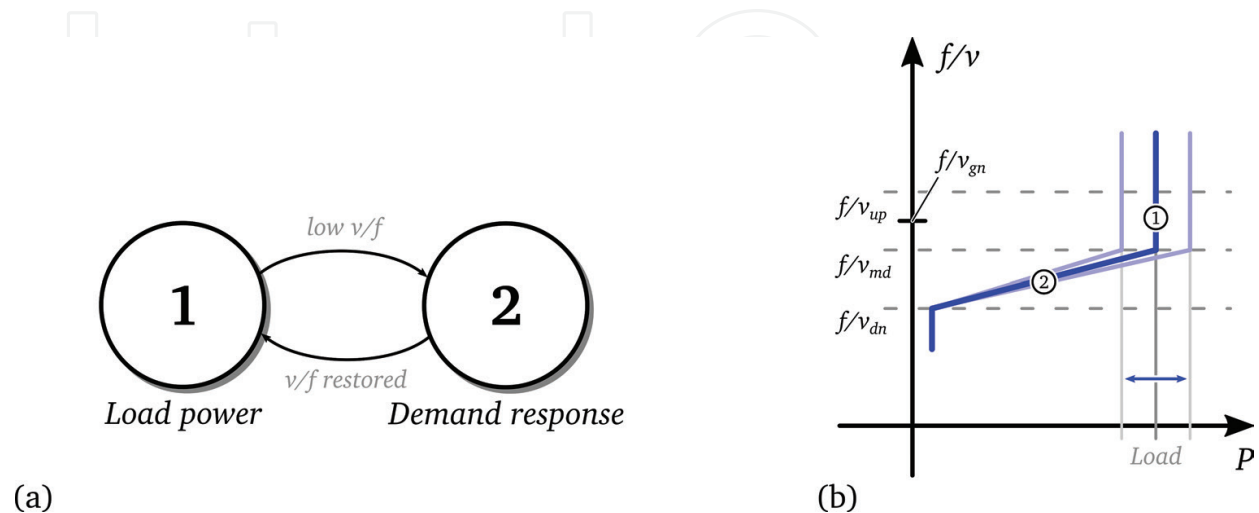


Figure 8. Load primary controller operation modes.

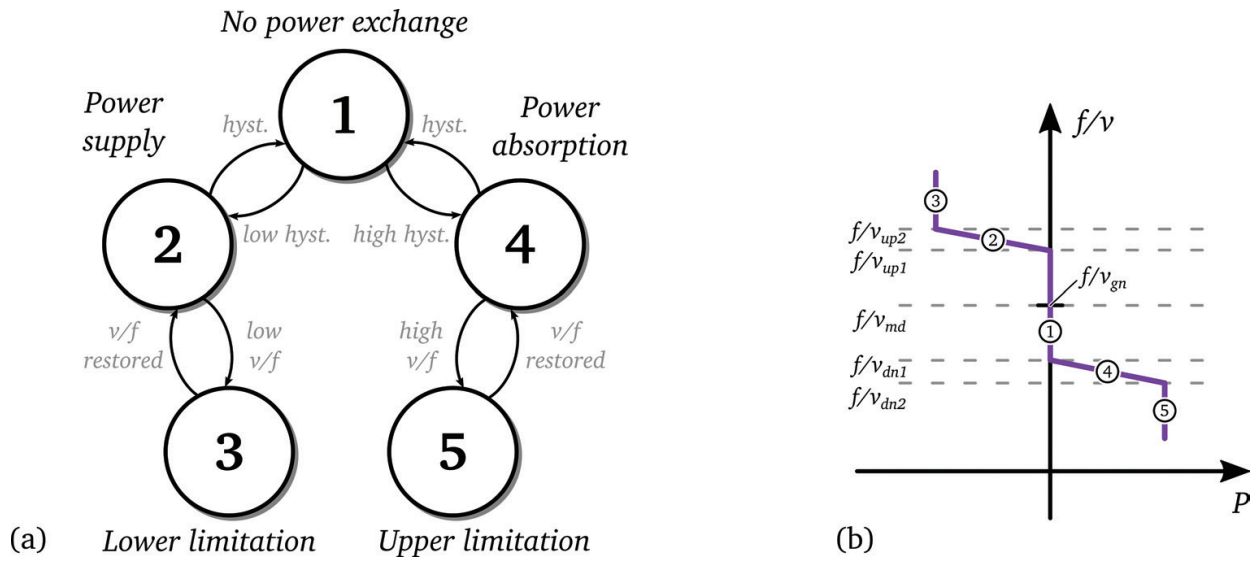


Figure 9. Grid connection primary controller operation modes.

