

École polytechnique de Louvain

Dual Linear Active Disturbance Rejection Control Applied to Grid-Forming Converters

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Abstract

The development of renewable energy sources in the context of the energy transition leads to a rapid increase in the use of converters in the electrical grid. This implies new challenges, such as physical limitations of converters, or grid stability and inertia. To address those, the control of the converters is the center of the subject. Much research is underway on Grid-Forming (GFM) control, and in particular that which mimics legacy generators, the Virtual Synchronous Generator (VSG) control. At UCLouvain, research is ongoing to further improve this control by adding a Linear Active Disturbance Rejection Control (LADRC) algorithm to it. The purpose is to make the converter response more flexible and predictable in the face of the system's unknowns.

This master thesis studies the application of a second LADRC to the converter control. While the first LADRC is dedicated to the active power and frequency loop, the second LADRC is dedicated to the reactive power and voltage loop. Theoretical analyses have shown the potential of using two LADRCs in a simplified system, with a semi-analytic approach. Then different models have been discussed and analyzed parametrically in time-domain, and small-signal stability is investigated. Finally, more complete models have been simulated to take a larger scale view. Though further research is necessary to justify the use of a second LADRC.

Résumé

Le développement des sources d'énergies renouvelables dans le contexte de la transition énergétique mène à une augmentation rapide de l'utilisation des convertisseurs dans le réseau électrique. Cela implique des nouveaux défis, tels que les limitations physiques des convertisseurs, ou la stabilité et l'inertie du réseau. Pour y répondre, le contrôle des convertisseurs est au centre du sujet. Beaucoup de recherche est faite sur le contrôle « formeur de réseau », et en particulier celui qui imite les générateurs habituels, le contrôle « générateur synchrone virtuel ». À l'UCLouvain, de la recherche est en cours pour améliorer davantage ce contrôle en y ajoutant un algorithme de « contrôle actif de rejet de perturbation linéaire » (LADRC). L'objectif est de rendre la réponse du convertisseur plus flexible et prévisible face aux inconnues du système.

Ce mémoire de master étudie l'application d'un second LADRC au contrôle du convertisseur. Tandis que le premier LADRC est dédié à la boucle en puissance active et fréquence, le second LADRC est dédié à la boucle en puissance réactive et tension. Des analyses théoriques ont montré le potentiel d'utiliser deux LADRCs dans un système simplifié, avec une approche semi-analytique. Ensuite différents modèles ont été discutés et analysés de façon paramétrique en domaine temporel, et la stabilité petit-signal a été étudiée. Finalement, des modèles plus complets ont été simulés pour prendre une vue à plus large échelle. Cependant, des recherches supplémentaires sont nécessaires pour justifier l'utilisation d'un second LADRC.

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Abbreviations

AC	Alternating Current
aFRR	automatic Frequency Restoration Reserve
CESA	Continental Europe Synchronous Area
DC	Direct Current
EAC	Equal Area Criterion
ENTSO-E	European Network of Transmission System Operators
ESO	Extended State Observer
EUT	Equipment Under Test
FCR	Frequency Containment Reserve
FRT	Fault Ride Through
GFL	Grid-Following
GFM	Grid-Forming
HV	High Voltage
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
LADRC	Linear Active Disturbance Rejection Control
P-LADRC	LADRC applied to the P entry of the P-f loop
Q-LADRC	LADRC applied to the Q entry of the Q-V loop
V-LADRC	LADRC applied to the V entry of the Q-V loop
PV-LADRC	Simultaneous application of P-LADRC and V-LADRC
LTI	Linear Time-Invariant
MIMO	Multiple-Input Multiple-Output
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PCS	Power Collection System
PD	Proportional & Derivative (controller)
PI	Proportional & Integral (controller)
PID	Proportional & Integral & Derivative (controller)
PLL	Phase Locked Loop
PoC	Point of Connection
PPM	Power Park Module
PWM	Pulse Width Modulation
RfG	Requirements for Generators
RK45	Runge-Kutta method of order 4 or 5
RoCof	Rate of Change of Frequency
SCR	Short-Circuit Ratio
TSO	Transmission System Operator
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine (= VSG)

Variables

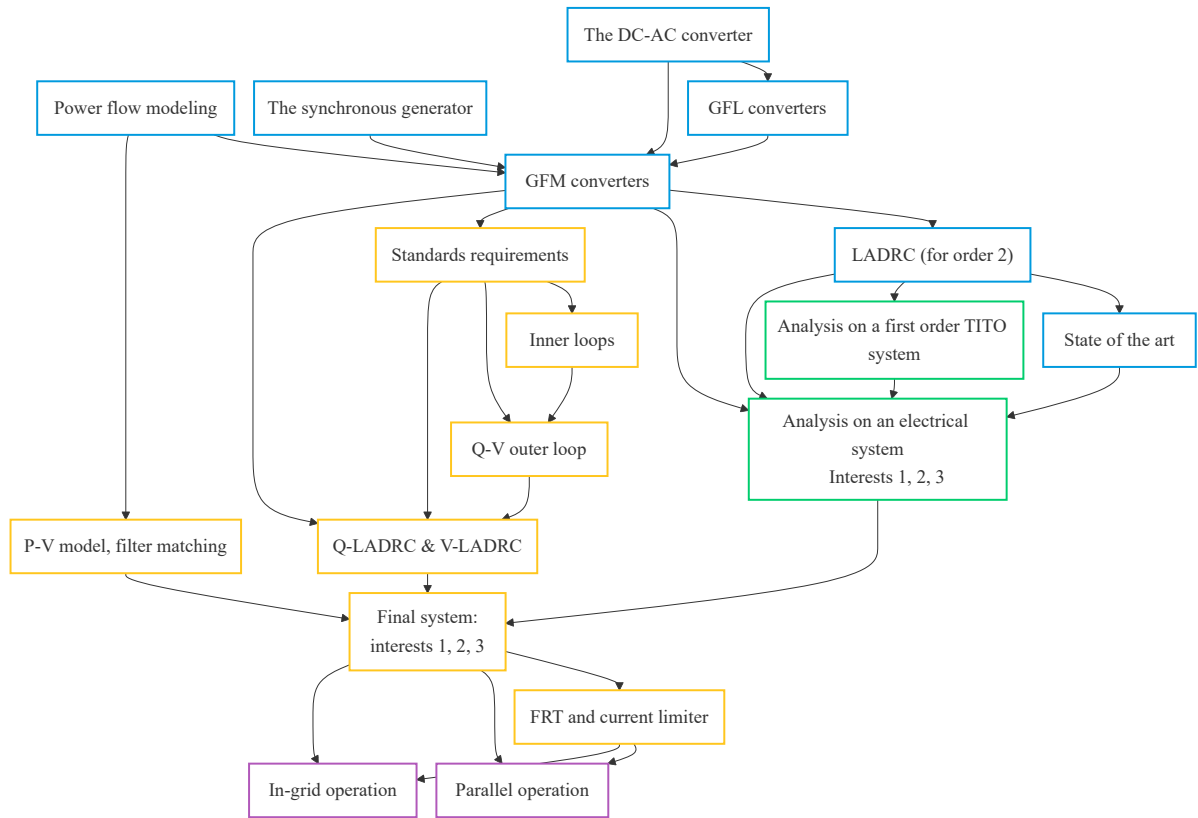
The recurring variables are listed below. The other variables are clearly defined where they are used.

$b_{0,P}$	Estimate of the internal loop for the active power
$b_{0,V}$	Estimate of the internal loop for the voltage
C_f [s]	Normalized capacitance of the filter
D	Damping coefficient
δ [rad or °]	Phase angle of the converter (relatively to the infinite grid phase angle 0°)
ΔV	Voltage difference between the converter output and the infinite grid voltage
D_p	P - f droop coefficient (for the droop-based GFM)
D_q	Q - V droop coefficient (for the outer loop)
f [Hz]	Frequency (general)
H [s]	(Virtual) inertia constant
I [p.u.]	Current flowing through the grid
I_c [p.u.]	Current flowing in the converter (and R_f , X_f)
$k_{p,i}$, $k_{i,i}$	Proportional and integral gains of the inner current loop
$k_{p,v}$, $k_{i,v}$	Proportional and integral gains of the inner voltage loop
$K_{p,P}$ and $K_{d,P}$	Proportional and derivative gains for the P-LADRC PD controller
$K_{p,V}$	Proportional gain for the V-LADRC P controller
ω [rad/s]	Angular frequency or angular speed (general)
$\omega_0, \omega_{0,P}, \omega_{0,Q}, \omega_{0,V}$ [rad/s]	ESO observer bandwidth for the (P-) (Q-) (V-) LADRC
ω_B [rad/s]	Base frequency ($=2\pi \cdot 50$ [rad/s])
$\omega_{desired}$ [rad/s]	Desired cutoff frequency for the replacement dynamics
ω_{GFM} [p.u.]	Frequency generated by the VSG
ω_{model} [rad/s]	Cutoff frequency of the model dynamics
$\omega_n = \omega_g = \omega_{ref} = 1$ [p.u.]	Nominal grid frequency
ω_v [rad/s]	Cutoff frequency of transient virtual resistance high-pass filter
P [p.u.]	Active power (general)
P^* [p.u.]	Main output of the P-LADRC controller, active power target for the VSG
P^{**} [p.u.]	Main input of the P-LADRC controller, active power target
P_{ref} [p.u.]	Active power set-point (reached in case of nominal frequency)
ϕ, φ	Phase angle (general)
Q [p.u.]	Reactive power (general)
Q_{ref} [p.u.]	Reactive power target
R	Resistance (general)
R_f [p.u.]	Resistance of the filter
R_g [p.u.]	Resistance of the grid

R_v [p.u.]	Damping virtual resistance
σ_a	External droop coefficient for the frequency
σ_b	External droop coefficient for the voltage
σ_p	P - f droop coefficient (for the VSG)
τ_i [s]	Time constant of the inner current loop
τ_f [s]	Q - V droop low-pass filter time constant
τ_v [s]	Time constant of the Q - V outer loop
$\tau_{v,inner}$ [s]	Time constant of the inner voltage loop
θ [rad]	Angle of the equivalent impedance phasor
θ_{grid} [rad]	Phase angle of the infinite grid (absolute)
$\theta_c = \theta_{GFM}$ [rad]	Phase angle of the (GFM) converter (absolute)
V^* [p.u.]	Main output of the V-LADRC controller, voltage target for the Q - V loop
V^{**} [p.u.]	Main input of the V-LADRC controller, voltage target
$V_{ref}, V_{PCC,ref}$ [p.u.]	Reference voltage set-point
V_c [p.u.]	Converter output voltage
V_{DC}	Voltage across the DC link capacitor
$V_n = V_g = 1$ [p.u.]	Infinite grid voltage
V_{PCC} [p.u.]	Voltage at PCC
X	Reactance (general)
X_f [p.u.]	Reactance of the filter
X_g [p.u.]	Reactance of the grid
Z [p.u.]	Impedance (general)
Z_g [p.u.]	Grid equivalent impedance

Structure

The content of this work is organized with the following indicative structure.



- Chapter 1: Technical background
- Chapter 2: LADRC Analysis, theoretical insight
- Chapter 3: Design and analysis of the Q - V loop
- Chapter 4: More realistic situations
- Direct logical origin

Introduction

Throughout history, the world has faced numerous challenges, and our contemporary era has no exception. Nowadays, climate change is becoming a major concern, and people all over the world are working hard to tackle it. On the other hand, the search for human progress - longevity, health, knowledge, safety, freedom - has never seemed to have so few limits, except for the availability of energy [1][2][3].

If energy is the engine of civilization, it is also the central knot of its problem. In 2024, the fossil part of the 177 [PWh] of global primary energy consumption (Fig. 1) has emitted the majority of the 38.6 billion tons of CO₂ associated to fuels and industry (Fig. 2) [4][5].

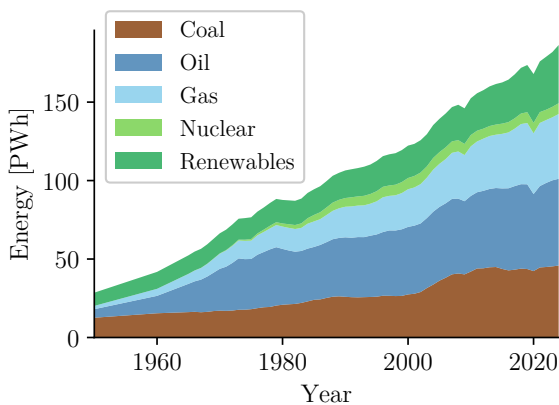


Figure 1: World primary energy consumption by source type, adapted from [4]. No substitution can be clearly observed.

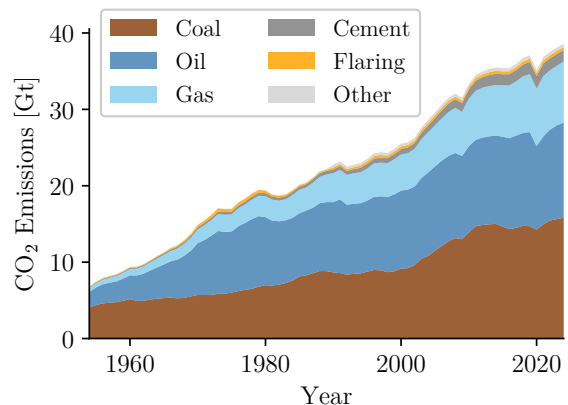


Figure 2: World CO₂ emissions by fuel or industry type, adapted from [5]. Emissions continue to increase from every sources.

The objective is clear: energy must be decoupled from greenhouse gas emissions. And fortunately, solutions exist. Those include electricity production from solar and wind power, with battery storage, and large-scale electricity exchanges between distant regions with HVDC lines. As shown in Fig. 3, the renewable electricity sources are by far less emitting than fossil sources [6]. Nowadays, 59% of the global electricity is still produced by fossil fuels, but this trend has already been downward for the past few years (Fig. 4) [7].

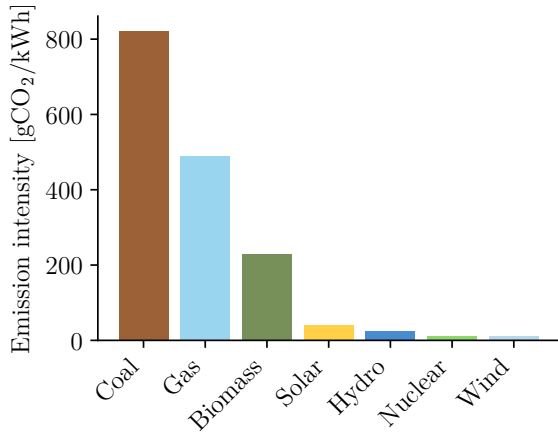


Figure 3: Reference emission intensity for different types of electricity sources, adapted from [6].

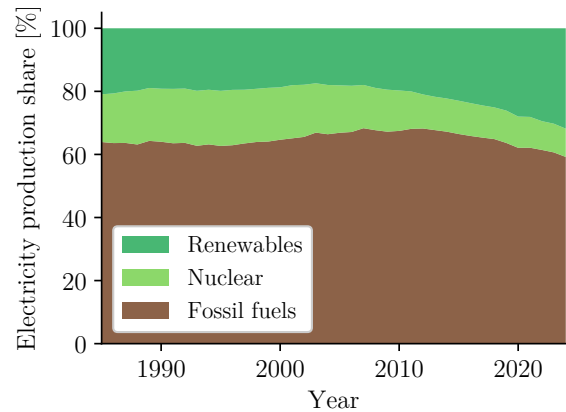


Figure 4: World electricity mix, adapted from [7]. Relative fossil fuels share tends to decrease since the 2010s.

However, these solutions also come with their share of drawbacks. Among them, the stability of the electrical grid is severely compromised [8][9][10].

Indeed, while conventional power plants provide a natural inertia that stabilizes the network thanks to the large mass of their rotating rotor, the mentioned solutions can only work thanks to power electronics converters which may not be as suitable. Indeed, these renewable energy sources naturally imply a *Direct Current* (DC) side, whereas electricity is transported and distributed in *Alternating Current* (AC). Consequently, a power electronics DC-AC converter, also known as an *inverter*, is needed [11][12][13].

For these converters, creating a sinusoidal wave (AC) from a constant source (DC) is not an easy task. An electronic controller, like a small embedded computer, must be used to drive the converter as desired. The control of the converter is essential to make it produce a precisely appropriate voltage, with the right magnitude and frequency.

However there is not a single way of controlling a converter. Given the importance of successfully transitioning to more sustainable energy sources, much research is underway to control converters in a way that does not weaken the electrical grid.

In this work, a very particular control of converters is studied. A mathematical algorithm named *Linear Active Disturbance Rejection Control* (LADRC) has been applied to the *Grid-Forming* (GFM) control of converters. GFM control is already a subject on its own, and the use of one LADRC to control the frequency (or power) is already being studied. The novelty in this work is to use two LADRCs to control both the frequency (or power) and the voltage of the GFM converters.

It is a research project, meaning that there are still many unknowns on the subject. The objective of this work is to study whether such a control is relevant or not, as well as its limitations and opportunities.

- Chapter 1 first presents the important concepts concerning power systems in general. Next, the field of converter control is explained, including GFM control. Finally, the mathematics of LADRC are presented, along with the state of the art in its application to converters. The technical questions that this work could address are also discussed.
- Chapter 2 studies the use of two LADRCs in the frequency domain for a simplified system, with a semi-analytical approach. It should then be possible to establish theoretical expectations for the case of a real system.
- Chapter 3 analyzes the application of the two LADRCs to a real system using a numerical approach. The first LADRC is used in the same loop already studied in the literature. For the second LADRC, the voltage loop is designed based on European standards requirements. Two ways of using the second LADRC are then compared. Next, the final complete model is summarized and analyzed. Finally, the converter current limitation while using LADRCs is investigated. Time-domain simulations are compared with a code implementation of the equations. Small-signal stability of the considered systems is studied parametrically.
- Chapter 4 finally considers more realistic situations to observe possible interactions between multiple converters. First, parallel operation of two converters is examined. Second, a more advanced model of grid is considered based on the IEEE 9-bus model. A futuristic scenario with a generalized use of converters in the grid is examined, with the perspective of showing a possible advantage of using LADRCs.

Chapter 1

Technical background

In this chapter

A few concepts are important to understand the technical developments covered in the next chapters. To summarize, this first chapter will explain:

1. Power flow modeling: in the transmission grid, active power depends mainly on the phase angle difference, while reactive power depends mainly on the voltage magnitude difference between two nodes.
2. The synchronous generator: the dynamic response is governed by the rotating mass of the rotor, giving it an *inertia*. The static operation is governed by *droop control*.
3. The DC-AC converter: made of transistors, the converter behavior only relies on its control strategy.
4. Grid-Following (GFL) converters: the legacy solution of control. Dependency on measurements, notably the PLL, is the main drawback of this strategy.
5. Grid-Forming (GFM) converters: the emerging solution of control. Regulation of active power with a droop allows synchronization without PLL. The inertia of the synchronous generator can be virtually implemented to imitate traditional generators dynamics.
6. Linear Active Disturbance Rejection Control (LADRC) applied to GFM: perturbations and unknowns can be rejected to obtain a desired and predictable fixed-order response.
7. State of the art: LADRC has already been applied to the P - f loop. Resonances and stability issues have already been studied. Since this loop is coupled with the Q - V loop, objectives of this work are established for the use of a second LADRC in GFM converter control.

1.1 Power flow modeling

In this section

In a transmission grid containing sources and loads, power is transmitted through lines. Active power depends mainly on the phase angle difference, while reactive power depends mainly on the voltage magnitude difference between two nodes.

From the source to the load, electrical power is transported through an intricate AC electrical network. This can be viewed as a grid of transmission lines. Power flow is the overall analysis of the situation. It determines how much power is produced by each source and how much is transported by each line in the network. By the conservation of energy, the power produced by the sources balances the power consumed by the loads, including losses in the lines.

To compute the power flow, an electrical model of the situation must be considered. A model does not necessarily have to be exact, but it must be close enough to reality to fit the situation operationally. For instance, a transmission line is not simply a perfect wire, but rather an integration of infinitesimal lengths with infinitesimal series impedances and parallel admittances. However, short overhead AC lines can be approximated by a simple series impedance [14].

To analyze more locally the power flow from a generator to a load through the grid, let us consider the simplified model represented in Fig. 1.1. This schematic is a single-phase equivalent of the real life three-phase power system. The generator is modeled by a voltage source $\bar{V}_1 = V_1 \angle \delta$. Assuming a strong network (infinite bus), the load seen from the generator can be modeled by a voltage source $\bar{V}_2 = V_2 \angle 0$. Both are connected through an equivalent impedance $\bar{Z} = Z \angle \theta$ [15][16].

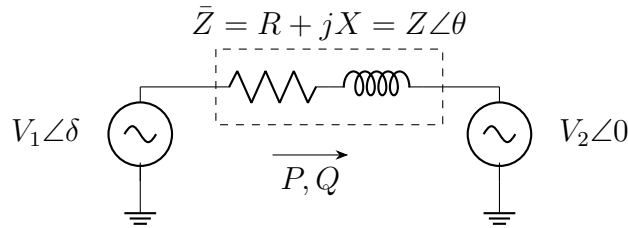


Figure 1.1: Model of power flowing through a line.

In *per unit*, the power flowing from the source is written:

$$P_1 = \frac{V_1^2}{Z} \cos \theta - \frac{V_1 V_2}{Z} \cos (\theta + \delta) \quad (1.1)$$

$$Q_1 = \frac{V_1^2}{Z} \sin \theta - \frac{V_1 V_2}{Z} \sin (\theta + \delta) \quad (1.2)$$

Assuming a lossless line model, which is approximately the case for transmission lines,

$\theta \approx 90^\circ$ ($R = 0, \bar{Z} = jX$) [17]. Eqs. (1.1) and (1.2) become:

$$P \approx \frac{V_1 V_2}{X} \sin \delta \quad (1.3)$$

$$Q \approx \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos \delta \quad (1.4)$$

From (1.3), it can be easily seen that active power is positive (flowing from the source to the load) when the generator phase $\delta > 0$. It is quite intuitive: to carry the load, the generator must be *leading* (i.e. in phase advance).

Those equations are non-linear, hence they are often linearized for small values of δ and $\Delta V = V_1 - V_2$ (small value of ΔV implies $V_1 \approx V_2$, in practice ≈ 1). Hence (1.1) and (1.2) can be approximated by a linear system [16]:

$$\begin{bmatrix} P \\ Q \end{bmatrix} \approx \frac{1}{R^2 + X^2} \begin{bmatrix} X & R \\ -R & X \end{bmatrix} \begin{bmatrix} \delta \\ \Delta V \end{bmatrix} \quad (1.5)$$

Equation (1.5) show that the active and reactive powers are coupled, since they both depend on the two variables δ and ΔV .

If lossless lines are considered ($R = 0$), (1.3) and (1.4) give the following linear system:

$$\begin{bmatrix} P \\ Q \end{bmatrix} \approx \begin{bmatrix} \frac{1}{X} & 0 \\ 0 & \frac{1}{X} \end{bmatrix} \begin{bmatrix} \delta \\ \Delta V \end{bmatrix} \quad (1.6)$$

Equation (1.6) show that the lossless lines assumption allows the decoupling of the active and reactive powers. An important rule of thumb can be here observed: active power is approximately proportional to the generator phase angle δ while reactive power is approximately proportional to the voltage difference ΔV .

When dealing with alternating voltages and currents synchronized in frequency, it is common practice to use the phasor notation in complex numbers. For instance, $\bar{V} = V \angle \phi$ is the phasor representation for the time-domain voltage $v(t) = V \cos(\omega t + \phi)$, where $\omega = 2\pi \cdot f$ [rad/s] is the angular frequency (with f the frequency, typically 50 [Hz]), and ϕ [rad] the phase of the voltage (relatively to a voltage reference with phase 0 [rad/s] and the same frequency).

However when the frequency of two sources is not exactly the same, their instantaneous phase difference is not constant anymore.

Let two voltages be $v_1(t) = \Re(V_1 e^{j(\omega_1 t + \phi_1)})$ and $v_2(t) = \Re(V_2 e^{j(\omega_2 t + \phi_2)})$. Their phase difference is written:

$$\delta(t) = \varphi_1(t) - \varphi_2(t) = (\omega_1 - \omega_2)t + (\phi_1 - \phi_2)$$

Consequently, phase angle difference δ is directly linked to the difference of angular frequencies ω_1 and ω_2 [18][19]:

$$\begin{aligned} \frac{d\delta}{dt} &= \omega_1 - \omega_2 \\ &= 2\pi(f_1 - f_2) \end{aligned}$$

Remark

f_1 can be different from f_2 for only a short duration, otherwise synchronism would be lost [11][20].

This means that phase angle difference δ is the integral of frequency deviation. Hence if the generator instantaneously turns faster than the grid frequency, angle δ and so active power P increase (the generator "leads more" than before). Oppositely, if the generator instantaneously turns slower than the grid, transmitted active power decreases [20].

1.2 The synchronous generator

In this section

Traditional generators are seen as a reference in power systems. To summarize, the dynamic response is governed by the rotating mass of the rotor, giving it an *inertia*. The static operation is governed by *droop control*.

The synchronous generator, represented in Fig. 1.2, is an electromechanical converter designed such that the mechanical rotation speed is physically linked to the generated AC electrical frequency [11]. The generator (typically) consists of a fixed stator on which the three-phase coils are mounted, and a rotating rotor which contains DC-powered field windings and possibly permanent magnets. The rotor is driven by a turbine which rotates thanks to an energy input (flow of water in the case of hydroelectricity, or steam cycle linked to nuclear fission or the combustion of gas, fuel oil, etc.). The rotation of the rotor relative to the stator allows the creation of induced voltage (electromotive force) through electromagnetic interactions between the coils [21].

Power conservation implies proportionality between produced current and effective resisting torque applied to the turbine. Once connected to the grid, active power is hence controlled with a feedback loop on the energy source [22]. Reactive power is controlled by acting on the field windings voltage [18][23].

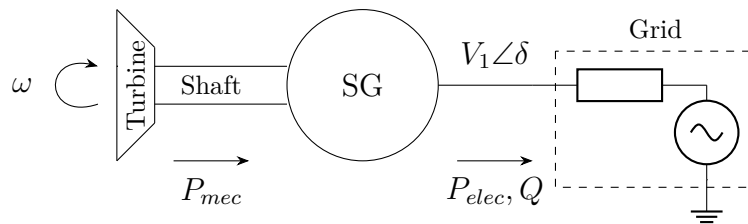


Figure 1.2: Schematic representation of a synchronous generator converting mechanical power into electrical power [16].

Dynamically, energy conservation implies a fundamental relation between power balance and rotation speed [15][19][24].

This relation is written:

$$\begin{aligned} P_{mec} - P_{elec} &= \frac{dE_{kin}}{dt} \\ &= \frac{d}{dt} \left(\frac{1}{2} J \omega^2 \right) \\ &= J \omega \frac{d\omega}{dt} \end{aligned}$$

Let us define the inertia constant $H = \frac{E_{kin}}{S_n} = \frac{J \omega_n^2}{2 S_n}$ [s], representing the duration during which the generator could provide nominal power S_n using kinetic energy depending on the moment of inertia J [$kg \cdot m^2$]. For $\omega \approx \omega_n$ (nominal frequency = $2\pi \cdot 50$ [rad/s]), the dynamic equation can be expressed:

$$2H \frac{d\omega}{dt} = \frac{\omega_n}{S_n} (P_{mec} - P_{elec})$$

In *per unit*:

$$2H \frac{d\omega}{dt} = P_{mec} - P_{elec} \quad (1.7)$$

This relation is quite intuitive: in steady-state (equilibrium), $\frac{d\omega}{dt} = 0$ implies the conservation of power ($P_{mec} = P_{elec}$). When the load (P_{elec}) increases but input power (P_{mec}) remains the same, the rotation speed of the rotor decreases (*Rate of Change of Frequency*, RoCoF $\frac{d\omega}{dt} < 0$) because kinetic energy of the rotating mass is converted into electrical energy. To re-accelerate, P_{mec} must increase (for instance by burning more fuel) [24][25].

With a damping term, the *per unit* relation can be written [15][19]:

$$2H \frac{d\omega}{dt} = P_{mec} - P_{elec} - D(\omega - \omega_g)$$

In a simple "1 source, 1 load" system, frequency control and power balance could be easily achieved with a PI controller in a feedback loop. Such a controller adapts its output with both a Proportional and an Integral action on an error between a measured quantity and the expected value. This typically allows canceling a static error that could occur with a simple P (Proportional) controller.

However in the case of a synchronous generator contributing in a large grid with a lot of other synchronous generators, each machine must, on its own scale, contribute avoiding a frequency collapse.

Since it is unrealistic to centralize the control of the entire fleet of generators in a large grid, a practical approach is to define individually a static law between grid frequency (hence rotor speed, because of synchronism) ω and mechanical power P_{mec} . This is called *droop control* and can be written [15][16]:

$$P_{mec} = P_{mec,0} + \frac{1}{\sigma_p} (\omega_n - \omega_{elec}) \quad (1.8)$$

This approach allows synchronous generators to individually increase their power when grid frequency decreases, and inversely decrease their power when grid frequency increases, in a compensation perspective. It allows the grid frequency to stabilize at a new working point (primary control, *Frequency Control Reserve*, FCR). On a longer timescale, a slower secondary control (*automatic Frequency Restoration Reserves*, aFRR) is needed to recover the desired nominal frequency ω_n [21][26], but this will not be discussed in this work since it is not essential for the functioning of the generator.

1.3 The DC-AC converter

In this section

Converters are power electronics devices. To summarize, converters are made of transistors, and the behavior only relies on the control strategy.

The DC-AC converter, also called *inverter*, allows converting a DC source (e.g. a photovoltaic installation) into an AC source that can be connected to the grid, as represented in Fig. 1.3. It mainly consists in pairs of transistors that act like switches, controlled at their base by a control signal, as represented in Fig. 1.4. This control signal allows creating synthetically the desired waveform on AC side.

However, since transistors act like switches, their control and output are nearly binary (either conducting or blocking). Hence it is generally not possible to create directly a sine waveform at the output. Instead, a *Pulse Width Modulation* (PWM) is used to control the converter. The principle of PWM is to produce a fast succession of ON-OFF states which, by means, interprets the desired waveform. This can be done, for instance, by comparing the reference signal (the desired sine) to a high frequency triangular carrier signal [21][27]. The output voltage of the transistors, being high frequency rectangles, must still be filtered to recover the final AC waveform [25][28] .

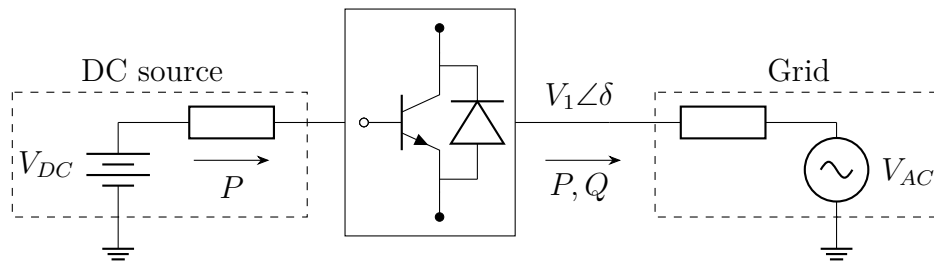


Figure 1.3: Schematic representation of a power electronics converter interfacing a DC source with an AC system, inspired from [16].

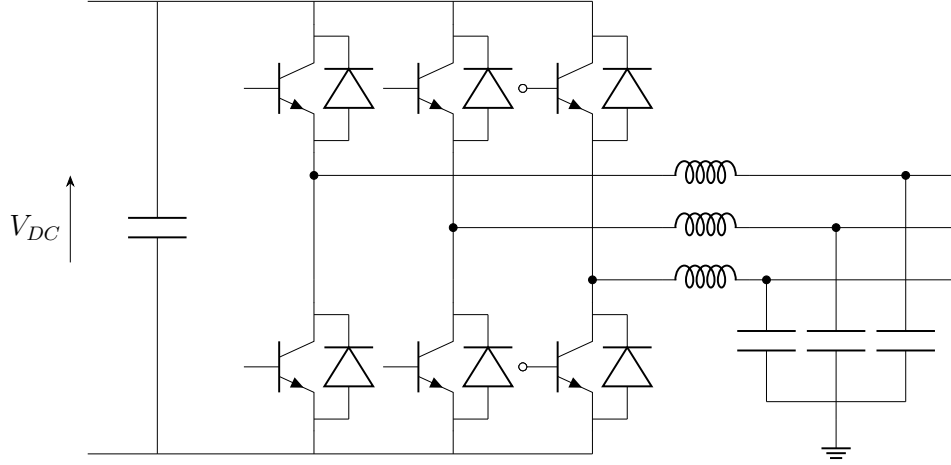


Figure 1.4: Example circuit of a three-phase DC-AC converter [16].

Once connected to the grid, active and reactive powers are controlled by varying the phase and the amplitude of the reference control signal, in accordance to (1.1) and (1.2). A DC-DC converter between the DC source and the inverter may also be used to adapt the DC-link voltage, which changes the available AC voltage range of the inverter.

However, without rotating mass, the dynamic behavior of the inverter is not as intuitive as for the synchronous generator. The angular frequency ω of the output being synthetic (asked with the control signal), the behavior of the converter may be completely different from that of the traditional generators, depending on how the converter is controlled. For instance, the RoCoF $\frac{d\omega}{dt}$ may not be directly dependent on the power balance, if such a dependency is not integrated in the control. To avoid losing the synchronism between the inverter and the grid, the control strategy is thus of the utmost importance.

1.4 Grid-Following (GFL) converters: the legacy solution

In this section

The most common way of controlling a converter is to make it follow the existing grid voltage and frequency. Hence Grid-Following converters act like current sources. To summarize, dependency on measurements, notably the PLL, is the main drawback of this strategy.

It is an absolute necessity for the converter output to be synchronized with the grid frequency, otherwise the converter would inevitably experience enormous current and power fluctuations. Intuitively, a frequency beat between the grid and the inverter output would inevitably create a moment where the instantaneous voltage of the network is at its maximum while that of the inverter is at its minimum, which would act like a short circuit.

The first solution, which is the most widely adopted, is to use directly the grid frequency for the control signal. The control sine wave at the correct frequency is then phase-shifted

by the adequate δ angle (in accordance to (1.1) and (1.2)), thanks to a feedback loop.

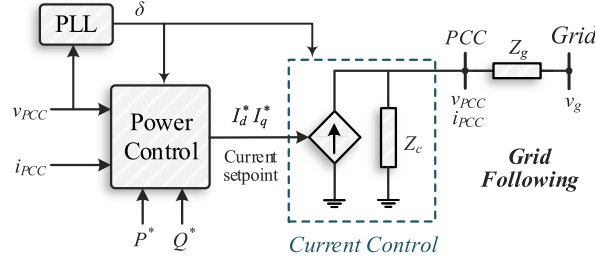


Figure 1.5: Grid-Following block diagram from [23].

As represented in Fig. 1.5, the reference phase and frequency at the operating point are obtained by a *Phase-Locked Loop* (PLL) from output voltage measurement. Assuming a stable voltage, the target powers P^* and Q^* are obtained with a fast control loop on the current. This control implies most of the time a PI controller on the current error that translates into a change of control signal [11][22][24]. (The output voltage is thus varied but the control is made on current.)

The current loop being fast, the output voltage amplitude and frequency are quickly adapted to the grid such that the current keeps constant. By doing it this way, the DC-AC converter acts like a *current source*. The output voltage amplitude and frequency may indeed vary freely provided that the current is the one that was requested. (The power must secondly be adapted to the change of voltage with a slower loop.) The output impedance of an inverter controlled in this way is $Z_c = \frac{\Delta V}{\Delta I} \approx \frac{\Delta V}{0} \rightarrow \infty$: it is the characteristic of a current source. The source *follows* both voltage amplitude and frequency, so such a control strategy is called *Grid-Following* (GFL) [23].

If Grid-Following control is widely used for DC-AC converters, it has however a few serious drawbacks especially for large-scale applications (e.g. HVDC converters).

First, GFL performance degrades considerably when the grid is "weak" (*Short Circuit Ratio*, $SCR < 3$), worsening the voltage stability. The interaction between the PLL and the high-impedance grid can cause low-frequency oscillations or grid synchronization instability [22][29][30]. The PLL may also struggle to track the grid phase during high variations or voltage dips [11].

Second, GFL control does not intrinsically provide a specific response to load variations. Bringing virtual inertia to the system is possible, but it relies on the PLL capability to accurately measure the frequency, needed to compute the RoCoF $\frac{d\omega}{dt}$. Consequently, reaction to a disturbance takes more time than with a synchronous generator whose dynamical response is physical [31].

Third, since GFL relies fundamentally on external measurements (notably the PLL), it cannot be used in isolated mode [9][24]. This is hence problematic in smaller scale applications, like micro-grids.

Finally, when a fault appears, GFL often reduces active power to limit the current. That may worsen the power unbalance, hence the frequency drop, possibly triggering a cascading fall [20][24].

1.5 Grid-Forming (GFM) converters: the emerging solution

In this section

To avoid the drawbacks of the GFL, research is made for controlling converters without following an existing grid. Regulation of active power with a droop allows synchronization without a PLL. Hence a Grid-Following converters act like a voltage source. The inertia of the synchronous generator can be virtually implemented to imitate traditional generators dynamics.

To address the GFL drawbacks, another control strategy named *Grid-Forming* (GFM) can be used. Grid-Forming is required for small "1 source, 1 load" installations, and is more and more integrated into larger scale power systems solutions [24]

Unlike GFL that controls the current, GFM is designed to control the voltage and therefore to resist to the hazards of the grid voltage. In accordance to (1.3), transmitted active power P mainly depends on the angle δ . Hence a feedback loop on the voltage angle δ is sufficient to maintain the inverter output voltage synchronized with the grid frequency. In most cases, a PLL is thus not needed for GFM [19][22]. Moreover, in accordance to (1.4), a feedback loop on the voltage magnitude allows controlling the reactive power Q .

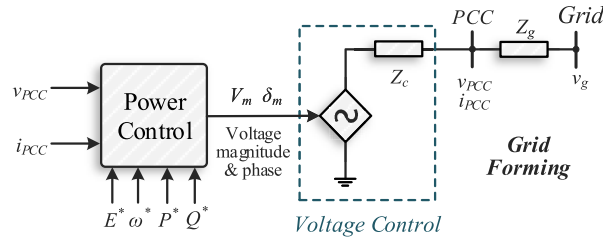


Figure 1.6: Grid-Forming block diagram from [23].

As represented in Fig. 1.6, by controlling the converter directly with the voltage, the GFM controlled DC-AC converter acts like a voltage source. The output impedance of an inverter controlled this way is $Z_c = \frac{\Delta V}{\Delta I} \approx \frac{0}{\Delta I} = 0$, which is characteristic of a voltage source.

In practice, there are many possibilities to implement the Grid-Forming control. The simplest solution to allow synchronization is the droop-based GFM: set frequency depends linearly on the active power. When measured power (P) is higher than the reference power (P_{ref}), frequency of the converter output (ω) must decrease in order to progressively reduce the angle δ and thus the active power output. This feedback process allows the inverter to keep power almost constant while remaining synchronized with the grid. For a

decoupled case, the relation is written [32]:

$$\omega = \omega_{ref} - D_p(P - P_{ref}) \quad (1.9)$$

The same method applies for voltage and reactive power:

$$V = V_{ref} - D_q(Q - Q_{ref}) \quad (1.10)$$

Where D_p and D_q are droop coefficients, ω_{ref} , V_{ref} , P_{ref} , Q_{ref} are the reference frequency, voltage, and powers expected in normal operation. Droop control is illustrated in Fig. 1.7.

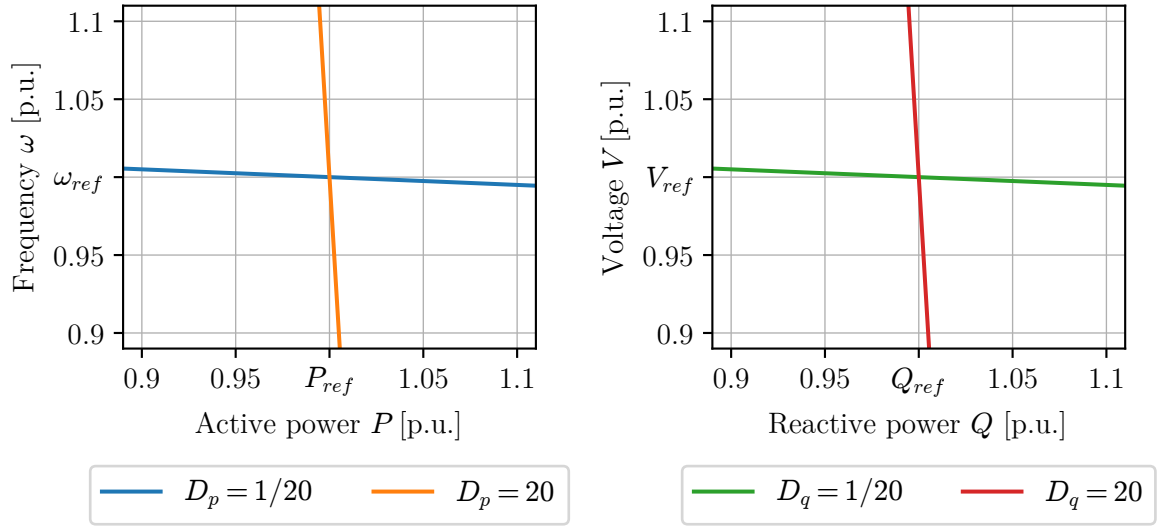


Figure 1.7: Droop control of P - f and Q - V loops. With low droop coefficients D_p and D_q , active and reactive powers are widely varied to maintain frequency and voltage near the reference values, which is expected in a Grid-Forming philosophy. With high droop coefficients D_p and D_q , active and reactive powers are maintained close to their reference values, almost whatever the frequency and the voltage, which is more in line with a Grid-Following philosophy.

For synchronous generators, the purpose of droop control (cf. (1.8): power in function of the frequency) is only the grid Frequency Containment Reserve (FCR). Indeed, the control of the machine itself is by feedback on the energy source like fuel arrival.

However for the GFM, droop control (frequency in function of the power) has a fundamental role that is necessary for the operation of the converter.

Intuitively, a SG with no droop ($\sigma_p \rightarrow \infty$) provides constant power whatever the grid frequency, while a GFM with no droop ($D_p = 0$) would force output frequency to exactly ω_{ref} , corresponding to an unsynchronized case. That case is forbidden when connected to the grid due to the consequences mentioned earlier. Nevertheless, GFM droop control also serves mathematically for the FCR.