of the system. An example of this situation is an excess of generated energy that causes an increment in the voltage or frequency; as our purpose is to extract as much energy as possible from RESs, we could employ the connection to the mains grid to send this extra power to the grid.

3.5. Interface converters

Interface ac-dc converters located along the microgrid provide an extra degree of freedom in the management of microgrids, as we can control them to perform diverse operations. The most typical approach would be to employ these converters to compensate the v/f deviations in the ac and dc subgrid of the hybrid microgrid [5, 22, 24]. The converters would transfer power from one subgrid to the other in order to equalize the excess of generated or demanded power at both systems.

As shown in Figure 10, interface converters carry out the power transfer between different subgrids with a droop controller. Unlike classical approaches, this droop is based on the difference between the frequency deviation in the ac subgrid and the voltage deviation in the dc part.

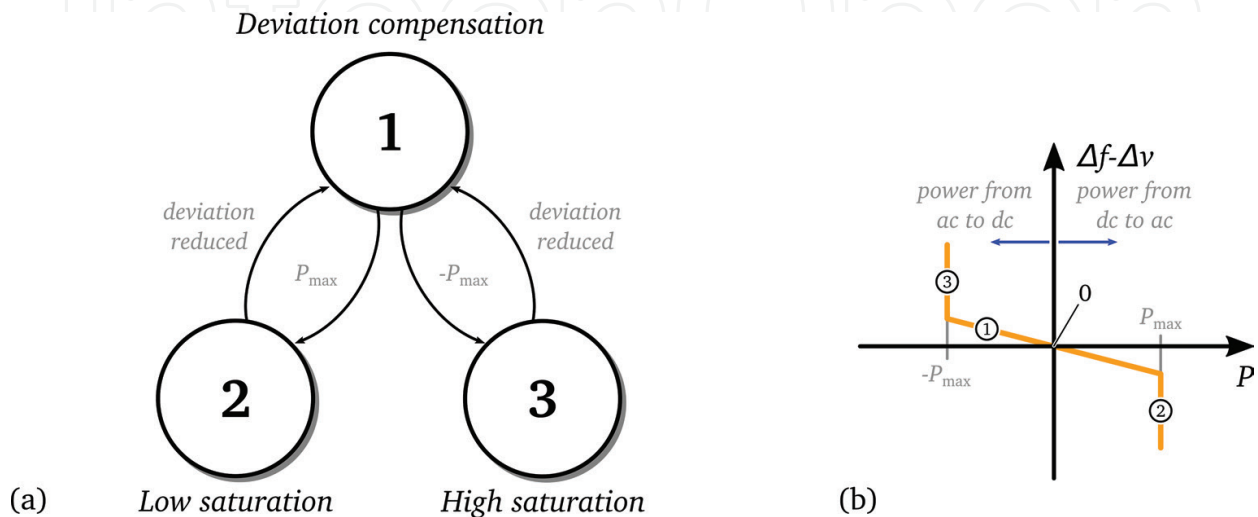


Figure 10. Interface converter primary controller operation modes.

Whenever there is a mismatch between these deviations, ac-dc converters located in the microgrid will transfer power to balance them. Modes 2 and 3 correspond to the maximum power that ac-dc systems can transfer in both directions.

According to Ref. [5], other techniques can be employed in the control of interface converters integrated at hybrid ac/dc microgrids such as the state of charge balancing of ESSs located in the ac and dc subgrid of the system.