About Grid-Following and Grid-Forming behaviors and philosophies

In steady-state, Grid-Following and Grid-Forming converters are able to produce the same result. Following the choice of the droop coefficient D_p , both strategies theoretically allow rather fixing the active power P or the frequency ω . Similarly, following the choice of the droop coefficient D_q , both strategies theoretically allow rather fixing the reactive power Q or the voltage V .

The behavior difference between GFL and GFM controls is thus only dynamic, i.e. when the quantities are varying.

In this work, the **dynamic** behavior called ***Grid-Following behavior*** is characterized by a fast yielding to voltage and frequency disturbances, due to the converter acting like a current source. Hence dynamically, maintaining the active and reactive powers is prioritized by the fast current regulation. This should not be confused by the static choice of prioritizing P and Q in **steady-state** by choosing $D_p \gg 1$ and $D_q \gg 1$, called in this work the ***Grid-Following philosophy***.

In this work, the **dynamic** behavior called ***Grid-Forming behavior*** is characterized by a rigid response to voltage and frequency disturbances, because the converter acts like a voltage source. Hence dynamically, maintaining the voltage and the frequency is prioritized by the fast voltage regulation. This should not be confused by the static choice of prioritizing ω and V in **steady-state** by choosing $D_p \ll 1$ and $D_q \ll 1$, called in this work the ***Grid-Forming philosophy***.¹

Practical situations most often combine the corresponding *behavior* and *philosophy*. For example, a photovoltaic installation where an MPPT² fixes the injection of active power P has typically a Grid-Following philosophy. The converter must also have a Grid-Following behavior, since a variation of P to support the frequency is impossible without deviating from the MPP.

On the contrary, a standalone battery installation has typically a Grid-Forming philosophy, because the regulation of the voltage and the frequency is prioritized. The converter must also have a Grid-Forming behavior, since the voltage must be created, and no other source could manage the disturbances.

However, it is conceptually not excluded to combine different behavior and philosophy. For example, the photovoltaic installation could be associated with a battery to support the grid (Grid-Forming behavior) while prioritizing active power injection in steady-state (Grid-Following philosophy).

On the contrary, the standalone installation could prioritize fixed power injection (Grid-Following philosophy) while creating the voltage (Grid-Forming behavior), assuming that the load has a droop allowing a steady-state convergence for the fixed value of P .

¹These definitions are also used when no droop is considered, by appropriately considering D_p or D_q equal to 0 or ∞ following the situation.

²MPPT for *Maximum Power Point Tracking* (example of usage: regulation of the terminal voltage of a photovoltaic cell to maximize electrical power obtained from solar power).

However, GFM droop control is a first order system, while the synchronous generator mechanical equation (1.7) is of the second order. It means that the dynamic response is intrinsically different, which may lead to undesired effects. Indeed, due to the absence of inertia, RoCoF is higher with a droop-based GFM than with synchronous generators, which can cause more frequent tripping of security equipments [23][33].

Another GFM control implementation is by emulating synthetically the dynamic inertial response of a synchronous generator. By taking (1.7) as relation for the frequency in function of power, the GFM DC-AC converter inherits from a virtual inertia H and a damping term D that may be chosen by the operator, in accordance with the regulations and the wishes of the TSO. Control of the reactive power often imitates the automatic regulator (AVR) of the synchronous generator. Such a GFM implementation is called *Virtual Synchronous Machine* (VSM) or *Virtual Synchronous Generator* (VSG) [10][18][34][35].

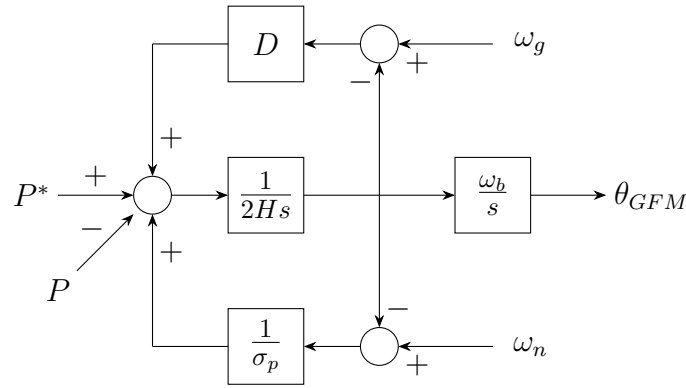


Figure 1.8: Block diagram of a VSG GFM controller with droop control (active power loop) [16].

The VSG GFM controller is represented in Fig. 1.8, where $\omega_n = 1$ [p.u.] is the nominal frequency, ω_g is the grid frequency, and θ_{GFM} is the phase angle of the output voltage of the converter. The VSG GFM also relies on a droop coefficient σ_p , that also serves for FCR just like with a classical synchronous generator.

However, many challenges complicate the use of a simple VSG GFM as such. First, in the case of a weak grid (low SCR, high impedance), low frequency oscillations may occur due to a resonance in the bandwidth of the VSG controller. Considering larger virtual inertia and virtual damping may help damping those oscillations [9].

In a strong grid, low inductance X value may prevent the inverter from achieving the desired voltage at the Point of Common Coupling (PCC), due to the non-zero impedance of the filter. Hence according to (1.3), injecting active power results in an increase of the output voltage of the converter (before the filter), leading to a risk of disconnection due to overvoltage.

In a resistive grid ($R \approx X$), coupling between $P - \delta$ and $Q - V$ loops is no more negligible (cf. (1.1) and (1.2)), hence complicating synchronization (risk of stalling). Virtual impedance with a high inductance may help to synchronize [36].

Moreover, in case of fault near in the grid, converter current must be quickly limited, because semi-conductor materials cannot stand high overcurrents like traditional synchronous generators [19][37]. However an abrupt saturation may break the synchronization. A virtual impedance may be used to limit current more softly, allowing to keep the voltage source behavior [23].

Finally, in the case of a quite isolated grid, high RoCoF $\frac{d\omega}{dt}$ may occur. For synchronous generators, this results in a mechanical shock to the shaft, but the machine is designed to resist. The inertia comes from the high kinetic energy of the rotor, and high overcurrent can be provided through the windings for a short time, for the inertial response. For VSG DC-AC converters however, the artificial inertia must be carried by energy on the DC bus. If the DC source cannot provide this energy instantaneously, the DC capacitance (visible in Fig. 1.4) discharges, and the DC voltage may drop. To respect physical limits of the electronics, parameters of the VSG controller must also be carefully tuned, in particular the sizing of the inertia coefficient H . The choice of parameters strongly depends on the grid characteristics that may evolve over time, which is problematic. Furthermore, controller relies on numerical measurements, hence its response may be very sensitive to measurement noise [38].

1.6 Linear Active Disturbance Rejection Control (LADRC) applied to GFM

In this section

Thanks to an innovative mathematical algorithm abbreviated *LADRC*, perturbations and unknowns can be rejected to obtain a desired and predictable fixed-order response. Theoretical developments regarding the LADRC applied to the P - f loop are presented.

With the aim of making GFM control more robust and resilient when facing changes in system characteristics and unexpected high variations from noise or faults, an additional layer of control may be added to the droop-based or VSG GFM control.

In particular, *Active Disturbance Rejection Control* (ADRC) is a promising solution to complement previous GFM control. In a few words, ADRC is a control method that intrinsically ignores unexpected disturbances (like noise or sudden parameters changes) by following a fixed-order response. Hence it also allows having a consistent and desirable response without even knowing the system parameters. The core principle is to rely on an *Extended State Observer* (ESO) to have a control based on an *estimation* of the system state instead of a direct measurement. The ADRC being quite complicated with a lot of mathematical parameters without physical meaning, a simplified version named *Linear Active Disturbance Rejection Control* (LADRC) is primarily used by engineers. Fig. 1.9 shows how LADRC control may be added to a classic GFM control.

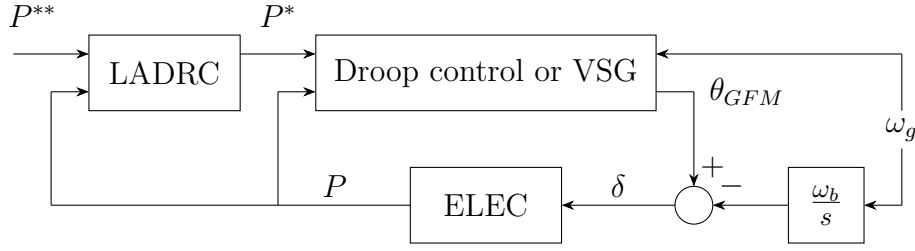


Figure 1.9: Block diagram of a GFM controller with LADRC (active power loop) [16].

Since synchronous generators mechanical equation (1.7) and hence VSG system is of order 2, the development of a second-order LADRC is desired. The following development is inspired from [39], [38] and [16].

Let us consider a second-order process $G(s)$ with a DC gain K , a damping factor D and a time constant T . The Laplace equation is given by:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{T^2 s^2 + 2DTs + 1} \quad (1.11)$$

In time domain, the equation is written:

$$T^2 \ddot{y}(t) + 2DT \dot{y}(t) + y(t) = Ku(t) \quad (1.12)$$

Let $b = \frac{K}{T^2}$ and let us add an input disturbance $d(t)$.

$$T^2 \ddot{y}(t) + 2DT \dot{y}(t) + y(t) = T^2 bu(t) + d(t) \quad (1.13)$$

Let us split b into a known and unknown part $b = b_0 + \Delta b$, and isolate the second-order term:

$$\ddot{y}(t) = \underbrace{-\frac{2D}{T} \dot{y}(t) - \frac{1}{T^2} y(t) + \frac{1}{T^2} d(t) + \Delta b u(t) + b_0 u(t)}_{\text{generalized disturbance}} \quad (1.14)$$

$$= f(t) + b_0 u(t) \quad (1.15)$$

As represented here above, the goal is to consider all the terms that are not of second-order ($\propto \dot{y}(t)$ and $y(t)$), the disturbance ($\propto d(t)$) and the unknown part ($\propto \Delta b$) as a generalized disturbance $f(t)$ that will be ignored with the controller, in the aim of having a nearly second-order response to $u(t)$.

The state-space representation of (1.15) is:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ b_0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} f(t) \quad (1.16)$$

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \quad (1.17)$$

In this state-space representation, $x_1 = y$ represents the system output ($\rightarrow$ voltage or angle) and $x_2 = \dot{y}$ represents the system speed ($\rightarrow$ voltage derivative or frequency).

This is enough for a classical PID control response, but for an active disturbance rejection control, a third state variable is needed to estimate the generalized disturbance $f(t)$ and manage it. A dedicated *Extended State Observer* (ESO) is designed to give estimations $\hat{x}_1(t) = \hat{y}(t)$, $\hat{x}_2(t) = \dot{\hat{y}}(t)$ and $\hat{x}_3(t) = \hat{f}(t)$:

$$\begin{bmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \\ \dot{\hat{x}}_3(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{bmatrix} + \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} (y(t) - \hat{x}_1(t)) \quad (1.18)$$

$$= \underbrace{\begin{bmatrix} -l_1 & 1 & 0 \\ -l_2 & 0 & 1 \\ -l_3 & 0 & 0 \end{bmatrix}}_{A'} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{bmatrix} + \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} y(t) \quad (1.19)$$

$$y(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{bmatrix} \quad (1.20)$$

With l_1, l_2, l_3 the observer gains (to be determined).

The stability of the system depends on matrix A' eigenvalues. Those are solutions of equation:

$$\det(s\mathbf{I} - \mathbf{A}') = 0 \quad (1.21)$$

$$= s^3 + l_1 s^2 + l_2 s + l_3 \quad (1.22)$$

It is common to design the ESO such that it has only one multiple pole ω_0 .

$$0 = s^3 + l_1 s^2 + l_2 s + l_3 = (s + \omega_0)^3 = s^3 + 3\omega_0 s^2 + 3\omega_0^2 s + \omega_0^3 \quad (1.23)$$

By identification it is shown that a triple pole $s_0 = -\omega_0$ is only possible with:

$$l_1 = 3\omega_0 \quad l_2 = 3\omega_0^2 \quad l_3 = \omega_0^3 \quad (1.24)$$

The angular frequency ω_0 is named the *observer bandwidth*.

The process $G(s)$, from which the generalized disturbance estimated by the ESO $\hat{f} = \hat{x}_3$ is deduced, can now be controlled by a more classic PD control, thanks to the states $\hat{y} = \hat{x}_1$ and $\dot{\hat{y}} = \hat{x}_2$ estimations. The LADRC controller loops are represented in Fig. 1.10.

Assuming a perfect ESO and b_0 of the process is known, the system response is:

$$\ddot{y} = u_0 \quad (1.25)$$

With the LADRC controller, the transfer function of the control loop becomes:

$$\frac{y}{y^{**}} = \frac{K_p}{s^2 + K_d s + K_p} = \frac{1}{\frac{1}{K_p} s^2 + \frac{K_d}{K_p} s + 1} \quad (1.26)$$

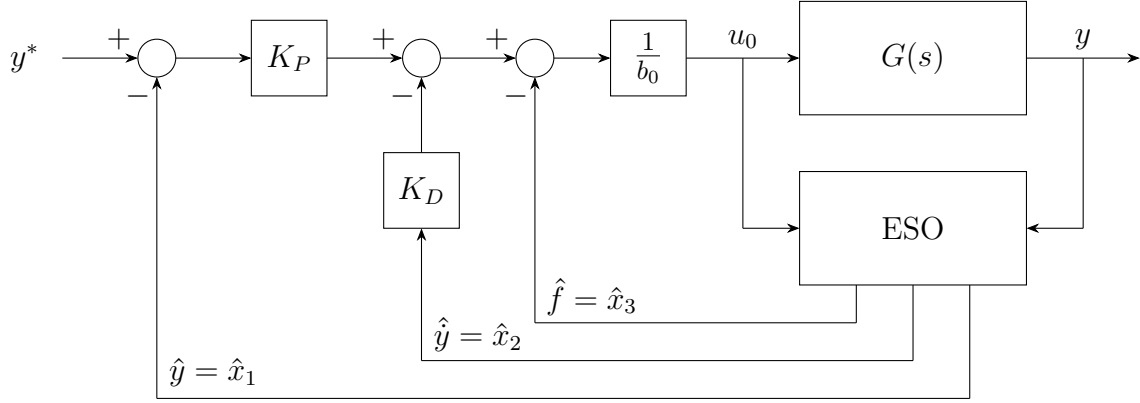


Figure 1.10: Second-order LADRC controller, from [39].

Hence K_p and K_d gains can be chosen to have any desired second-order response with unity DC gain (which is not problematic from a control perspective). Time constant (inverse of the natural frequency) is $\tau = \frac{1}{\sqrt{K_p}}$ and damping factor is $D = \frac{K_d}{2\sqrt{K_p}}$ such that the control loop response can be expressed under the standard form:

$$\frac{y}{y^{**}} = \frac{1}{\tau^2 s^2 + 2D\tau s + 1}$$

In practice however, the ESO is not perfect. Perturbation rejection and PD control is not exact, since the system relies on estimations. Moreover, ESO is not instantaneous, its time response highly depends on the chosen value for the observer bandwidth ω_0 . Furthermore, the system relies on the supposedly known part b_0 of b . Even if the difference $\Delta b = b - b_0$ is supposed to be part of the generalized disturbance that is rejected, it is reasonable to think the estimations will be as good as b_0 is close to b [16][38][39].

1.7 State of the art

In this section

LADRC has already been applied to the P - f loop. Resonances and stability issues have been already studied. Since this loop is coupled with the Q - V loop, objectives of this work are established for the use of a second LADRC in GFM converter control.

For several years now, the LADRC applied to GFM has been studied and several conclusions have been drawn.

- LADRC allows GFM active power P response to be almost independent from grid characteristics, as shown in Fig. 1.11. Changes of parameters (e.g. grid impedance variation due to the disconnection of a line) are treated like a disturbance and rejected in real time. The active power response is also similar no matter if the grid is strong (high SCR) or weak (low SCR) [16][17]. This means LADRC allows having a uniform response without needing to know the exact parameters of the grid, which is beneficial in the context of low overcurrent limit for the power electronics converters asked to provide inertia.

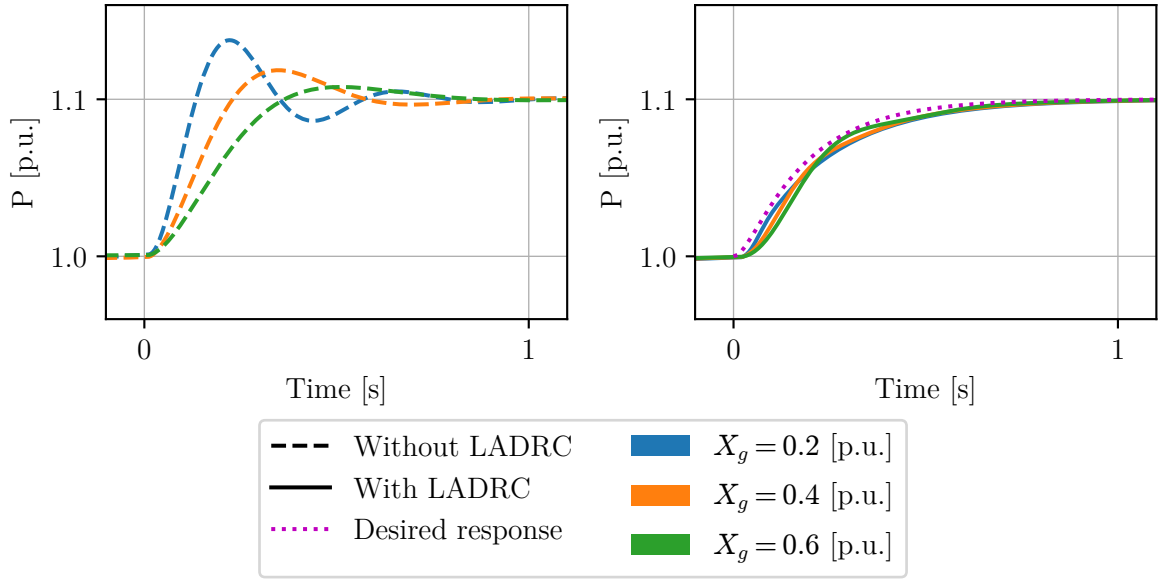


Figure 1.11: Active power P response to a step of target from 1 [p.u.] to 1.1 [p.u.] at $t = 0$ [s]. Considered system for this example will be described in Chapter 3. Without using LADRC, the response varies significantly with the (unknown) grid inductance X_g . With using LADRC, the response is almost independent from grid characteristics, and is close to the expected response.

- For a classical VSG, inertia was directly fixed by the inertia coefficient H . With LADRC, the equivalent inertia H_{eq} mainly depends on the external droop coefficient σ_p and the observer bandwidth ω_0 , rather than the H coefficient defined in the system. It is observed that coefficient H is mostly important for the fast transient dynamic but is insignificant during a constant frequency ramp. This questions the frequency ramp method to compare inertia provided by generators of different nature. The decoupling between *fast* and *slow* inertial responses opens perspectives for the compliance with TSO requirements and converters limits [15].
- *Equal Area Criterion* (EAC) has been adapted for the angle-related stability of the LADRC GFM. For the synchronous generator (and classic GFM), a grid fault ($\rightarrow X$ impedance increase) impacts the system's ability to evacuate power: P_e curve collapses while P_m remains constant. The EAC for LADRC GFM has shown a fundamental difference: the increasing grid impedance X acts like a multiplier of the reference power P^{**} while the electrical power remains constant [40].
- While proposed LADRC has been developed for a second-order system due to the second-order mechanical response of the synchronous generator, it was shown that by considering the dynamics of the electrical components (notably the LC filter), the complete system is of order 4. Resonances may induce instabilities if the observer bandwidth is inadequate. Parametric analyses have been made regarding the necessary precautions relative to stability for the second-order LADRC. A frequency analysis revealed that the system amplifies disturbances and shows risks of resonance

when the observer bandwidth approaches the fundamental frequency of the grid ("wall of 50Hz") [16].

- A recent study has provided a first analytical model of sequence impedance for a LADRC GFM converter. The positive and negative sequence impedances $\bar{Z}_p(s)$ and $\bar{Z}_n(s)$ have been derived by linearization of the control loops, including the ESO. The authors demonstrate that adding LADRC radically alters the nature of the converter, particularly at low frequencies. Below 50Hz, the converter without LADRC has a low impedance, which is typical of a GFM (voltage source), but with LADRC the converter has a significant impedance, which is closer to a GFL (current source). Around 50Hz, the impedance is low due to the synchronization of the inverter with the grid. The impedance with LADRC is still higher than without, confirming the previous comparison with GFL and GFM, respectively. Above 100Hz, sequence impedance with or without LADRC is quite the same, as this falls outside the LADRC observer bandwidth. By simply tuning ω_0 , the converter can switch between pure Grid-Forming behavior and near Grid-Following behavior. This may avoid subsynchronous resonances by shifting the system's passive regions [41].

To summarize, LADRC applied to GFM converters seems to be a promising solution to meet the flexibility requirements of tomorrow's grid. However, many challenges remain before large-scale usage can be achieved. Instabilities may occur due to electrical dynamics (4^{th} order system but 2^{nd} order control). Observer bandwidth ω_0 tuning is a delicate but encouraging operation for inertial response and stability.

To the best of the author's knowledge, current literature often focuses on a single converter connected to an infinite bus. There is a lack of studies on the stability of systems with multiple LADRC GFM converters in parallel. How do their observers interact? Are there risks of cross-resonance between ESO of different units? Moreover, LADRC has only been applied to active power loop $P - \delta$ to manage inertia. Applying LADRC to both active and reactive power loops ($Q - V$) may be interesting to study possible decoupling between the loops, which is highly relevant in resistive (low-voltage) grids. Is LADRC helpful in the voltage control? Are there any interactions possible between active and reactive control loops?

The goals of this work are:

- To model and study the response, dynamics, and stability of the LADRC applied to the $Q - V$ loop.
- To model and study the response, dynamics, and stability of the LADRC applied to both $P - \delta$ and $Q - V$ loops, and to search possible interactions and decoupling between both loops.
- To evaluate and investigate compliance with standards and physical limits of the converters.
- To analyze more realistic situations where LADRC converters are put in parallel or scattered in a grid model.

Chapter 2

LADRC Analysis: Theoretical insight

In this chapter

As explained in Section 1.6, the LADRC aims to replace an (unknown) internal model dynamics by another desired response. A few works already proved that N LADRCs can be used to control the N outputs of an N -inputs unknown system (*decoupling* of the N loops) [42]. However, this perfect loop decoupling has only been shown with the assumption of an ideal observer (ESO), which implies an infinite observer bandwidth ω_0 . This assumption is also known to be unrealistic in practice, due to the extreme sensitivity to measurement noise.

This chapter aims to further study the interest of using multiple LADRCs while not considering the observer to be ideal, which is more realistic.

In the following sections, the various potential interests of a multi-LADRC use are studied for a simple Two-Input Two-Output system (might be generalized to any Multiple-Input Multiple-Output system) and then for a converter control system. The interests presented in Chapter 1 are summarized:

1. Independence of the control to the system characteristics
2. Behavior change in function of the observer bandwidth ω_0
3. Decoupling of the control loops

The results concerning these interests are shown in the Laplace frequency domain. These are summarized:

- LADRC observer bandwidth ω_0 can be used to switch between an input-rejection mode to a model-rejection mode, that may be used to switch from a Grid-Forming to a Grid-Following behavior.
- No critical interactions are observed when using multiple LADRCs, allowing the decoupling of the control loops.
- External disturbances are more rejected with more than one LADRC.

About methodology

The following results have been obtained with a *semi-analytical* approach. Even in a reduced case, analytical calculation by hand of a multi-LADRC controlled system is impractical due to the growing length of the expressions. Since it might however be useful to observe key analytical relations, symbolic expressions have been derived numerically using the *SymPy* Python library. The entire analytical expressions have not been written in this work because of their length and because they are not of interest to the human eye. Key factorizations and limits have been instead provided for the understanding purpose.

2.1 Analysis on a first-order Two-Input Two-Output system

In this section

A simple study case is taken to better understand how does the LADRCs behave when their observer bandwidths ω_0 are not infinite. The conclusions based on the simplified system will then be extended to the converter control electrical system.

To summarize, it will be shown that with a low observer bandwidth, LADRC provides an *input rejection* while with a high observer bandwidth, LADRC provides a *model rejection*. It will also be confirmed that dynamics is replaced by the expected one for the corresponding loop, that cross-coupling is attenuated for the corresponding loop, and that external disturbances are increasingly rejected by increasing ω_0 .

2.1.1 The first-order Two-Input Two-Output system with LADRC on y_1 and y_2 loops

Let us take a simple Two-Input Two-Output algebraic linear combination system represented by the following matrix system:

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \underbrace{\begin{bmatrix} A & B \\ C & D \end{bmatrix}}_{\mathbf{M}} \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} \quad (2.1)$$

This system is controlled by controllers with transfer functions $C_1(s)$ and $C_2(s)$ whose role is to cancel the errors $y_1^* - y_1$ and $y_2^* - y_2$ where y_1^* and y_2^* are the system targets and y_1 and y_2 are the system outputs. For the purpose, $C_1(s)$ and $C_2(s)$ are chosen to be PI controllers, which is a basic standard choice to avoid static error. They can be written:

$$C_1(s) = k_{p,1} + \frac{k_{i,1}}{s} \quad C_2(s) = k_{p,2} + \frac{k_{i,2}}{s}$$

Moreover, external disturbances Δu_1 and Δu_2 are considered.

Let us add two LADRCs blocks to the first and second branches of the system, as represented in Fig. 2.1. Since the internal system of the two loops is of order 1, two first-order LADRCs (second-order ESO) are used, whose equations are detailed in Appendix A.

2.1. Analysis on a first-order Two-Input Two-Output system

Intuitively, each LADRC should allow replacing the dynamics of its respective loop (include cross-coupling) by any desired first-order response.

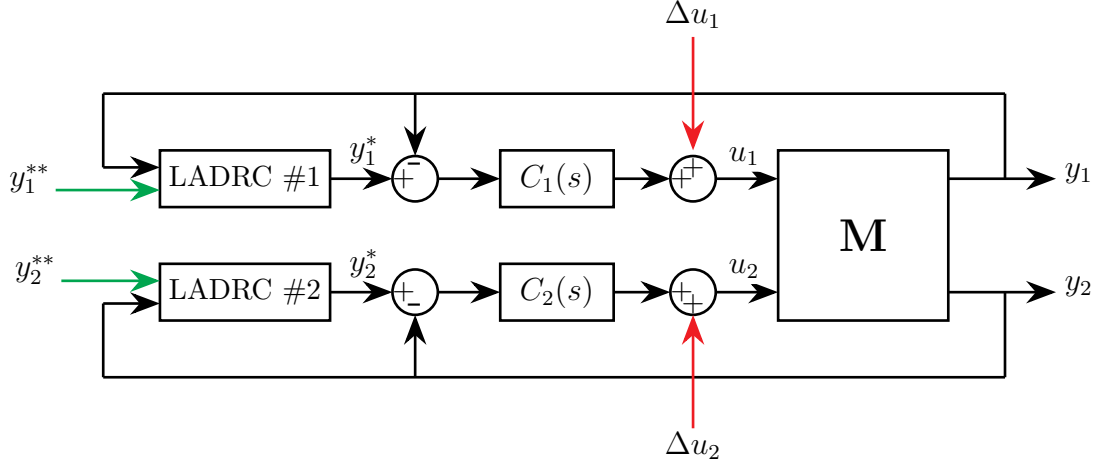


Figure 2.1: Two-Input Two-Output system with LADRC on y_1 and y_2 . System core $\mathbf{M}$ gives a linear combination y_1 and y_2 of the inputs u_1 and u_2 . Inputs may be disturbed by external Δu_1 and Δu_2 . Controllers C_1 and C_2 allow the system to converge towards targets y_1^* and y_2^* . Each LADRC serves to replace the dynamics of its respective loop (include cross-coupling) by any desired first-order response.

Analytical computation confirms the preserved linearity of the system: expressions of y_1 and y_2 depend linearly on y_1^* , y_2^* , Δu_1 , Δu_2 . Hence the following transfer functions do not depend on these targets and disturbances.

Reaction to changes of target

$$\frac{\partial y_1}{\partial y_1^{**}} = f_{1,1}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.2)$$

$$\frac{\partial y_1}{\partial y_2^{**}} = sB \cdot f_{1,2}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.3)$$

$$\frac{\partial y_2}{\partial y_1^{**}} = sC \cdot f_{1,3}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.4)$$

$$\frac{\partial y_2}{\partial y_2^{**}} = f_{1,4}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.5)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_1}{\partial y_1^{**}} = 1 \quad (2.6) \quad \lim_{s \rightarrow \infty} \frac{\partial y_1}{\partial y_1^{**}} = \frac{K_{p,1}}{b_{0,1}} \frac{Ak_{p,1} + (AD - BC)k_{p,1}k_{p,2}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.10)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_1}{\partial y_2^{**}} = 0 \quad (2.7) \quad \lim_{s \rightarrow \infty} \frac{\partial y_1}{\partial y_2^{**}} = \frac{K_{p,2}}{b_{0,2}} \frac{Bk_{p,2}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.11)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_2}{\partial y_1^{**}} = 0 \quad (2.8) \quad \lim_{s \rightarrow \infty} \frac{\partial y_2}{\partial y_1^{**}} = \frac{K_{p,1}}{b_{0,1}} \frac{Ck_{p,1}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.12)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_2}{\partial y_2^{**}} = 1 \quad (2.9) \quad \lim_{s \rightarrow \infty} \frac{\partial y_2}{\partial y_2^{**}} = \frac{K_{p,2}}{b_{0,2}} \frac{Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.13)$$

2.1. Analysis on a first-order Two-Input Two-Output system

As can be seen with transfer functions (2.3) and (2.4)¹, off-diagonal terms B and C are responsible for the system cross-coupling of loops. For instance if $B \neq 0$, a change of y_2^* target will inevitably impact y_1 output, as confirmed by limits in $s \rightarrow \infty$ ((2.11), (2.12)).

About limits in $s \rightarrow 0$ and $s \rightarrow \infty$

The *Initial Value Theorem* states that the instantaneous initial response $y(t = 0^+)$ of a time-domain signal equals $\lim_{s \rightarrow \infty} sY(s)$ with $Y(s)$ being the Laplace transform of $y(t)$.

Knowing that for an LTI system, $Y(s) = H(s)X(s)$, and knowing that a step input $x(t) = u(t)$ is written $X(s) = U(s) = \frac{1}{s}$ in frequency domain, it can be concluded that the instantaneous initial response $y(t = 0^+)$ to a step input equals $\lim_{s \rightarrow \infty} H(s)$.

With the same reasoning on the *Final Value Theorem*, it can be concluded that the steady-state response $y(t \rightarrow \infty)$ to a step input equals the limit $\lim_{s \rightarrow 0} H(s)$.

Limits (2.6) and (2.9) show that the system output reaches the target value after an undetermined time (steady-state). Limits (2.7) and (2.8) show that the loop's cross-coupling fades after an undetermined time (steady-state).

By extra analyses, it is possible and particularly interesting to see that limits in $s \rightarrow \infty$ for a change of y^{**} target are only multiplied by a factor $\frac{K_p}{b_0}$ compared to the case without LADRC. This factor is equal to 1 when the LADRC desired response (tuned with K_p) cutoff frequency corresponds to the one of the system (linked with the internal gain b , parametrized in b_0). It is also important to see that limits (2.11) and (2.12) are different from zero (effect of cross-coupling is non-zero even with LADRC), which can be attributed to the finite value of the observer bandwidth ω_0 .

Reaction to external disturbances

Regarding the reaction to external disturbances, the transfer functions are:

$$\frac{\partial y_1}{\partial \Delta u_1} = s \cdot f_{2,1}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.14)$$

$$\frac{\partial y_1}{\partial \Delta u_2} = sB \cdot f_{2,2}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.15)$$

$$\frac{\partial y_2}{\partial \Delta u_1} = sC \cdot f_{2,3}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.16)$$

$$\frac{\partial y_2}{\partial \Delta u_2} = s \cdot f_{2,4}(s, A, B, C, D, k_{p,1}, k_{i,1}, k_{p,2}, k_{i,2}, K_{p,1}, b_{0,1}, \omega_{0,1}, K_{p,2}, b_{0,2}, \omega_{0,2}) \quad (2.17)$$

¹These expressions are possible factorizations of the simplified transfer functions. Highlighting B or C does not mean the expression is proportional to the factor (because the rest of the expression also depends on it), but instead that the expression is zero if the factor is 0.

$$\lim_{s \rightarrow 0} \frac{\partial y_1}{\partial \Delta u_1} = 0 \quad (2.18) \quad \lim_{s \rightarrow \infty} \frac{\partial y_1}{\partial \Delta u_1} = \frac{A + (AD - BC)k_{p,2}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.22)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_1}{\partial \Delta u_2} = 0 \quad (2.19) \quad \lim_{s \rightarrow \infty} \frac{\partial y_1}{\partial \Delta u_2} = \frac{B}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.23)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_2}{\partial \Delta u_1} = 0 \quad (2.20) \quad \lim_{s \rightarrow \infty} \frac{\partial y_2}{\partial \Delta u_1} = \frac{C}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.24)$$

$$\lim_{s \rightarrow 0} \frac{\partial y_2}{\partial \Delta u_2} = 0 \quad (2.21) \quad \lim_{s \rightarrow \infty} \frac{\partial y_2}{\partial \Delta u_2} = \frac{D + (AD - BC)k_{p,1}}{Ak_{p,1} + Dk_{p,2} + (AD - BC)k_{p,1}k_{p,2} + 1} \quad (2.25)$$

The same observations can be made about the role of B and C in the cross-coupling of loops, as seen in transfer functions (2.15) and (2.16). The limits in $s \rightarrow 0$ show that the step perturbations are faded after an undetermined time (steady-state).

The limits (2.23) and (2.24) are different from zero (effect of cross-coupling is non-zero even with LADRCs). By extra analyses, it is possible and particularly interesting to see that limits in $s \rightarrow \infty$ are identical to the case without LADRC. Hence even with LADRC, a step of disturbance Δu_1 or Δu_2 immediately disturbs respectively the y_2 or y_1 output, which can be attributed to the finite value of the observers bandwidth $\omega_{0,1}$ and $\omega_{0,2}$.

2.1.2 Frequency responses of the Two-Input Two-Output system with or without LADRC(s), behavior change in function of the observer bandwidth ω_0

The previous results already showed important information about response of the system and cross-coupling of loops with or without mono-LADRC and dual-LADRC in the non-ideal case where observers bandwidth is not infinite. However, it has not been practically possible to observe analytically the frequency responses, except for the particular $s \rightarrow 0$ and $s \rightarrow \infty$ values. In this section, some of these transfer functions are represented graphically and interpreted.

Bode plot in magnitude and phase is the most common graphic representation of transfer functions. In this section, only the magnitude plots will be analyzed, and phase plots are placed in Appendix B. Since the current Two-Input Two-Output system does not stand for any physical system, arbitrary parameters have been chosen for the numerical values. To better analyze the impact of including zero, one, or two LADRCs in the system, parameters are kept symmetrical between the two branches.

Except for mentioned deviations, the parameters are the following. The linear system matrix $\mathbf{M}$ is chosen such that the cross-coupling is moderate:

$$\mathbf{M} = \begin{bmatrix} 1 & 0.2 \\ 0.2 & 1 \end{bmatrix} \quad (2.26)$$

The $C_1(s)$ and $C_2(s)$ controllers are mainly proportional, with a moderate integrator: $k_{p,1} = k_{p,2} = 1$, $k_{i,1} = k_{i,2} = 0.1$. Assuming low cross-coupling ($B = C \ll A = D$), the

remaining transfer functions are written:

$$\frac{\partial y_1}{\partial y_1^*} = \frac{Ak_{p,1}s + Ak_{i,1}}{(Ak_{p,1} + 1)s + Ak_{i,1}} \quad \frac{\partial y_2}{\partial y_2^*} = \frac{Dk_{p,2}s + Dk_{i,2}}{(Dk_{p,2} + 1)s + Dk_{i,2}}$$

As seen in the theory of LADRC for a first-order system placed in Appendix A, only a form of low-pass filter can be desired, meaning that the proportional effect of the PI will be rejected. The LADRC is based on the integral part, hence the gains can be identified: $b_{0,1} = Ak_{i,1} = 0.1$ and $b_{0,2} = Dk_{i,2} = 0.1$. The desired response is tuned with $K_{p,1} = K_{p,2} = 100$ in order to replace the PI dynamics with low-pass filters of cutoff frequency $K_{p,1,2}$.

Because of the symmetry of the system, this section focuses on responses of y_1 and y_2 to changes of y_1^{**} (or y_1^* in the cases without LADRC) target or disturbance of Δu_1 only.

The LADRC observers bandwidth $\omega_{0,1}$ and $\omega_{0,2}$ have been varied to see how the control behavior changes, when reacting to a change of y_1^{**} target or of external disturbance Δu_1 . As reminder, it is expected that the LADRC is able to replace the internal dynamics and reject disturbances only with a sufficiently high bandwidth ω_0 (near ideal case). It will be interesting to see what happens when the observer bandwidth is low or zero.

Reaction to a change of target

Results in Fig. 2.2 for $\partial y_1 / \partial y_1^{**}$ confirm the expectations: with a very high bandwidth (almost infinite, near ideal case, yellow curve), the internal dynamics is entirely replaced with the desired dynamics (rejection of the internal model). When the bandwidth is high but limited (here $\omega_0 = 1000$ [rad/s], green curve), the model is rejected only up to $\omega = \omega_0$, which corresponds to a minimum of the magnitude. In higher frequencies, the magnitude of the response is governed by the internal model and amplified by a factor K_p/b_0 , as seen with limit (2.10).

When the bandwidth is zero (navy curve), the input is entirely rejected in the low frequencies, but is also governed by the internal model and amplified by a factor K_p/b_0 in high frequencies. For example, in the case of a step of y_1^{**} target, y_1 would instantaneously react at $t = 0^+$, but the LADRC with zero ω_0 will progressively cancel this reaction and recover the previous state of the system. When the bandwidth is low (here $\omega_0 = 0.001$ [rad/s], lagoon blue curve), input rejection occurs only for frequencies above ω_0 , which corresponds to a minimum of the magnitude. Response is similar either with LADRC on y_1 only or with LADRC on y_1 and y_2 .

This evolution of behavior is particularly interesting, because it means that by changing the observer bandwidth, it is possible to switch from an input-rejection mode (with $\omega_0 = 0$) to a model-rejection mode (with $\omega_0 \rightarrow \infty$). It would be interesting to have an analytic assessment also for intermediate ω_0 values. As explained earlier, it is not practically possible to analyze the analytic expressions due to their excessive lengths. However, it can be seen in the magnitude Bode plots that the curves shape is quite linear (in log-log scale), their slopes are always the same (± 20 [dB/dec]), and inflection points are located near known values of frequencies. With the help of analytic values provided by the presented

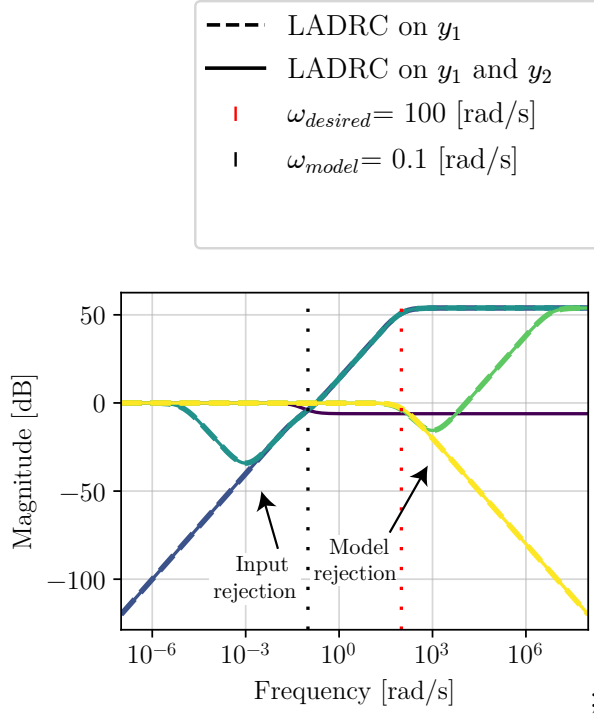


Figure 2.2: Magnitude of $\partial y_1/\partial y_1^{**}$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$. Low ω_0 leads to a rejection of the input ($\lim_{s \rightarrow 0} \frac{\partial y_1}{\partial y_1^{**}} \rightarrow -\infty [dB]$), while high ω_0 leads to a rejection of the model and the replacement of the internal dynamics with a desired dynamic ($\lim_{s \rightarrow \infty} \frac{\partial y_1}{\partial y_1^{**}} \rightarrow -\infty [dB]$).

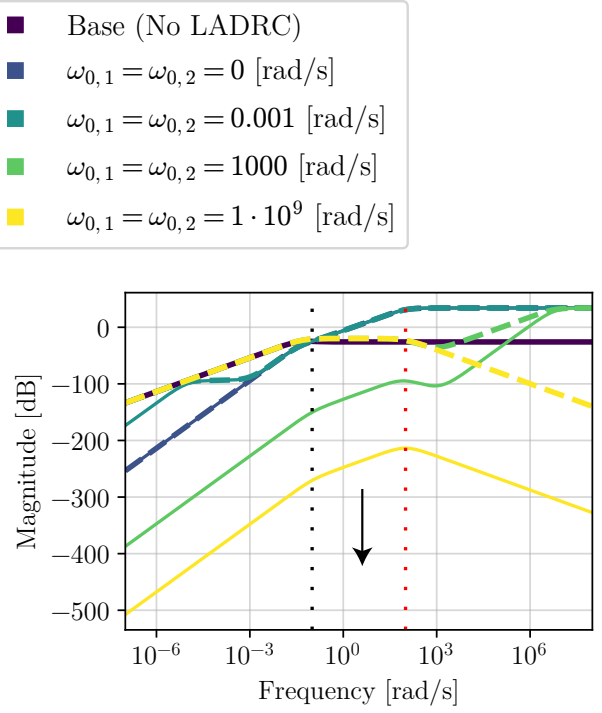


Figure 2.3: Magnitude of $\partial y_2/\partial y_1^{**}$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$. With LADRC on y_1 only, input is rejected in low frequencies for low ω_0 , and model is rejected in high frequencies for high ω_0 . With LADRC on both y_1 and y_2 , cross-coupling is increasingly attenuated with increasing ω_0 .