4. Simulation results

We have carried out different simulations in the Matlab/Simulink® environment in order to observe the operation modes of primary controllers of a hybrid ac/dc microgrid.

4.1. Simulation scenario

A generation system, a storage system, and a load in the ac as well as dc subgrid of the microgrid compose the simulation scenario, and an interface ac/dc converter links these subgrids (**Figure 11**). We must mention that in this case, the hybrid microgrid also includes a connection point to the main ac grid in order to observe its behavior. As shown in the following sections, the islanded operation is a particular case of microgrids connected to the main grid; the difference is that islanded microgrids do not exchange any power with this grid.

In order to evaluate the behavior of the different agents connected to the hybrid ac/dc microgrid, we introduce a power disturbance in the ac subgrid of the microgrid. The results would be equivalent if we introduce the disturbance in the dc part, so for the sake of simplicity we do not contemplate this case in this chapter.

Figure 12 shows the primary curves employed for ESSs, DG systems, loads, and the connection to the main grid. The purpose is to validate the operation modes of the different agents participating in the regulation of the microgrid, so we have made no distinction in the configuration of DG, ESSs, and loads of the ac and dc part.

In the proposed scenario, if the demanded and generated power is balanced, all systems remain in an equilibrium state and ac and dc buses remain at their rated values (**State 0**). When the voltage or frequency are out of their rated values, ESSs carry out the regulation of the bus based on a predefined droop curve as shown in **Figure 12 (State I)**.

When storage systems reach their boundary operation, the microgrid exchanges power with the main ac grid to carry out the regulation (**State II**). For instance, when the voltage or frequency reaches a certain upper boundary, instead of taking DG systems out of their maximum power point, the exceeding power is supplied to the main ac grid. This is a key aspect of systems connected to the main grid because energy from RESs is not wasted and could be beneficial from the point of view of the electric market.

A similar situation occurs when the voltage or frequency fall below the limit; instead of reducing the power consumed by loads—that could lead to a malfunction of the load—this lack of power is covered by absorbing power from the main grid (**State II**).

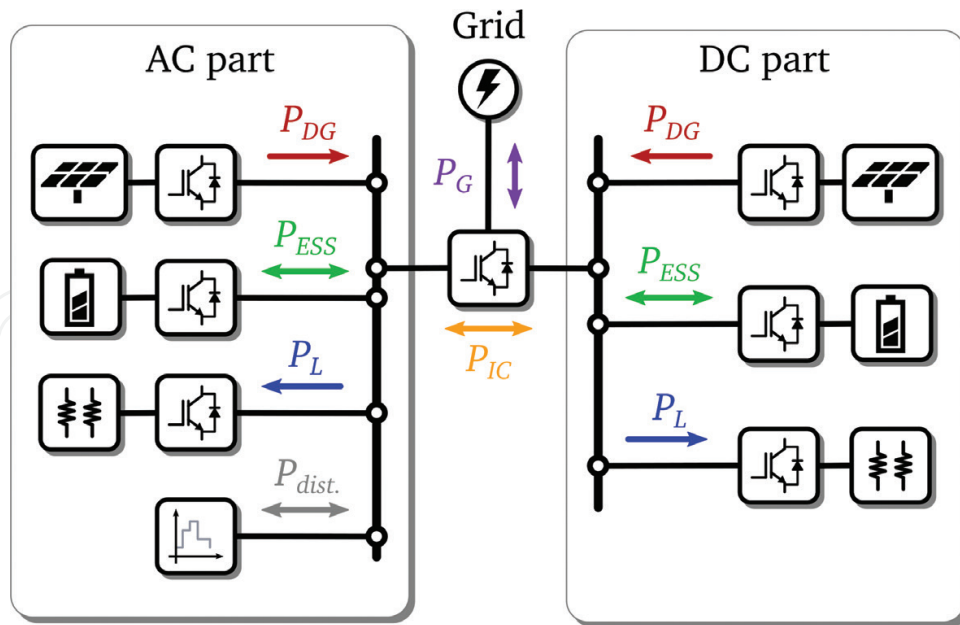


Figure 11. Simulated hybrid ac/dc microgrid scenario.

Usually the exchange of power with the main grid is limited—either by technical or by economical limitations—so when the voltage or frequency reaches the next upper or lower limit, generation systems, and loads are employed to contribute in the power regulation. Therefore, **State III** occurs when DG systems are out of their MPP and are controlled by a droop curve to regulate the power they generate. **State IV**, on the other hand, relates to the situation where loads reduce their consumed power, also known as demand-response.

On an islanded system, where no power can be exchanged with the main grid, if storage systems reach their upper or lower boundaries of operation, DG systems and loads directly carry out the regulation. This means there would not be any State II, and the system would directly enter into the State III or IV.

4.2. Modes of operation under disturbances

In order to reproduce the states mentioned in Section 4.1, we have simulated two different power disturbances, a positive and a negative step-shaped profile. We must mention that all

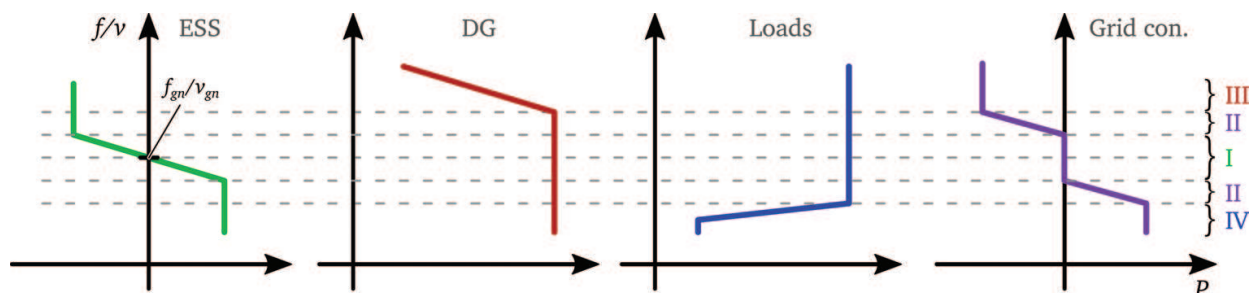


Figure 12. Primary controllers of the simulated scenario.

the variables of the following simulations are normalized and shown in per unit (p.u.) values to facilitate the analysis.

4.2.1. Positive power disturbance

The aim of this simulation is to observe the modes of operation of ESS, DG systems, and the grid connection for positive power disturbances or deviations occurring in the microgrid.

Figure 13 shows the most relevant variables of the hybrid ac/dc microgrid during the simulation. We resume these parameters below:

- AC subgrid: we show the frequency and the powers of the DG, ESS, and load. The sign of powers is determined based on whether the device supplies (positive sign) or absorbs (negative sign) power from the ac bus. Therefore, the power of DG systems has a positive sign whereas we represent load power with negative sign.
- DC subgrid: regarding the dc subgrid of the microgrid, we represent the voltage and powers in the figure. The sign of these powers are determined following the same rule as in the ac part.
- Disturbance power: we illustrate the power profile separately and its sign is dependent on whether the power is supplied or absorbed from the ac bus.
- Interface converter: we also illustrate the power transferred between the ac and dc subgrids separately in the graph. Positive power means the power is transferred from the ac subgrid to the dc one, and vice versa.

As we can observe, in the figure we can distinguish different stages during the simulation, based on the values of the frequency and voltage of the hybrid ac/dc microgrid.

The system begins at an equilibrium state with no power disturbance, which in this case is named State 0. At this stage, the demanded and generated power are balanced so the ac and dc buses remain at their rated values.

At the instant $t = 1$ s, a positive power step is introduced and therefore ESSs start regulating the bus by absorbing power, entering into State I. The interface converter transfers the power from the ESS located in the dc subgrid to the ac one in order to compensate v/f deviations in the system, as previously explained in Section 3.5.

At $t = 2$ s, a higher power disturbance is introduced in the system and ESSs continue regulating the bus in State I until they reach their maximum power value. When this boundary is exceeded ($v/f = 1.03$ p.u.), the system enters State II and the extra power is supplied to the main ac grid.