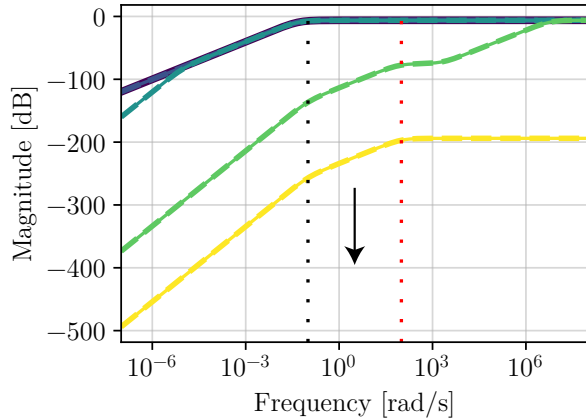


Figure 2.4: Magnitude of $\partial y_1/\Delta du_1$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$. The disturbance is increasingly rejected with increasing ω_0 . LADRC on y_1 only is sufficient.

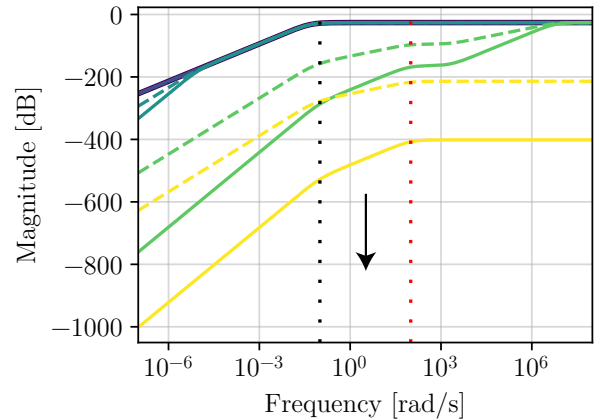


Figure 2.5: Magnitude of $\partial y_2/\Delta du_1$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$. The disturbance is increasingly rejected with increasing ω_0 with LADRC on y_1 only, and even further rejected with LADRC on both y_1 and y_2 .

limits in $s \rightarrow 0$ and $s \rightarrow \infty$, it is hence possible to analyze the behavior change in function of ω_0 with an analytical geometric approach based on an *asymptotic approximation* of the responses.

To remain *without loss of generality* (though with this applied simplified case), it has been necessary to analyze all the ways to order the four relevant frequencies $\omega, \omega_0, \omega_{desired}, \omega_{model}$. Analytic prototypes of the $4! = 24$ combinations of these frequencies have been realized to try to analyze the behavior of every system possibilities in every frequency range. Because this process has been quite redundant and because derived expressions are bound to this non-physical simplified system, only global results are presented here below. Further research is necessary to prove these results can be generalized to any system. With this method, it can be concluded:

- Input rejection in $\omega \in [\omega_0, \min(\omega_{desired}, \omega_{model})]$ when $\omega_0 < \min(\omega_{desired}, \omega_{model})$
- Model rejection in $\omega \in [\min(\omega_{desired}, \omega_{model}), \omega_0]$ when $\omega_0 > \min(\omega_{desired}, \omega_{model})$

Regarding the impact of a y_1^{**} change on the other y_2 output, the magnitude of the response for different ω_0 values is represented in Fig. 2.3. With LADRC on y_1 only, it can be seen an input rejection for low ω_0 values, and a model rejection for high ω_0 values compared to the base response (in accordance to the $\partial y_1 / \partial y_1^{**}$ response previously explained). With LADRC on both y_1 and y_2 , a stronger attenuation of the cross-coupling is observed. In fact the cross-coupling tends to zero ($-\infty$ [dB]) when $\omega_0 \rightarrow \infty$, which is the expected behavior.

Reaction to a disturbance

When it comes to the external disturbance (Δu_1), Fig. 2.4 shows that LADRC on y_1 is sufficient to reject the impact of the disturbance on y_1 , with higher attenuation with high bandwidths ω_0 . The impact on y_2 is also attenuated with LADRC on y_1 , but is even further attenuated with LADRC on both y_1 and y_2 , as shown in Fig. 2.5.

2.1.3 Conclusion on LADRC on the Two-Input Two-Output system

In conclusion to the study case of the simplified Two-Input Two-Output system, the frequency analysis and representation of the transfer functions $\partial y_1 / \partial y_1^{**}$ and $\partial y_1 / \partial \Delta u_1$, associated with the symbolic expressions of the particular limits in $s \rightarrow 0$ and $s \rightarrow \infty$, has provided precious information regarding the behavior of the system with two LADRCs when the observers bandwidth is not infinite.

Adding an LADRC to a branch allows, in the observer bandwidth, the replacement of the internal dynamics. The coupled responses are also better attenuated. LADRC also helps to attenuate the external disturbances. LADRC allows having either an input-rejection or a model-rejection, following the chosen observers bandwidth. Finally, multi-LADRC allows decoupling the control loops as much as observers bandwidth is sufficiently high. No undesired interactions have been discovered between the loops when LADRC is applied to both loops.

2.2 Analysis on an electrical P - δ and Q - V system

In this section

The previous section aimed to show the capability of the multi-LADRC on an arbitrary system, which was useful to better see the results thanks to the symmetry and simplicity of the considered system. It remains to be shown that these results can be transposed to a more complex system such as a converter control. In particular, it is interesting to see the impact of using LADRCs of different orders and different controller types in the same system.

To summarize, it will be shown that the switching from an *input rejection* to a *model rejection* mode by varying the LADRC observer bandwidth ω_0 is confirmed with the converter control model, allowing a behavior change from Grid-Forming to Grid-Following. As expected, the use of LADRC also helps making the control independent from the grid characteristics, including the reduction of cross-coupling of the loops due to the resistive part of the lines.

2.2.1 The Grid-Forming VSG control system with P-LADRC and Q-LADRC

Let us take a complete converter control schematic to see the interests of LADRC interests in the electrical context. To limit the length of the symbolic expressions, only the linear case of the electrical system is considered (power flow through a short line for small values of δ and ΔV), described by (1.5). As a reminder, the linear system is the following:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \underbrace{\frac{1}{R^2 + X^2} \begin{bmatrix} X & R \\ -R & X \end{bmatrix}}_{\text{ELEC}} \begin{bmatrix} \delta \\ \Delta V \end{bmatrix} \quad (2.27)$$

Where R and X are respectively the total equivalent resistance and reactance of the power flow system (grid + line + filter).

The inputs δ and ΔV represent *differences* of states between the two sides of the impedance (the "controlled" converter side, and the "uncontrolled" grid side). As a reminder, $\delta = \varphi_1 - \varphi_2$ is the phase angle shift and $\Delta V = V_1 - V_2$ the voltage magnitude difference across the two terminals of the equivalent impedance (grid + line + filter). Hence unexpected disturbances coming from the grid side can be included in the analysis by external disturbances $\Delta\delta$ and $\Delta\Delta V$.

The active power P loop is first controlled with a Virtual Synchronous Generator (VSG) Grid-Forming (GFM) control, as explained in Section 1.5. It is assumed that $\omega_g \approx \omega_n = 1$ [p.u.], hence the phase shift is expressed: $\delta = \theta_{GFM} - \theta_{grid} = \frac{\omega_B}{s} (\omega_{GFM} - \omega_n)$. The damping and droop parts can also be merged, and a single coefficient $\sigma = \left(\frac{1}{\sigma_p} + D\right)^{-1}$ is used in order to simplify the symbolic expressions. Under these conditions, the VSG

output in the Laplace domain can be expressed as:

$$\delta(s) = \frac{\omega_B (P - P^*) - \omega_n 2Hs}{s (2Hs + \frac{1}{\sigma})} \quad (2.28)$$

The reactive power Q loop is first controlled by acting on the voltage of the converter, hence by changing ΔV . At this point, it is yet unclear what should be the reactive power loop. This topic is discussed in detail later in this work (Chapter 3). However, a droop control, binding the reactive power Q and the voltage, should be considered to allow parallel operation of multiple converters (similarly to the droop on the P - f loop allowing multiple converters to operate distantly in the same grid). Hence the voltage target should be of the form: $V^* = V_{ref} + D_q(Q^* - Q)$. However, to cancel the static error while having an instantaneous voltage response, at least a PI controller is needed for the regulation. It is assumed that $V_{grid} \approx V_n = 1$ [p.u.]. Hence the voltage difference is expressed: $\Delta V = V^* - V_n$. Under this condition, a simple Q - V droop controller output in the Laplace domain can be expressed as:

$$\Delta V = \left(k_{p,Q} + \frac{k_{i,Q}}{s} \right) (D_q (Q - Q^*)) - V_n \quad (2.29)$$

Where D_q is the Q - V droop coefficient (typically $0.01 < D_q < 0.1$, as will be discussed later in this work, in Section 3.1).

Remark

This Q - V loop is an example of what could be used to control Q as an output, in the same way P is controlled as an output. However, there is a big difference in the reason why controlling these quantities. Regulation of P is indeed intrinsic to the Grid-Forming principle, while regulation of Q is not directly an expected behavior for a Grid-Forming converter. A dedicated section (3.4) explores the details and the consequences of this fact.

Let us add two LADRC blocks to two loops of the system.

The first internal loop is the P - δ loop, that is of order 2 (VSG of order 2 + ELEC of order 0 because linearized). Thus the P -LADRC should be of the second-order (third order ESO), such that the observer can appropriately estimate the two internal states for this P - δ loop. Intuitively, this P-LADRC should allow replacing the dynamics of this P - δ loop (including cross-coupling) by any second-order response.

The second internal loop is the Q - V loop, that is of order 1 (Q - V droop and PI of order 1 + ELEC of order 0 because linearized). Thus the Q -LADRC should be the first-order (second-order ESO), such that the observer can appropriately estimate the unique internal state for this Q - V loop. Intuitively, this LADRC should allow replacing the dynamics of this Q - V loop (including cross-coupling) by any first-order response.

The system is represented in Fig. 2.6.

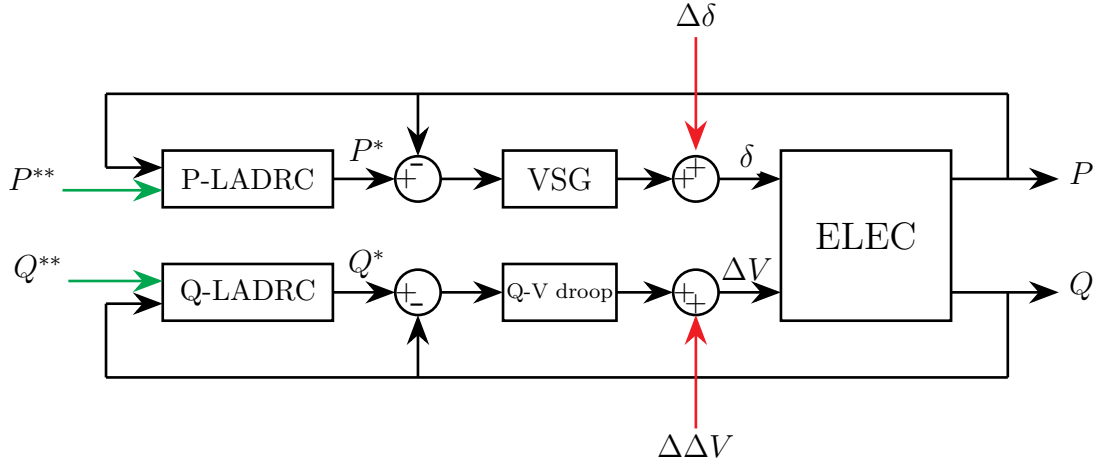


Figure 2.6: Grid-Forming VSG control system with P-LADRC and Q-LADRC. The ELEC part is the linearized model of the grid, giving active and reactive powers P and Q in function of the phase shift δ and the voltage difference ΔV between the converter (Point of Common Coupling) and the grid equivalent. P-LADRC and Q-LADRC serve to replace the dynamics of, respectively, the active power-frequency and reactive power-voltage loops (include cross-coupling) by any second-order and first-order responses.

Remark

By using LADRCs with constant P^{**} and Q^{**} power targets, the system is configured in a *Grid-Following philosophy*, referring to the definitions in Section 1.5.

As expected, analytical computation confirms the preserved linearity of the system: expressions of P and Q depend linearly on P^* , Q^* , $\Delta\delta$, $\Delta\Delta V$. Hence the following transfer functions do not depend on these targets and disturbances.

Reaction to changes of target

$$\frac{\partial P}{\partial P^{**}} = \sigma \cdot g_{1,1}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P}, K_{d,P}, b_{0,P}, \omega_{0,P}) \quad (2.30)$$

$$\frac{\partial P}{\partial Q^{**}} = s D_q R \cdot g_{1,2}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P}, K_{d,P}, b_{0,P}, \omega_{0,P}) \quad (2.31)$$

$$\frac{\partial Q}{\partial P^{**}} = -s \sigma R \cdot g_{1,3}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P}, K_{d,P}, b_{0,P}, \omega_{0,P}) \quad (2.32)$$

$$\frac{\partial Q}{\partial Q^{**}} = D_q \cdot g_{1,4}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P}, K_{d,P}, b_{0,P}, \omega_{0,P}) \quad (2.33)$$

$$\lim_{s \rightarrow 0} \frac{\partial P}{\partial P^{**}} = 1 \quad (2.34)$$

$$\lim_{s \rightarrow 0} \frac{\partial P}{\partial Q^{**}} = 0 \quad (2.35)$$

$$\lim_{s \rightarrow 0} \frac{\partial Q}{\partial P^{**}} = 0 \quad (2.36)$$

$$\lim_{s \rightarrow 0} \frac{\partial Q}{\partial Q^{**}} = 1 \quad (2.37)$$

$$\lim_{s \rightarrow \infty} \frac{\partial P}{\partial P^{**}} = 0 \quad (2.38)$$

$$\lim_{s \rightarrow \infty} \frac{\partial P}{\partial Q^{**}} = \frac{K_{p,Q}}{b_{0,Q}} \frac{D_q k_{p,Q} R}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.39)$$

$$\lim_{s \rightarrow \infty} \frac{\partial Q}{\partial P^{**}} = 0 \quad (2.40)$$

$$\lim_{s \rightarrow \infty} \frac{\partial Q}{\partial Q^{**}} = \frac{K_{p,Q}}{b_{0,Q}} \frac{D_q k_{p,Q} X}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.41)$$

As can be seen with the transfer functions (2.30-2.33), the intensity of the response directly depends on the value of the droop coefficient related to the input branch. Moreover, the cross-coupled responses (2.31) and (2.32) directly depend on the value of the resistive part of the system, as expected.

The limits in $s \rightarrow 0$ (2.34-2.37) confirm the expected steady-state response on a step of P^* and Q^* targets: in an undetermined time, the cross-coupling responses are faded, while direct responses reached the target values.

The limits in $s \rightarrow \infty$ for a change of P^* (2.38) and (2.40) are zero, which is due to the double-integrator behavior of the VSG (no proportional component), also seen as inertia. The limits in $s \rightarrow \infty$ for a change of Q^* ((2.39) and (2.41)) directly depend on the value of the Q - V droop coefficient D_q . A $\frac{K_{p,Q}}{b_{0,Q}}$ factor appears for the $s \rightarrow \infty$ limits of $\partial P/\partial Q^{**}$ and $\partial Q/\partial Q^{**}$, as suggested by the limits of the simplified Two-Input Two-Output case ((2.11) and (2.13)).

Reaction to external disturbances

Regarding the reaction to external disturbances, the transfer functions and limits are:

$$\frac{\partial P}{\partial \Delta \delta} = s \cdot g_{2,1}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P,Q}, K_{d,P,Q}, b_{0,P,Q}, \omega_{0,P,Q}) \quad (2.42)$$

$$\frac{\partial P}{\partial \Delta \Delta V} = sR \cdot g_{2,2}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P,Q}, K_{d,P,Q}, b_{0,P,Q}, \omega_{0,P,Q}) \quad (2.43)$$

$$\frac{\partial Q}{\partial \Delta \delta} = -sR \cdot g_{2,3}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P,Q}, K_{d,P,Q}, b_{0,P,Q}, \omega_{0,P,Q}) \quad (2.44)$$

$$\frac{\partial Q}{\partial \Delta \Delta V} = s \cdot g_{2,4}(s, R, X, \sigma, \omega_b, k_{p,Q}, k_{i,Q}, D_q, K_{p,P,Q}, K_{d,P,Q}, b_{0,P,Q}, \omega_{0,P,Q}) \quad (2.45)$$

$$\lim_{s \rightarrow 0} \frac{\partial P}{\partial \Delta \delta} = 0 \quad (2.46) \qquad \lim_{s \rightarrow \infty} \frac{\partial P}{\partial \Delta \delta} = \frac{D_q k_{p,Q} + X}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.50)$$

$$\lim_{s \rightarrow 0} \frac{\partial P}{\partial \Delta \Delta V} = 0 \quad (2.47) \qquad \lim_{s \rightarrow \infty} \frac{\partial P}{\partial \Delta \Delta V} = \frac{R}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.51)$$

$$\lim_{s \rightarrow 0} \frac{\partial Q}{\partial \Delta \delta} = 0 \quad (2.48) \qquad \lim_{s \rightarrow \infty} \frac{\partial Q}{\partial \Delta \delta} = \frac{-R}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.52)$$

$$\lim_{s \rightarrow 0} \frac{\partial Q}{\partial \Delta \Delta V} = 0 \quad (2.49) \qquad \lim_{s \rightarrow \infty} \frac{\partial Q}{\partial \Delta \Delta V} = \frac{X}{D_q k_{p,Q} X + R^2 + X^2} \quad (2.53)$$

Limits in $s \rightarrow 0$ show the system fades steps of phase shifts and voltage drops coming from the grid (in an undetermined time, steady-state). Limits in $s \rightarrow \infty$ show that the instantaneous response to a disturbance coming from the grid side does not depend on the VSG parameters, this being due to the (intentionally) slow response of the VSG.

By extra analyses, it is possible to see that limits in $s \rightarrow \infty$ are identical to the case without LADRC, just like in the case of the simplified Two-Input Two-Output system analysis. Hence it cannot be attributed to the behavior of the VSG, but instead the finite value of the observer bandwidth $\omega_{0,P}$ and $\omega_{0,Q}$.

2.2.2 Frequency responses of the Grid-Forming VSG control system with or without LADRC(s)

The previous results confirmed important information about the system response and loop's coupling with or without mono-LADRC and dual-LADRC in the non-ideal case where observers bandwidth is not infinite. However, it has not been practically possible to observe analytically the frequency responses, except for the particular $s \rightarrow 0$ and $s \rightarrow \infty$ values. In this section, some of these transfer functions are represented graphically and interpreted following the three LADRC interests presented at the beginning of this chapter. The goal is to verify whether the results obtained previously still apply in the more complex case of converter control, and to interpret the results with electrical considerations. Only the magnitude plots will be analyzed, and phase plots are placed in Appendix B.

Except for mentioned deviations, the parameters are the following. The total impedance of the electrical part is chosen to be $\bar{Z} = R + jX = 0.2 + j1$ [p.u.], to keep consistent with the simplified case (2.26). This impedance being *total*, it does not show what is the ratio between the impedance of the filter and the impedance of the grid (*electrical distance*). However if it is assumed to be equally distributed, this corresponds to a quite weak grid ($SCR = 2 < 3$) with a moderate resistive part, which is mostly representative of a quite distant medium-to-high-voltage grid. Regarding the VSG parameters, parameters are: $\sigma = 1\%$, $H = 5$ [s], $\omega_B = 2\pi \cdot 50$ [rad/s], $\omega_n = 1$ [p.u.], which corresponds to a classic situation of an inertial, though damped VSG. Regarding the Q - V droop controller, a detailed discussion about parameters is provided later in this work (Chapter 3). However to keep consistent with the simplified case, the PI gains are chosen to be: $k_{p,Q} = 1$ and $k_{i,Q} = 0.1$, which corresponds to a quite high proportional action with a moderate integral action to cancel the static error. Moreover, $V_n = 1$ [p.u.] and $D_q = 10\%$.

Assuming low cross-coupling ($R \ll X$, i.e. inductive grid), the remaining base model transfer functions are written:

$$\frac{\partial P}{\partial P^*} = \frac{\frac{\omega_B}{2HX}}{s^2 + \frac{1}{2H\sigma}s + \frac{\omega_B}{2HX}} \quad \frac{\partial Q}{\partial Q^*} = \frac{D_q(k_{i,Q} + k_{p,Q}s)}{(D_q k_{p,Q} + X)s + D_q k_{i,Q}}$$

The P-LADRC gain can be immediately identified: $b_{0,P} = \frac{\omega_B}{2HX} \approx 31.4$. The Q-LADRC is based on the integral part, hence considering:

$$\frac{\partial Q}{\partial Q^*} \approx \frac{\frac{D_q k_{i,Q}}{X}}{s + \frac{D_q k_{i,Q}}{X}}$$

The Q-LADRC gain can be identified: $b_{0,Q} = \frac{D_q k_{i,Q}}{X} = 0.01$. P-LADRC is parametrized to replace the VSG dynamics (notably characterized by a natural frequency $\omega_{model,P} = \sqrt{31.4} = 5.49$ [rad/s]) by a critically damped second-order low-pass filter response of cutoff frequency $\omega_{desired,P} = 100$ [rad/s], implying $K_{p,P} = 10000$ and $K_{d,P} = 200$. Q-LADRC is parametrized to replace the Q - V controller dynamics (notably characterized by a cutoff frequency $\omega_{model,Q} = 0.01$ [rad/s]) by a first-order low-pass filter response of cutoff frequency $\omega_{desired,Q} = 1$ [rad/s], implying $K_{p,Q} = 1$. LADRC observers bandwidth are set to $\omega_{0,P} = \omega_{0,Q} = 2\pi \cdot 50$ [rad/s] as these are classical values used in practice.

2.2.3 Interest 1: independence of the control to the grid characteristics

To see how the response is independent on the unknown grid characteristics, the module of the equivalent impedance, $Z = \sqrt{R^2 + X^2}$ is varied by proportionally varying both the resistance R and the reactance X . The LADRC parameters $b_{0,P}$ and $b_{0,Q}$, that should be estimates of the (unknown) physical gains b_P and b_Q , are kept to their initial values corresponding to the default $X = 1$ [p.u.] case without loop's cross-coupling ($R = 0$ [p.u.]).

Reaction to a change of target

In Fig. 2.7 is represented the active power P response to a change of target P^{**} for various values of equivalent impedance Z . P-LADRC allows displacement of the VSG dynamics towards the desired response. The new dynamics corresponds to the desired response, in the observer bandwidth, when Z is lower than expected, i.e. when the actual gain b_P is higher than the estimated gain $b_{0,P}$. Otherwise, the response seems still dependent on the grid characteristics.

Hence regarding dynamics replacement, it would be better to underestimate the gain than the opposite. However, regarding small-signal stability, it is already known ([16]) that it is in practice better to overestimate the gain due to the inductive dynamics of the line neglected by the linearized model. This result unfortunately highlights the importance of a good gain estimate to meet the desired LADRC performance. An effect of resonance also appears with intermediate Z values, especially in the observer bandwidth when Z is high.

It seems like this second-order system is more sensitive to gain mis-estimation. However, the consequence must be nuanced by the fact that the logarithmic range of variation of Z is quite unrealistic. Moreover the grid operators should guarantee a certain (non-logarithmic) range for the grid impedance at the point of connection.

Fig. 2.8 shows the reactive power Q response to a change of target Q^{**} . P-LADRC has few influence, though small effects of resonance can be observed compared to the case without LADRC. Adding Q-LADRC allows dynamics replacement of the first-order Q - V control system, and response is independent on the equivalent impedance Z , in the observer bandwidth. Beyond the observer bandwidth the response shapes proportionally to the case without LADRC. Hence depending on the LADRC parameters, high frequency response of Q to a change of target Q^{**} may be amplified.

Reaction to a grid phase shift

Fig. 2.9 shows that the active power P reaction to a grid phase shift changes with P-LADRC, due to the dynamics replacement. Resonance effects are visible. Adding Q-LADRC has no influence.

Fig. 2.10 shows that P-LADRC allows attenuation of the impact of a grid phase shift on the reactive power Q , and adding Q-LADRC further attenuates this impact and in higher frequencies (temporally faster).

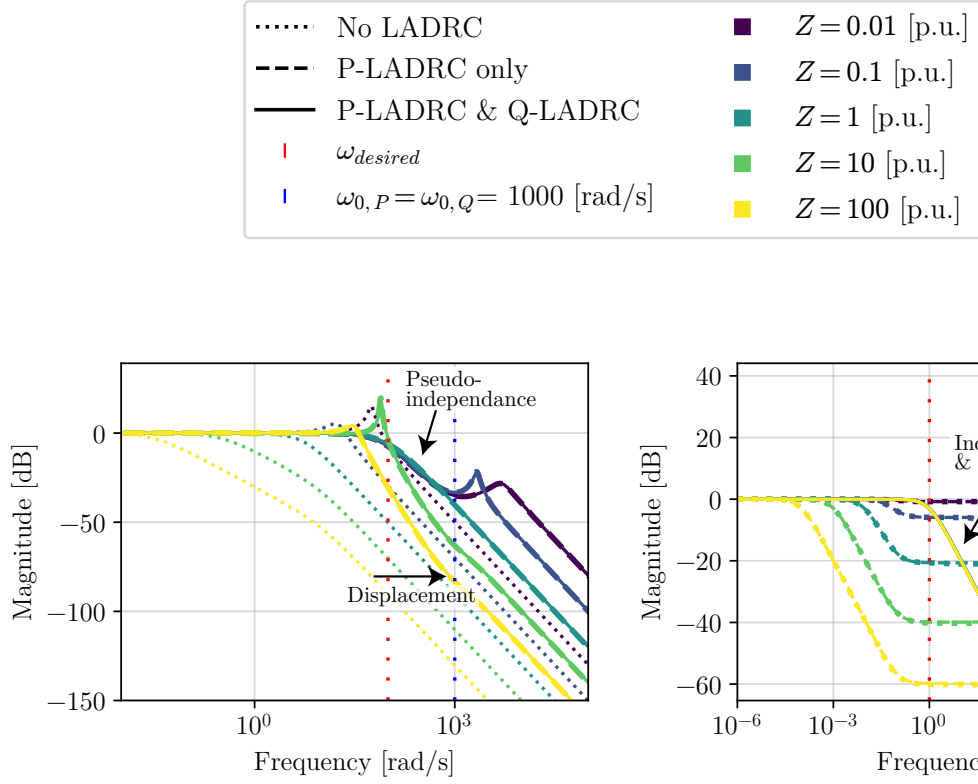


Figure 2.7: Magnitude of dP/dP^{**} for varying grid impedance Z . P-LADRC (either or not along with Q-LADRC) displaces the VSG dynamics towards desired response. However, dependence on Z is still present (particularly beyond observer bandwidth) and resonance may appear.

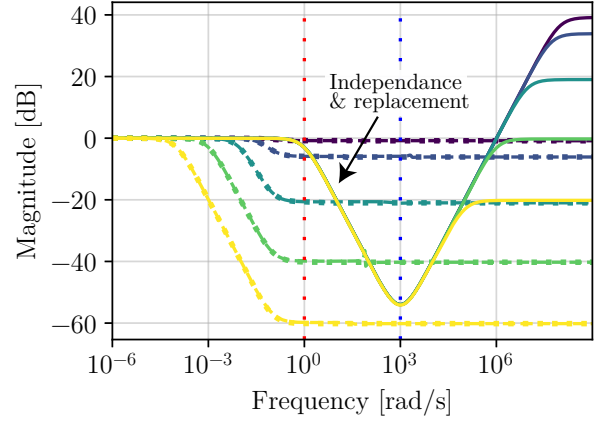


Figure 2.8: Magnitude of dQ/dQ^{**} for varying grid impedance Z . P-LADRC has no impact on the response. Q-LADRC allows independence on Z and dynamics replacement in the observer bandwidth.

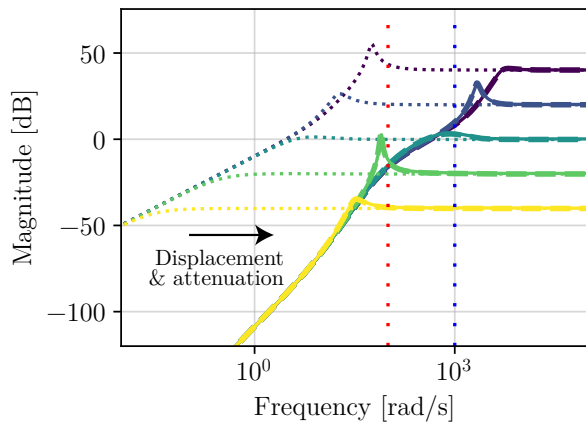


Figure 2.9: Magnitude of $dP/d\Delta\delta$ for varying grid impedance Z . P-LADRC (either or not along with Q-LADRC) changes the P response to grid phase shifts, by dynamics replacement.

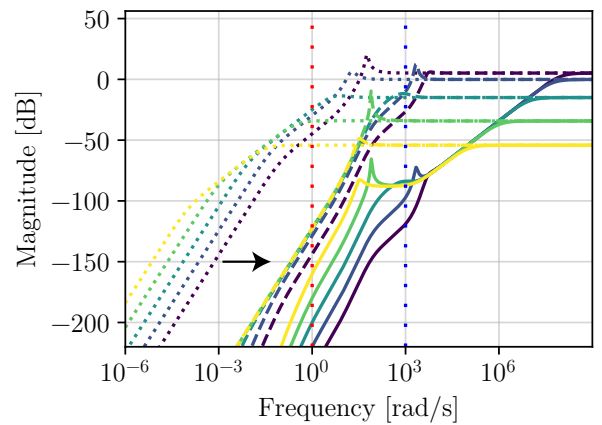


Figure 2.10: Magnitude of $dQ/d\Delta\delta$ for varying grid impedance Z . P-LADRC allows faster attenuation of the impact of grid phase shifts on Q . Adding Q-LADRC allows even further attenuation.

2.2.4 Interest 2: behavior change in function of ω_0

The LADRC observers bandwidths $\omega_{0,P}$ and $\omega_{0,Q}$ have been varied to see how the control behavior changes, when reacting to a change of target or of external disturbance. As a reminder, it is expected that the LADRC is able to replace the internal dynamics and reject disturbances only with a sufficiently high bandwidth ω_0 (near ideal case). Previous analysis on the simplified Two-Input Two-Output system showed input rejection when observer bandwidth ω_0 is low, and model rejection when observer bandwidth ω_0 is high.

Reaction to a change of target

Magnitude response of the active power P to a change of target P^{**} is shown in Fig. 2.11. As expected, P-LADRC with high $\omega_{0,P}$ allows inner dynamics replacement with the desired response. It is interesting to notice that whatever $\omega_{0,P}$, the response for $\omega > \omega_{0,P}$ is still the desired response. This is because the shape of the desired dynamics is the same as the original dynamics. Hence in these out-of-bandwidth frequencies, the model must not be actively rejected, and the static action, visible in limit (2.38), is sufficient. P-LADRC with low $\omega_{0,P}$ allows input rejection, as expected. Adding Q-LADRC has no influence on the response.

Similarly, magnitude response of the reactive power Q to a change of target Q^{**} is shown in Fig. 2.12. P-LADRC has no influence. Q-LADRC with high $\omega_{0,Q}$ allows model rejection for $\omega < \omega_{0,Q}$. The response in high frequencies converges towards the computed value with limit (2.41). Low $\omega_{0,Q}$ leads to input rejection for $\omega > \omega_{0,Q}$.

The evolution of behavior with the observers bandwidth ω_0 is similar to with the simplified Two-Input Two-Output system. Hence the same conclusion regarding behavior for intermediate ω_0 values can be extended for this converter control system. As a reminder:

- Input rejection in $\omega \in [\omega_0, \min(\omega_{desired}, \omega_{model})]$ when $\omega_0 < \min(\omega_{desired}, \omega_{model})$
- Model rejection in $\omega \in [\min(\omega_{desired}, \omega_{model}), \omega_0]$ when $\omega_0 > \min(\omega_{desired}, \omega_{model})$

Reaction to a grid phase shift and to a grid voltage drop

Fig. 2.13 represents the impact of a grid phase shift on the active power P . When $\omega_{0,P}$ is low, initial VSG response is conserved, hence it is the base Grid-Forming behavior. However, when $\omega_{0,P}$ is high, P-LADRC further attenuates the impact. This comes closer to a Grid-Following behavior: the system adapts quicker (its angle, like with a PLL) such that the external disturbance is dissolved and the converter output power (and current) is kept almost constant. This interpretation is coherent with existing works on the subject [41]. Adding Q-LADRC has no influence.

Similarly, Fig. 2.14 shows the impact of a voltage drop on the reactive power Q . P-LADRC has no influence. When $\omega_{0,Q}$ is low, initial Q - V controller response is conserved. The impact on Q is only attenuated after some time (in low frequencies) by maintaining

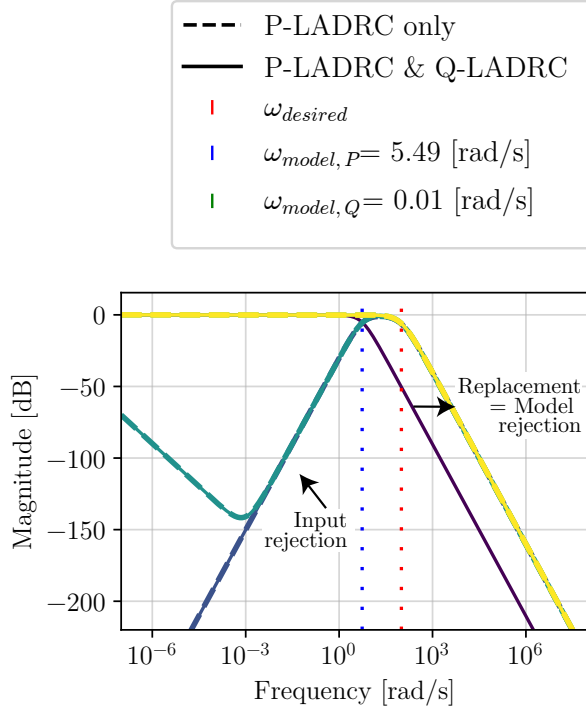


Figure 2.11: Magnitude of dP/dP^{**} for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$. High P-LADRC observer bandwidth $\omega_{0,P}$ leads to model rejection (dynamics replacement). Low $\omega_{0,P}$ leads to input rejection while also converging towards the desired dynamics in high frequencies. Adding Q-LADRC has no influence.

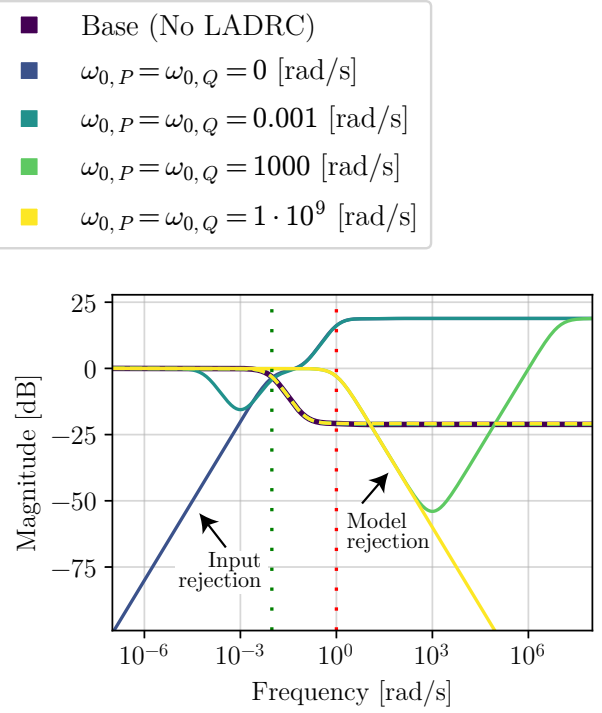


Figure 2.12: Magnitude of dQ/dQ^{**} for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$. Adding P-LADRC has no influence. High Q-LADRC observer bandwidth $\omega_{0,Q}$ leads to model rejection (dynamics replacement). Low $\omega_{0,Q}$ leads to input rejection.

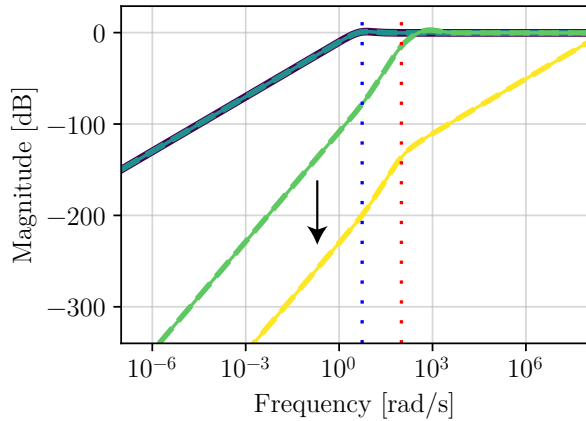


Figure 2.13: Magnitude of $dP/d\Delta\delta$ for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$. Grid-Forming behavior of the VSG is conserved with low $\omega_{0,P}$ P-LADRC. With a high bandwidth, P-LADRC allows quicker attenuation of the impact, more like a Grid-Following behavior.

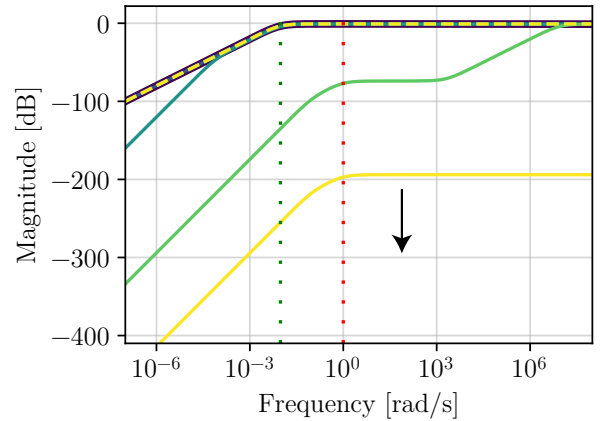


Figure 2.14: Magnitude of $dQ/d\Delta V$ for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$. Grid-Forming behavior of the Q - V droop response to voltage drops is conserved with low $\omega_{0,Q}$ Q-LADRC. With a high bandwidth, Q-LADRC allows attenuation of the impact, more like a Grid-Following behavior.

then slowly adapting the converter voltage, which is a Grid-Forming behavior². However, when $\omega_{0,Q}$ is high, Q-LADRC further attenuates the impact. This comes closer to a Grid-Following behavior: the system adapts quicker (its voltage, like with measurement) such that the external disturbance is dissolved and the converter output power (and current) is kept almost constant. The results are summarized in Table 2.1.

	Outer control	LADRC configuration	Behavior with low ω_0	Behavior with high ω_0
P - f loop	VSG Grid-Forming behavior	P-LADRC with const. P^{**} Grid-Following philosophy	Grid-Forming	Grid-Following
Q - V loop	PI Q - V loop Grid-Forming behavior	Q-LADRC with const. Q^{**} Grid-Following philosophy	Grid-Forming	Grid-Following

Table 2.1: Synthetic summary of results concerning the system behavior in function of the observer bandwidth ω_0 .

Hence it can be concluded that the possibility of continuum between Grid-Forming and Grid-Following by adapting the LADRC observer frequency ω_0 ([41]) may also exist for the Q - V loop. However, this must be confirmed with the Q - V system actually used. Similar analysis are made in time domain in further Section 3.6.

2.2.5 Interest 3: decoupling of the control loops

To see how control loops are decoupled with one or two LADRCs, the value of the resistive part R , responsible for the loop's cross-coupling, is varied.

Particular values are used for the analysis. Firstly, $R = 0$ [p.u.] is the reference case without cross-coupling: the control loops are already decoupled, as shown with the transfer functions (2.39) and (2.40). Secondly, the default value $R = 0.2$ [p.u.] is considered for a moderate cross-coupling.

Unlike the simplified system that could be made singular and uncontrollable when $A = B = C = D$, this linearized electrical system does not present such a singularity. Its determinant is $\det(\text{ELEC}) = \frac{1}{R^2 + X^2} = \frac{1}{Z^2}$, and can only tend to zero when the impedance is infinite (open circuit). Hence $R = X = 1$ [p.u.] is considered for demonstration.

A case where the cross-coupling is slightly larger than the direct action ($R = 1.2$ [p.u.]) is also studied, as well as a case where the cross-coupling is much larger than the direct action $R = 10$ [p.u.].

Reaction to a change of target

The active power response P to a change of reactive power target Q^{**} is represented in Fig. 2.15. With the P-LADRC alone, cross-coupling of loops is attenuated, even beyond observer bandwidth $\omega_{0,P}$. However, adding Q-LADRC unfortunately amplifies the loop's cross-coupling beyond observers bandwidth $\omega_{0,P} = \omega_{0,Q}$. An influence (slightly positive) is also visible in the bandwidth.

²However it is important to remember that unlike P regulation, which is necessary for Grid-Forming (frequency creation & synchronism), Q regulation is not required for Grid-Forming (voltage creation). In other words, the voltage could simply be maintained constant, without any adaptation.

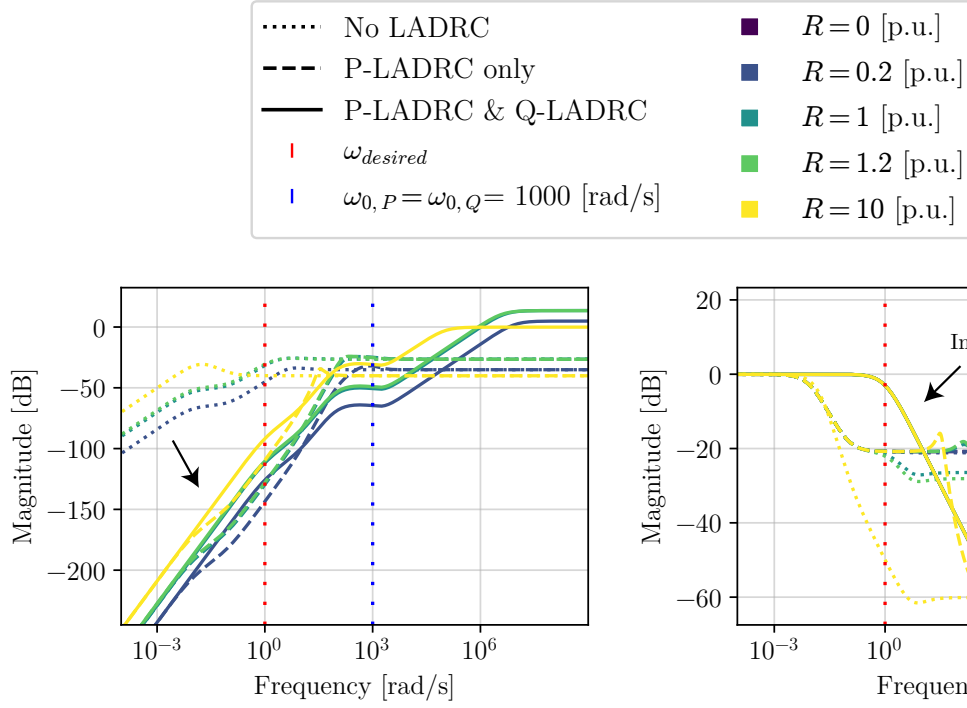


Figure 2.15: Magnitude of dP/dQ^{**} for varying the resistive part R . P-LADRC alone allows attenuating the effect of cross-coupling of loops, even beyond observer bandwidth $\omega_{0,P}$. Adding Q-LADRC has an influence in the bandwidth, and amplifies the cross-coupling of loops beyond the observers bandwidth $\omega_{0,P} = \omega_{0,Q}$.