Similarly, at $t = 3$ s, the power disturbance is increased and the microgrid continues supplying power to the main grid in State II until the maximum exchangeable power is reached. After exceeding this limit ($v/f = 1.06$ p.u.), the power supplied to the main grid is fixed and DG systems begin regulating the system.

After the instant $t = 4$ s, the disturbance is reverted and the system recovers its original equilibrium state.

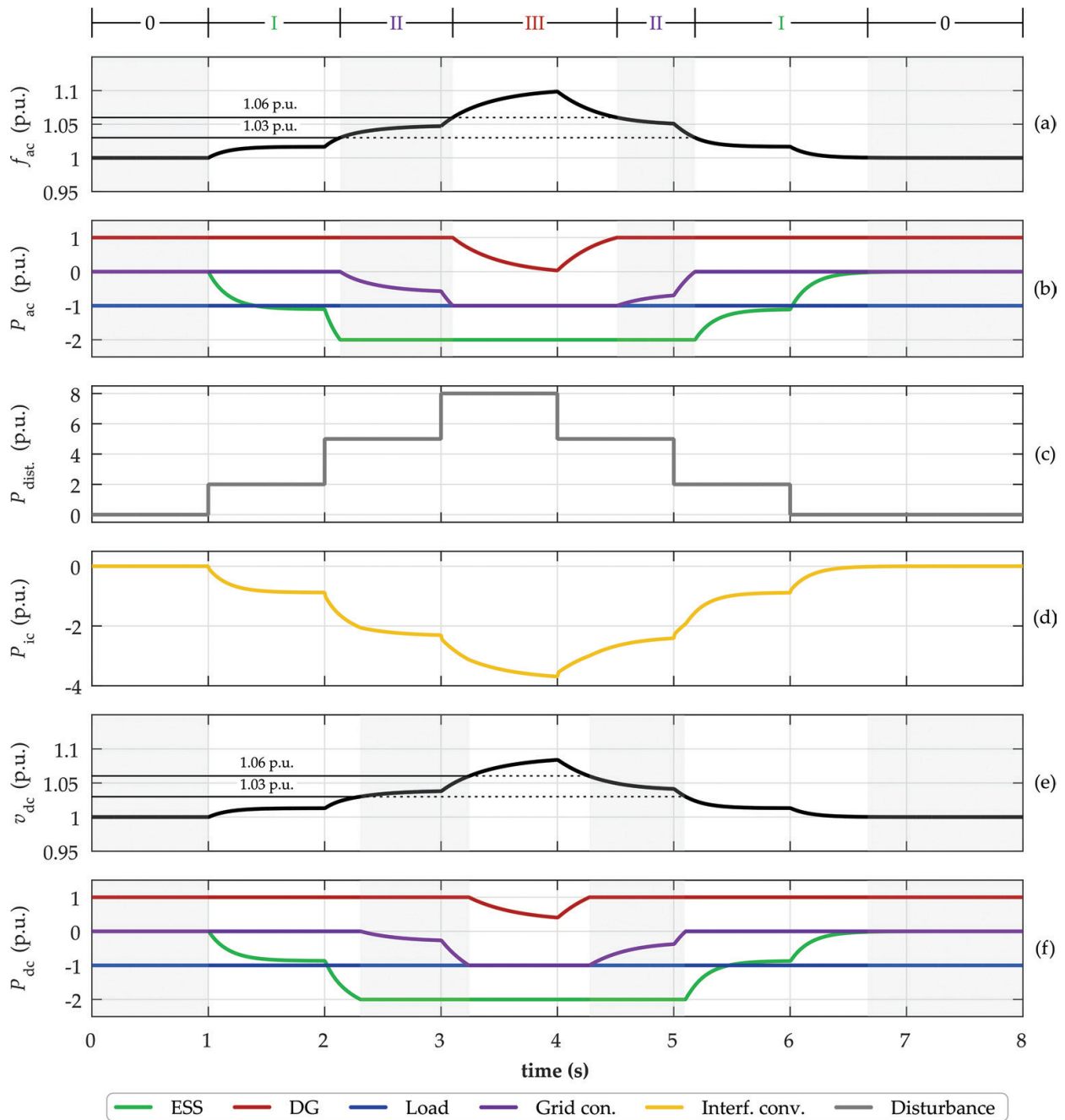


Figure 13. Microgrid response under positive power disturbances: (a) ac bus frequency, (b) ac subgrid power values, (c) disturbance power, (d) interface converter power, (e) dc bus voltage, and (f) dc subgrid power values.

In this simulation, we can see that the interface converter transfers power from the dc subgrid to the ac one in order to compensate the power deviations in both systems. However, it can be also noticed that the frequency in the ac grid and the voltage in the dc one do not reach their upper values at the same time, making the grids to change of state at different instants.

4.2.2. Negative power disturbance

In the following simulation, the main purpose is to observe the mode of operation of not only ESSs and the connection to the main grid but also the behavior of loads when lower limits

of v/f are reached. Therefore, in this case, the power disturbance of Section 4.2.1 has been inverted, emulating different values of demanded power.

We show the most relevant parameters of the hybrid ac/dc microgrid for this simulation in **Figure 14**. As we can observe, the system goes through a very similar process as in the previous case. The difference is that the voltage as well as frequency decrease instead of increasing due to the negative power disturbance.

In this context, the system begins in State 0 at an equilibrium point and enters into State I when the first negative power step is introduced. Afterwards, with the second power step the

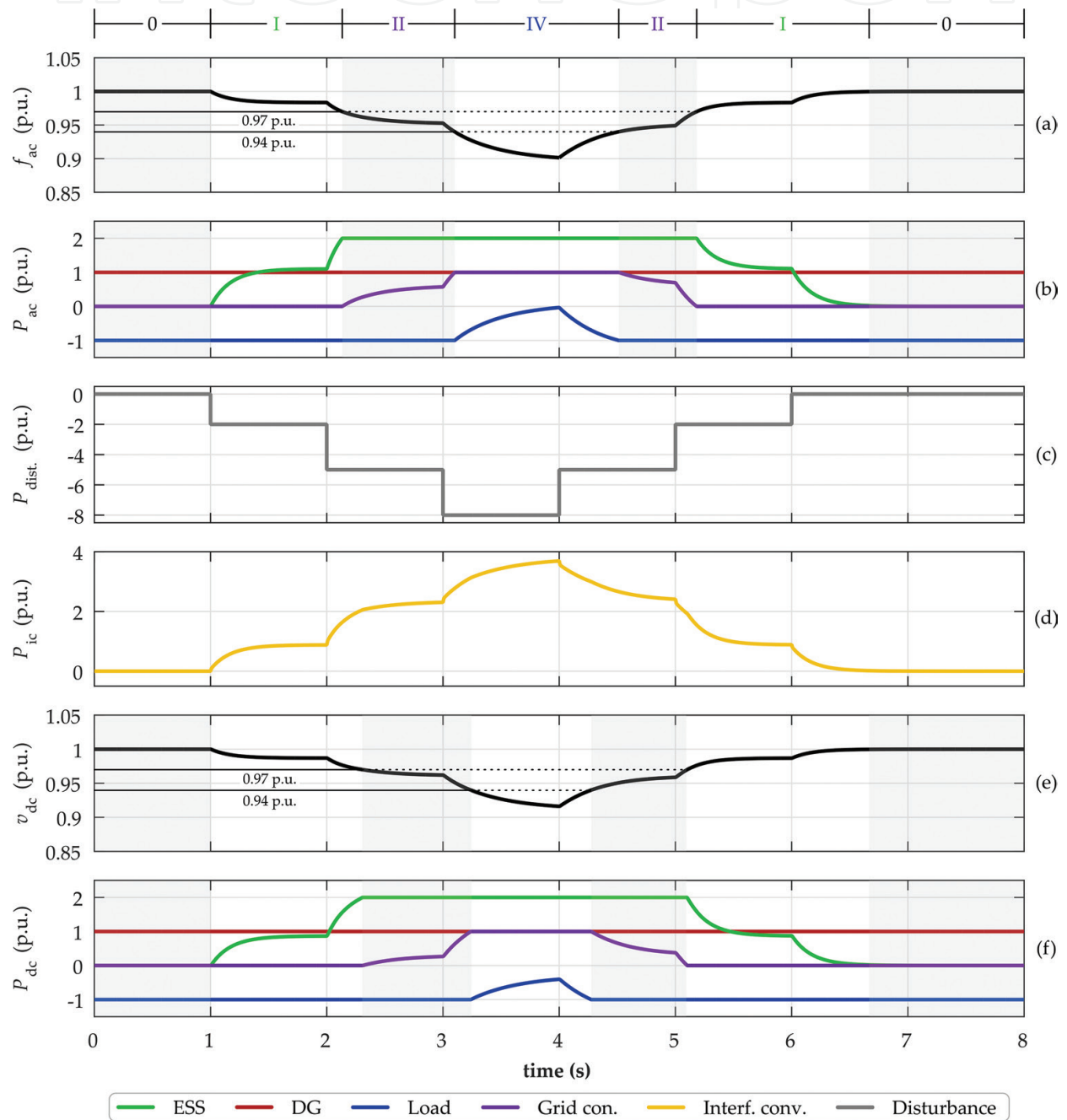


Figure 14. Microgrid response under negative power disturbances: (a) ac bus frequency, (b) ac subgrid power values, (c) disturbance power, (d) interface converter power, (e) dc bus voltage, and (f) dc subgrid power values.

microgrid reaches the $v/f = 0.97$ p.u. limit and enters into State II, where the lack of power is handled by absorbing power from the main grid. Finally, with the third negative power step the system reaches the $v/f = 0.94$ p.u. limit and, as no more power can be absorbed from the grid, loads begin reducing their demanded power (State IV).

In the proposed configuration, all the systems attached to the hybrid microgrid participate in the regulation of the system at different conditions. This structure facilitates the analysis of the mode-adaptive control techniques, but in a more realistic environment the most optimal approach would be to take advantage of the diverse characteristics of ESSs, DG systems, loads, and converters to design a bus regulating strategy composed by a mix of these systems for the entire v/f range.

5. Conclusions