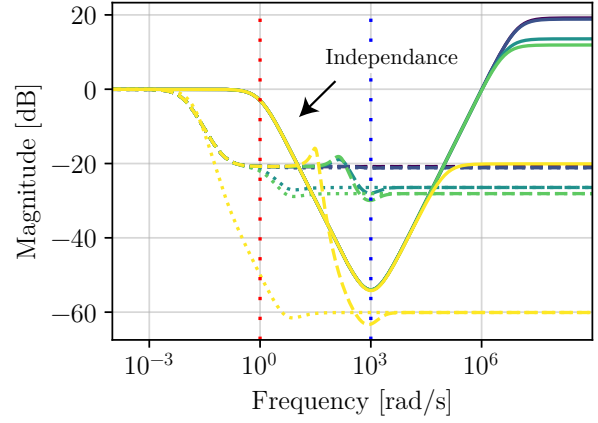


Figure 2.16: Magnitude of dQ/dQ^{**} for varying the resistive part R . P-LADRC has a positive influence, making the response close to the uncoupled non-resistive case below $\omega_{desired,P} = 100$ [rad/s]. Adding Q-LADRC allows dynamics replacement and independence on the resistive part R in the observer bandwidth.

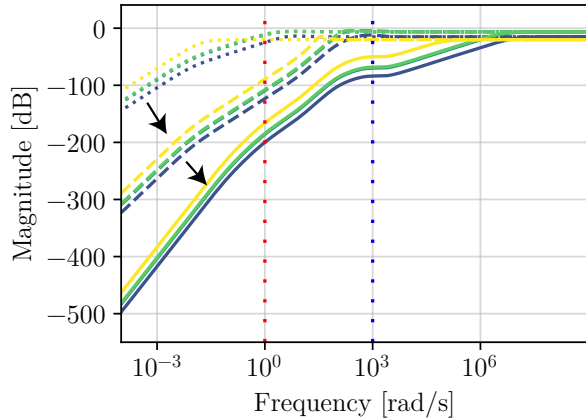


Figure 2.17: Magnitude of $dQ/d\Delta\delta$ for varying the resistive part R . P-LADRC allows stronger attenuation of the impact of a grid phase shift on Q . Adding Q-LADRC further attenuates this impact, and in higher frequencies (i.e. temporally faster).

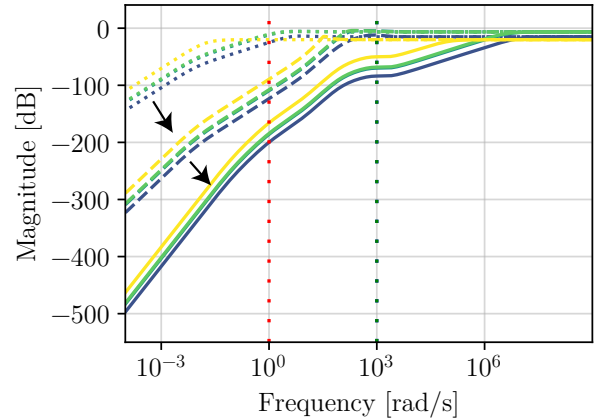


Figure 2.18: Magnitude of $dP/d\Delta V$ for varying the resistive part R . Identical to $dQ/d\Delta\delta$. P-LADRC allows stronger attenuation of the impact of a grid phase shift on Q . Adding Q-LADRC further attenuates this impact, and in higher frequencies (i.e. temporally faster).

The reactive power response Q to a change of reactive power target Q^{**} is represented in Fig. 2.16. P-LADRC has a positive influence, making the response close to the uncoupled non-resistive case, in the observer bandwidth below $\omega_{desired,P} = 100$ [rad/s]. Adding Q-LADRC allows dynamics replacement and independence on the resistive part R in the observer bandwidth. Beyond the observer bandwidth however, the response may be amplified, following the LADRC parameters, as seen with limit (2.41).

Reaction to a grid phase shift and to a grid voltage drop

Figs. 2.17 and 2.18 show, respectively, the reactive power Q response to a grid phase shift and the active power P response to a voltage drop. These responses are identical in amplitude (not in phase !), as limits (2.39) and (2.40) gave an indication. P-LADRC allows a stronger attenuation of the disturbance on the cross-coupled power. Adding Q-LADRC further attenuates this impact, and in higher frequencies (i.e. temporally faster).

2.2.6 Conclusion on LADRC interests on the Grid-Forming VSG control system with or without LADRC(s)

In conclusion, analysis of LADRC interests on the VSG control system mainly confirmed theoretical results obtained in the analysis of the simplified Two-Input Two-Output.

P-LADRC applied to the second-order system highlighted the importance of a good estimation of the system gain. A trade-off must be found between underestimating the gain for an accurate dynamics replacement, and overestimating the gain to save small-signal stability with the non-linear model.

LADRC observer bandwidth ω_0 can be used to switch between an input-rejection mode to a model-rejection mode. Practical interest of this possibility must still be discussed. Regarding the management of external disturbances, a low ω_0 bandwidth conserves the Grid-Forming behavior, while a high ω_0 tends to give a Grid-Following behavior by rejecting these disturbances instead of facing it with inertia or by maintaining voltage.

LADRC helps decoupling the loops. In overall, no critical interaction has been observed between the two loops with or without one or two LADRC(s). However, resonance effects may appear with the second-order system. LADRC on one loop may influence the other loop, and the impact may be considered negative when undesired amplifications occur in high frequencies due to the system parametrization.

Chapter 3

What should be the voltage response? Design and analysis of the Q - V loop

In this chapter

As a reminder, Grid-Forming converters aim to *create* their own voltage, in phase and amplitude, instead of relying on external measurements of existing and possibly weak signals. A major interest is to bring inertia to the grid. Since the inertia is assessed on the frequency response, that is a global variable, research focused primarily on the P - f loop. However, grid voltage stability and control, a more local question, is also a serious concern for the grid of today and tomorrow [43]. Given the freedom offered by converter control, it is therefore important to think about what should ideally be the voltage response of such converters.

The aim of the following sections is to discuss the design of the Q - V control loop, including application of LADRC. Time domain simulations of the system in Matlab Simulink are provided and analyzed. To summarize,

1. Standards requirements are examined to extract key figures for the design of the Q - V loop.
2. Inner loops are presented. The response strongly depends on the system characteristics.
3. Q - V outer loop helps making the response closer to predictable expectations.
4. Q -LADRC vs V -LADRC: LADRC can be applied by two ways on the Q - V loop. Time domain simulations and small-signal stability are analyzed.
5. The P - V_{PCC} system is linearized. A condition to limit cross-coupling is highlighted.
6. The final system is further analyzed in time domain and with extra small-signal stability analyses.
7. Behavior of the system with a current limiter in FRT conditions is assessed.

3.1 Standards requirements

In this section

As a starting point, it is interesting to have a look at the standards requirements and recommendations used in practice regarding electricity generators.

This section aims to synthesize useful information that will be used as a reference for the design of the Q - V loop. Since this work concerns a research topic in a rapidly evolving field, there is no unique absolute reference that could be followed. The context is focused on requirements for Grid-Forming converters on the continental European grid (known as *Continental Europe Synchronous Area*, CESA). The *European Network of Transmission System Operators for Electricity* (ENTSO-E) is an association of 40 European TSOs. It provides the technical content required to create and adapts EU legislation for coordination and strategy regarding the European grid [44]. When technical freedom is left to member states (or countries, or TSOs), the particular case of Belgium is considered, where Elia is the TSO.

To summarize, the expected behavior and key figures are found out.

- The inner current loop should be very fast, with a target time constant $\tau_i \approx 1$ [ms].
- The voltage loop should also be as fast as possible, with a target time constant $\tau_v \approx 20$ [ms].
- Current clipping is allowed but should be limited in time.

By early 2026, the stability of the European electricity grid becomes critical due to the very rapid installation of a large renewable electricity capacity. These new sources are mainly connected with Grid-Following converters, which leads to an overall lower inertia, and a reduced grid strength. Moreover, Elia points out a regulatory gap: the new EU Network Codes Requirements for Generators (RfG 2.0) is still under development, hence unified coordinated action regarding the Grid-Forming solution at the European level will yet take years before taking place. All TSOs are therefore left on their own to quickly solve their problems. To have already a clear idea of the future requirements, all TSOs make technical proposals, which has led to an ENTSO-E draft NC RfG 2.0 published in 2025. Elia mostly align with these directions, but would require even higher capabilities due to local aspects, based on internal studies [45][46].

When a reference converter size had to be considered, the largest size (type D) was focused (with the perspective of HVDC converters). When additional information was needed, it has been found in an older documents (2018, 2019) concerning *Power Park Modules* (PPMs) and HVDC converters. However, it is important to remember that these documents applied to Grid-Following converters, since Grid-Forming is a more recent topic. Therefore, a critical approach is necessary to assess whether the information is relevant to Grid-Forming converters.

About methodology

The objective of this work is not specifically to design a converter control system that would pass the certification tests, but instead to design a system that is realistic and meet general requirements. Hence the information gathered from the references is used in an indicative design purpose, but the requirements will not be strictly checked at the end of the process. A part of the design and of the final results would anyway depend on the technological choices (physical implementation of the converter), that is largely neglected at this stage of the research.

The information concerning voltage response is summarized below.

ENTSO-E Grid Forming capability of Power Park Modules (NC RfG 2.0 draft, 3rd October 2025) [46]

- In response to a grid disturbance, i.e. a step of phase angle and/or voltage magnitude, the converter should be "capable of not changing its amplitude and phase angle" when "current limits are not exceeded" [p.17].
→ Inherent to the Grid-Forming principle.

- "Following a grid-side voltage amplitude step change" or "phase angle step change", the current should "reach 90% of the expected value" in "less than 10 ms" [p.23]. "A settling time of 60 ms" is expected for "the dynamic response for voltage magnitude changes at the Point of Coupling" [p.24].

It is of common knowledge (and it can be calculated) that a first-order system reaches 95% of its response after 3 time constants. For the Q - V loop design, it is hence estimated that:

→ The current loop time constant must be less than $\tau_i \approx \frac{10}{3} = 3.33$ [ms]. In fact, a *voltage source* should not need a current loop. In practice, it is still required for technical reasons, including current saturation capability, as explained later in this work (Section 3.7). The current loop should be as fast as possible, given the limitations of the power electronics. A target time constant of $\tau_i = 1$ [ms] is used for the rest of this work.

→ The voltage loop time constant must be less than $\tau_v \approx \frac{60}{3} = 20$ [ms]. Here also, the voltage response must probably be as fast as possible. However since the inner current loop is *embedded* in the voltage loop (as will be discussed further in Section 3.2), we should have $\tau_v \gg \tau_i$. Moreover, it is likely that LADRC observer bandwidth will be limited by the small-signal stability of the system [16]. Hence the target time constant of $\tau_v = 20$ [ms] is used for the rest of this work.

- "Instantaneous reaction" of the converter "to maintain currents limits is allowed" [p.18]. "When reaching current capability limit", "no priority is given to any current component", i.e. "only the magnitude of the current may be limited" and "the resulting current [...] shall reflect a proportionally scaled-down vector sum of all ideal, unconstrained current components" [p.30].

"Up to 40 ms of current clipping is accepted after voltage angle jumps and magnitude steps. It is also acceptable [...] to provide current above 100% of nominal current, if capable of doing so" [p.31].

3.1. Standards requirements

→ Current saturation is allowed but another action must be added to relieve the system. A current margin should be planned (over-sizing) to allow operation. The 40 [ms] current clipping limit is in this case not applicable.

- Two examples of test setup are given and shown in Fig. 3.1. "Phase jumps may be introduced using a grid emulator or a passive system by switching a local load or grid impedance" [p.42]. When testing capability limits, "the applied phase jumps are determined by the unit's effective impedance and its operating point prior to the event, ensuring the unit reaches its capability limits" [p.46].

→ Disturbance may, but is not necessarily linked to a grid impedance change. When assessing the capability, since the disturbance must be beforehand calculated, a complex grid or load emulation is not necessary and the desired disturbance may be created simply by directly changing the Thévenin equivalent circuit of the grid.

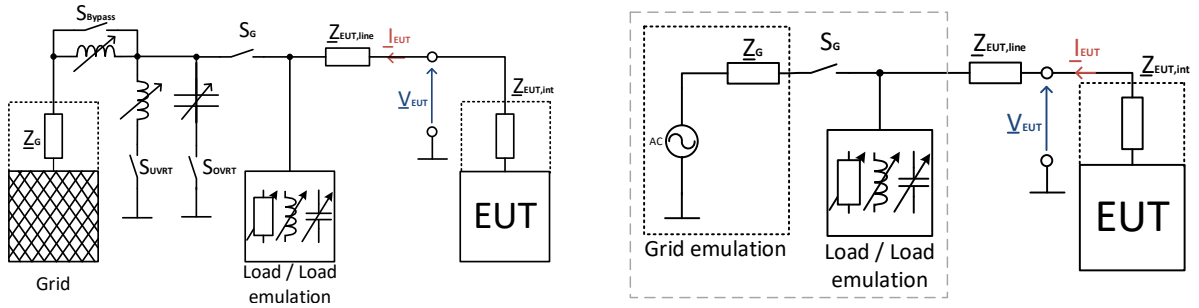


Figure 3.1: Two possible test bench setups for Equipment Under Test (EUT) being the Grid-Forming converter, from [46].

Elia additional technical requirements for grid-forming BESS (24th October 2025) [45]

- "Phase angle jump withstand capability": the converter "must, without disconnecting [...] and without interruption of operation, be able to withstand a momentary voltage phase jump of up to $\pm 45^\circ$ at the Point of Coupling". ("Based on the internal Elia study" [p.24].)

Elia RFG Requirements of General Application (22th August 2019) [47]

- The converter "should be able to support the network during fast transient voltages and networks short circuits" and should "remain connected as long as the voltage [...] is above the profile of" Fig. 3.2 [p.34].
- "The prioritizing of active or reactive power contribution is to be defined as site specific" [p.31].
- The Q - V droop coefficient can be chosen in "a range of at least 2 to 7%" [p.28].

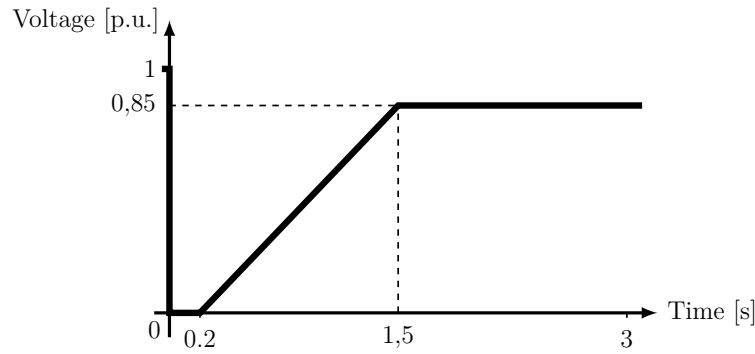


Figure 3.2: Fault-Ride-Through (FRT) profile for Type D PPM, adapted from [47].

Elia proposal for NC HVDC Requirements (17 May 2018) [48]

- "The HVDC system shall be equipped with a reactive power ramp rate limiter with settles the controlled AC voltage [...] in a programmable time span ranging between 1s and 60s" [p.14].
→ The voltage loop is fast only to deal with perturbations. The response to a change of target is imposed to be a ramp, that is much slower than the dynamics of the voltage loop without ramp rate limiter. For a Grid-Forming, the ramp rate limiter would probably act directly on the voltage instead of the reactive power.
- "Reactive power contribution shall have priority during low or high voltage operation and during faults for which Fault-Ride-Through capability is required" [p.14].
→ This indication opens the discussion, whether it is a behavior specific to Grid-Following or whether it is also applicable to Grid-Forming. Since RfG requirements and further Grid-Forming references do not decide on the need for a power priority, this questions remains unanswered. However if priority had to be given to P or Q , the mechanism could not be at the current saturation level, because it was clearly expressed that the saturation of current components must be proportional.
- "A HVDC system shall be able to recover active power transmission following fault clearance [...] within maximum 200ms" [p.15].
→ This indication also opens the discussion, whether it is a behavior specific to Grid-Following or whether it is also applicable to Grid-Forming. If synthetic inertia of the VSG is kept unchanged, active power may artificially take time to recover. After a fault clearance, it may be interesting to temporarily decrease the inertia constant H .

3.2 Inner loops

In this section

The considered electrical system and the inner loops required to control the converter will be presented. Because the converter output is separated from the controlled node by a filter, and for safety reasons, voltage and current inner loops are required.

To summarize, it is shown that an outer voltage loop is also needed because inner loops response strongly depends on grid characteristics.

The electrical system used in this work is represented in Fig. 3.3.

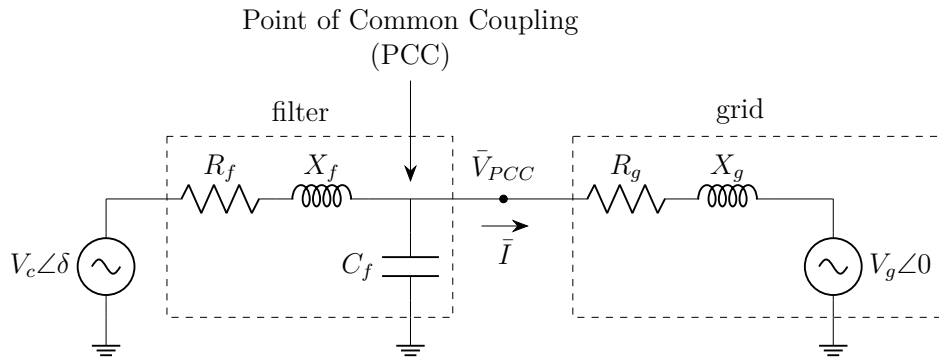


Figure 3.3: Single-phase equivalent circuit considered in this work. On the left side is the Grid-Forming converter. Power electronics output voltage magnitude is V_c and the phase δ is defined relatively to the reference phase of the grid. The converter is connected to the grid at the Point of Common Coupling (PCC) through an RLC filter. The grid is modeled as a Thévenin equivalent with a voltage source of magnitude $V_g = 1$ [p.u.], and an equivalent impedance that includes the line impedance.

From an operator perspective, the relevant voltage to be regulated is the voltage at the Point of Common Coupling (PCC) [46]. Because the PCC is separated by the output of the power electronics by the filter, an inner voltage loop must be used. As explained in the previous Section 3.1, even for a Grid-Forming converter, a fast inner current loop is also used in practice to allow current saturation for the protection of the device [23][33].

The system aims to control an AC voltage, which is by definition highly variable in the time domain. However, the relevant quantities are not the temporal evolution of the signal, but instead the amplitude and the frequency of the voltage, which are constant quantities in steady-state [16]. Hence it is common practice to use a *vector control*, which means controlling the system in a frame rotating with the system angle. To that end, the control system is designed in the Park's domain [16][25].

For the phase angle reference of the Park transforms, it is important that the frequency is the same as the one computed by the VSG. It ensures indeed that the measurements (inputs) and the output voltage are coherent, and allows a steady-state control operation.

3.2. Inner loops

However, the angle itself is arbitrary in the sense that the *direct* (d) and *quadrature* (q) axes, which form the orthogonal rotating frame, can be oriented arbitrarily¹. Hence for the converter control, the phase angle of the VSG is used for the transforms, and voltage is controlled such that the direct axis (d) is in phase with the voltage at the PCC. Therefore in steady-state, $V_{PCC,d} = |V_{ref}| = V_{ref,d}$ and $V_{PCC,q} = V_{ref,q} = 0$.

Because of the RLC filter, the d and q components of the output voltage of the converter ($\bar{V}_c$) and of the voltage at PCC ($\bar{V}_{PCC}$) are coupled. Intuitively, due to the presence of an imaginary part in the impedance, a change of $V_{c,d}$ will of course result in a change of $V_{PCC,d}$, but also a little change of $V_{PCC,q}$ (cross-coupling).

The two inner loops offer the possibility to decouple the control loops for d and q voltage components thanks to a feedforward action, which enhances the control dynamics [25][33][49]. Therefore, a change of $V_{ref,d}$ will only change $V_{PCC,d}$, while $V_{PCC,q}$ is left mostly unchanged, except for small dynamic effects not taken into account by the feedforward action (which is only phasorial, i.e. quasi-static). These effects are observed later in Section 3.5.