In this chapter, the hierarchical control of microgrids has been initially revised, showing that this operation concept is very similar to the one employed in the conventional ac grid. One of the main differences is that, at microgrids, classical synchronous generators are replaced by converter-interfaced DG and ESSs, drastically reducing the inertial response of the system. In order to cope with this problem, the controllers of converter-interfaced devices are equipped with more advanced primary level techniques that contribute in the regulation of the microgrid.

Throughout the chapter, we have studied the different modes of operation of primary techniques and lower-level controllers of converter-interfaced generation, storage, loads, and other devices. Regarding lower-level techniques, we have shown that we can configure regulators to respond differently under power disturbances, providing more or less “inertial behavior.” In the case of upper-level/primary controllers, we have carried out a thorough analysis of their most relevant modes of operation. We can design these controllers to behave differently—by contributing in the bus regulation or not—depending on certain conditions such as the voltage or frequency level in the microgrid. This strategy is also known as a mode-adaptive control, as generation, storage systems or loads adapt their mode of operation depending on some external condition.

The simulations carried out in this chapter demonstrate that a mode-adaptive control is very useful to take advantage of DG systems and loads. In the proposed case, DG systems—which are usually based on RES—are only taken out of their MPP when the voltage or frequency of the bus reach a very high boundary, maximizing the energy produced. Similarly, loads only contribute in the regulation of the system when the voltage or frequency reaches a very low level, which avoids any possible malfunction of these devices. Although the proposed configuration is adequate to observe the mode-adaptive control operation of each device attached to the microgrid, throughout the chapter we highlight that the most optimal approach would be to design a bus-regulating strategy for the entire operation range composed by a combination of ESSs, DG systems, loads, and converters, taking advantage of their different dynamic characteristics.

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