Inner loops purpose is to quickly cancel control errors on the voltage at the PCC and on the current flowing through the converter. The dynamic response of the inner loops may not be that important on its own, because it is anyway intended to be accompanied by a slower outer loop (the Q - V droop control). To avoid static errors, PI controllers are used in inner loops. The choice of the gains is discussed in Appendix D.

A transient virtual resistance is added to the control system in order to damp oscillation modes coming from the grid. This is useful especially in inductive grids, where oscillations are weakly damped due to the lack of resistive parts [17]. The virtual resistance, often denoted R_v , is associated with a high-pass filter in order to have a significant damping effect only above the cutoff frequency ω_v , and potentially to avoid static error on the voltage (in the case where the outer voltage loop does not have a regulation mechanism like a PI controller, for instance) [50][51].

The considered control system is shown in Fig. 3.4. The block "VSG" is the P - f control loop previously presented in Fig. 1.8. The block " Q - V droop control" is the outer voltage loop that is discussed later in Section 3.3.

¹For the control of a synchronous machine, the direct axis is oriented with the north pole of the rotor windings [26]. However for a converter, such a physical interpretation does not make sense.

3.2. Inner loops

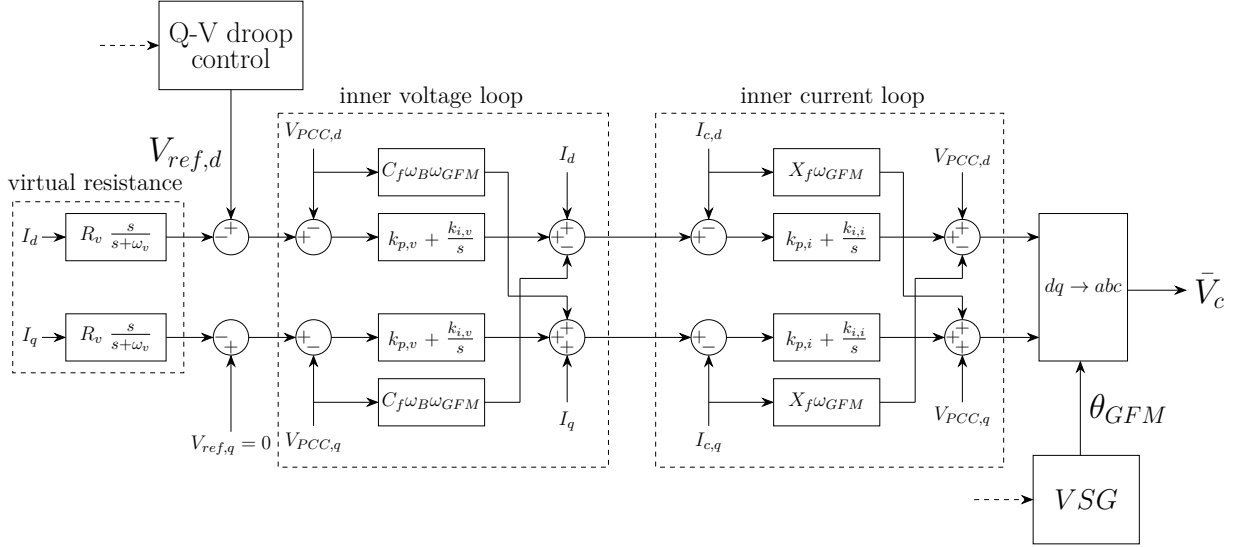


Figure 3.4: Block diagram of the Grid-Forming converter control system (without current saturation). Output voltage $\bar{V}_c$ phase angle is controlled by the VSG. Amplitude is controlled in Park's domain. Inner current loop is fast and includes a feedforward action to cancel the dq components coupling due to the filter inductance. Inner voltage loop includes a feedforward action to cancel the dq components coupling due to the filter capacitance. Transient virtual resistance damps oscillations modes frequent in inductive grids. Reference voltage for the PCC is given by the Q - V droop control block. Adapted from [16][17][25][33][49].

Inner loops response on various grid characteristics

It is already interesting to observe the behavior of the response provided by inner loops with different types of grid. The definition of a *strong* or *weak* grid, as well as of an *inductive* or *resistive* grid, is quite arbitrary. However, a grid is typically considered as *weak* when its *Short Circuit Ratio* ($SCR \approx \frac{1}{X}$) is lower than 3 [11]. Moreover, a grid is considered as *inductive* when its $X_g \gg R_g$, which is typical in high voltage transmission grids [52]. In this work, a grid is called *resistive* when this condition is not verified (typically with the X/R ratio near 1). Filter RL part time constant is matched with the grid impedance. Simulation parameters are summarized in Tables 3.1 and 3.2.

Parameter	Value for grid Strong & inductive	Value for grid Weak & inductive	Value for grid Weak & resistive
X_f [p.u.]	0.15	0.15	0.15
R_f [p.u.]	0.015	0.015	0.15
X_g [p.u.]	0.2	0.6	0.6
R_g [p.u.]	0.02	0.06	0.6

Table 3.1: Simulation parameters for the comparison of grid types, relatively to Fig. 3.3.

3.3. Q - V outer loop

Parameter	Value	Parameter	Value
H [s]	3.5	Q_{ref} [p.u.]	0
D	30	R_v [p.u.]	0.09
σ_p	1/40	ω_v [rad/s]	60
P_{ref} [p.u.]	1	C_f [s]	0.066

Table 3.2: Simulation parameters for the converter control, relatively to Figs. 3.3, 3.4 and 1.8.

The results of the PCC voltage response to a step of voltage target are shown in Fig. 3.5. It can be seen that the response varies significantly depending of the grid characteristics. When the grid is resistive, the overshoot and oscillations are more damped. The worst case is obtained with the strong and inductive grid, where the response is the least similar to the ideal step response. Voltage overshoot is generally undesired, because it may potentially trigger protection systems.

For these reasons, the inner loops must be accompanied by a slower outer loop, that may include a *dynamics replacement* with LADRC. Moreover, the Grid-Forming control is mostly interesting in situations where the grid is *not* strong, which limits the occurrence of the problem. Furthermore, a step response is a *worst case* situation regarding the dynamics. As found in the requirements (Section 3.1), the operator should instead ask for a rate-limited ramp response.

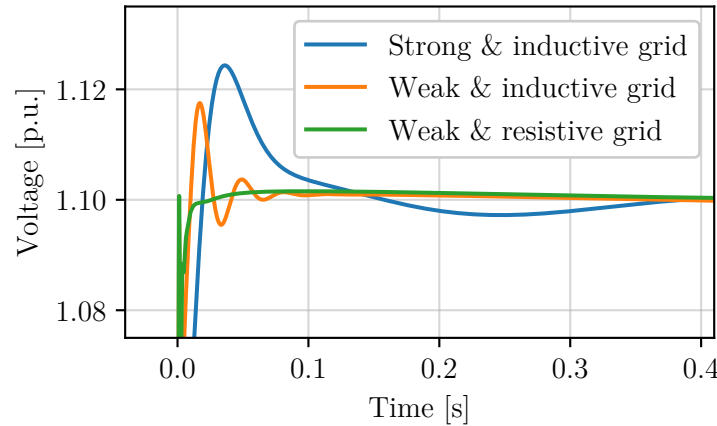


Figure 3.5: Comparison of inner loops response on different types of grid, for a step of voltage target from 1 [p.u.] to 1.1 [p.u.]. A resistive part helps damping the overshoot. Strong and inductive grid is the worst case referring to an ideal step response.

3.3 Q - V outer loop

In this section

The outer voltage loop, that also manages the Q - V droop is, discussed and tested. To summarize, it will be shown that by slightly slowing down the dynamics, the voltage response is made closer to predictable expectations.

By assuming the inner loops *ideal* (i.e. assuming that a change of PCC voltage target instantly results in this voltage at the PCC), the outer loop provides most of the Q - V control dynamics.

As a reminder, the P - δ dynamics is already chosen to be the *Virtual Synchronous Generator* (VSG, Fig. 1.8). That is quite a natural choice, because it allows providing inertia just like a traditional synchronous machine, which is a well-known behavior. Hence from an operator perspective, the Grid-Forming converter will still behave *as usual*, and the compatibility with existing equipments might also be easier.

For the Q - V dynamics however, the choice is less obvious. Because of standards requirements (Section 3.1) asking for a voltage response as fast as possible, the synchronous generator voltage dynamics is not the most appropriate. Indeed, this dynamics is penalized more by the (slow) rotor flux dynamics than by its voltage controller [26][53]–[55].

Another possibility would be using a PI controller with the voltage error between the measured PCC voltage and the target reference. However, using such an active controller is not useful, because the inner loops already contain a feedback system ensuring no static error on the PCC voltage.

Q - V loop model: feedforward with filter on $Q^* - Q$ and V^*

Thus a third possibility is simply using the desired voltage as reference, associated with a first-order low-pass filter to avoid high frequency noise and disturbances.

In this case, the outer loop Q - V model *feedforward with filter on $Q^* - Q$ and V^** , with a time constant τ_f , is written:

$$V_{ref,d} = \frac{1}{\tau_f s + 1} \left(V_{PCC,d}^* + D_q(Q^* - Q) \right) \quad (3.1)$$

Assuming the inner loops ideal (i.e. V_{PCC} is perfectly reached immediately), and by denoting $K_{grid} = \frac{X_g}{R_g^2 + X_g^2}$, the small signal closed-loop transfer function is:

$$\frac{\partial V_{PCC,d}}{\partial V_{ref,d}}(s) = \frac{1}{\tau_f s + D_q K_{grid} + 1} \quad (3.2)$$

$$\approx \frac{1}{\tau_f s + 1} \quad (3.3)$$

A time constant $\tau_v = \tau_f$ can be identified. Approximation (3.3) can be made when $D_q \ll 1$, which is the case in a Grid-Forming philosophy, and allows identifying a gain that does not depend on the grid characteristics.

Alternative model: feedforward with filter on $Q^* - Q$ only

A stiffer response to a voltage target change may be achieved by applying the low-pass filter only on the measurement of reactive power linked to the droop control. When neglecting the droop part, voltage response would thus entirely rely on the inner loop dynamics. While it would be probably be inadvisable due to the risks of overvoltage seen in Fig. 3.5, it might however be interesting when used with LADRC.

However this possibility has not been adopted in this work since it has been observed that a slight low-pass filter on the voltage target is useful to reject high frequency oscillations with LADRC. The entire comparison with the model used in this work can be found in Appendix F.

Example with the Q - V outer loop

Comparison between the theoretical (transfer functions neglecting inner loops) and simulation (complete system in Matlab Simulink) is made, based on an intermediate case whose parameters are shown in Table 3.3. The example is chosen to be generic, i.e. with an intermediate grid strength ($SCR = 2.5$) and an intermediate resistive part ($R = \frac{X}{5}$). Filter RL part time constant is matched with the grid impedance. For the Q - V outer loop, a time constant $\tau_v = 0.02$ [s] has been considered, in accordance to the standard requirements (Section 3.1).

Parameter	Value	Parameter	Value
H [s]	3.5	ω_v [rad/s]	60
D	30	X_f [p.u.]	0.15
σ_p	1/40	R_f [p.u.]	0.03
P_{ref} [p.u.]	1	C_f [s]	0.066
Q_{ref} [p.u.]	0	X_g [p.u.]	0.4
R_v [p.u.]	0.09	R_g [p.u.]	0.08

Table 3.3: Simulation parameters (generic example), relatively to Figs. 3.3, 3.4 and 1.8.

Responses with or without the outer loop are shown in Fig. 3.6. The outer loop has dynamics slower than the inner loops, hence those latter have few impact on the response and can legitimately be considered as quasi-instantaneous.

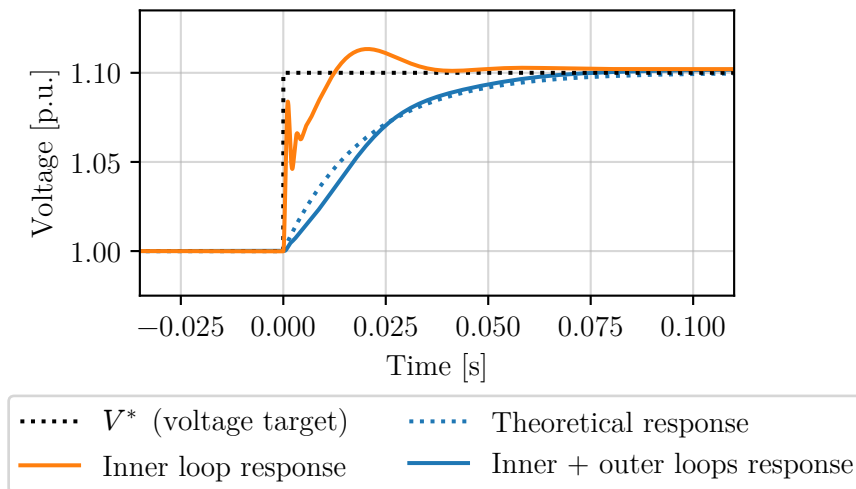


Figure 3.6: Response on a step of voltage target from 1 [p.u.] to 1.1 [p.u.] with or without the Q - V outer loop. With the outer loop, the response is much closer to the theoretical first-order response.

In conclusion to this section, the fastest response is achieved by not using the outer loop, but it includes a high dependency on grid characteristics and may lead to a voltage overshoot that may be problematic. Using the outer loop leads to an intermediately fast first-order response.

The results must however be nuanced, because standards requirements (Section 3.1) state that in practice, the TSO must ask for a rate-limited ramp for the voltage response to a change of target. Hence response on a voltage target step is not the only relevant information, and it can easily be imagined that the responses with or without the outer loop will give about the same response on such a slow ramp.

3.4 Q-LADRC vs V-LADRC

In this section

Once the GFM Q - V outer loop has been designed, a discussion on how to apply LADRC to it is made in this section. A brief summary of the situation is necessary to sense the need of this question. Quick reminders of the context are provided.

To summarize, to control the voltage of the converter, LADRC could be applied either on the Q input of the Q - V loop ($\rightarrow$ Q-LADRC), or on the V input of the Q - V loop ($\rightarrow$ V-LADRC).

- Time domain comparisons for a change of target show similar responses. However, for the reaction to an external disturbance, it is shown that V-LADRC stabilizes voltage faster, which is more appropriate in a Grid-Forming context.
- Small-signal analysis shows that Q-LADRC is more stable with a high observer bandwidth than V-LADRC.
- With LADRC, the outer loop filter should have a short time constant. The filter allows better attenuating the high-frequency oscillations, but a too long time constant brings undamped low-frequency oscillations with LADRC.

As a reminder, Grid-Forming control aims to make the converter maintain its own voltage, in magnitude and phase angle. The purpose is to use converters just like traditional synchronous generators, which notably bring inertia and low internal impedance, that are important for the grid stability.

For historical and technical reasons, electricity transmission and distribution is done in AC. Voltage magnitude V and frequency f are the two main relevant variables in a power grid, and should be kept near 1 [p.u.]. Voltage magnitude is a local variable, because it is distinct for each node of the circuit. Frequency is a global variable (i.e. is almost the same everywhere in the circuit) and is the derivative of the phase angle, which is a local variable.

Because the frequency synchronism must be guaranteed, but the converter is controlled with the phase angle, a Grid-Forming control intrinsically relies on an active power P reg-

ulation in transmission grids. Referring to (1.6), this P-frequency-angle control necessarily depends on the grid characteristics, which are more or less unknown. To keep the control response predictable, application of P-LADRC on the P - f loop has been proposed, which has lead to the block diagram in Fig. 3.7.

However, guaranteeing the local grid voltage magnitude can be achieved directly, because the converter is also controlled with its voltage magnitude. As discussed in Section 3.2, converter output and Point of Common Coupling (PCC) nodes are separated by a filter. But quasi-static feedforward action in inner loops allows directly controlling the PCC voltage magnitude with the converter output. Neglected dynamics due to the filter and grid impedances is discussed later in Section 3.5.

Hence it appears two ways to control the voltage magnitude of a grid node.

First, the same control schematic as for the active power could be translated to the reactive power. Referring to (1.6), this Q - V control necessarily depends on the grid characteristics, which are more or less unknown. To keep the control response predictable, application of Q-LADRC on the Q - V loop is proposed, which leads to the block diagram in Fig. 3.8. This is the case that has been analyzed in the analytics of Chapter 2, because of its similarity with the general cross-coupled MIMO control problem.

Second, since the Grid-Forming control does not intrinsically rely on a reactive power Q regulation, one of the models derived in Section 3.3 is sufficient to control the PCC voltage magnitude. (As a reminder, the reactive power Q in these Q - V loops is there only for a droop control, that is not intrinsically required). Therefore, the control response is already (almost) predictable when the model is slow compared to the inner loops dynamics. The small remaining dependencies on the system characteristics are linked to the Q - V droop, and the dq coupling dynamics between the filter and grid impedances, that were neglected. Hence in this case, the application of LADRC seems not as useful as for the P - f loop. However, V-LADRC is proposed to analyze its potential side-interests. It may also be interesting for grid characteristics independence if the alternative Q - V model, that relies directly on the inner loops, is considered. Such a V-LADRC leads to the block diagram in Fig. 3.9.

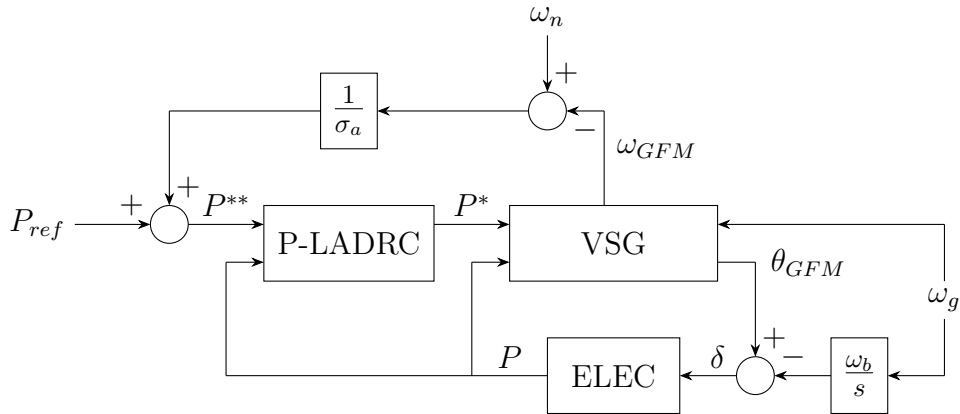


Figure 3.7: Block diagram of GFM frequency control with P-LADRC, adapted from [16].

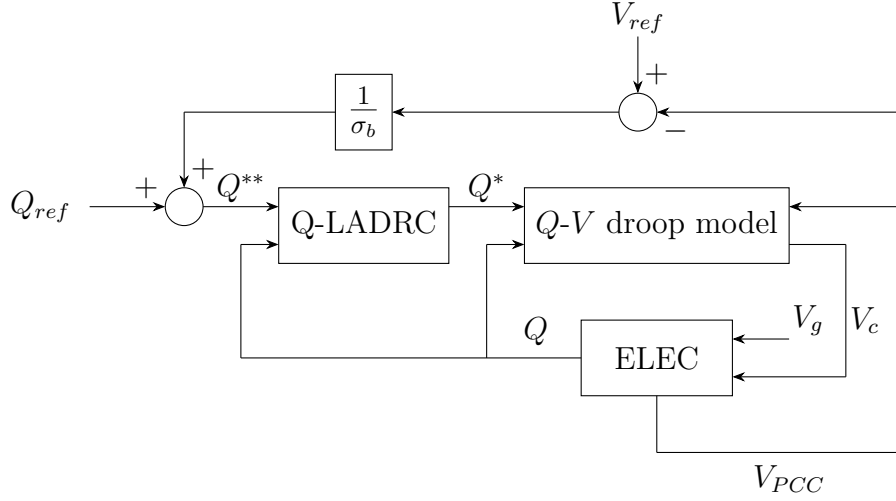


Figure 3.8: Block diagram of the GFM voltage control with Q-LADRC.

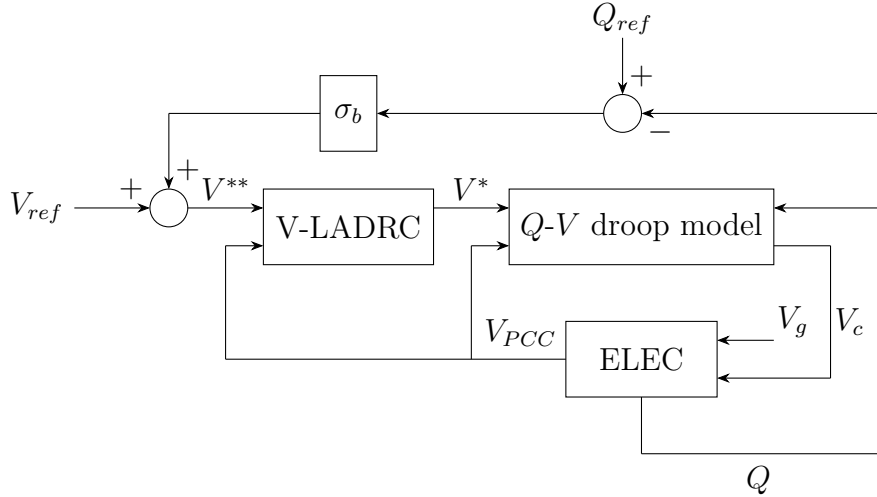


Figure 3.9: Block diagram of the GFM voltage control with V-LADRC.

3.4.1 Q-LADRC vs V-LADRC, time domain comparison

A comparison between Q-LADRC (Fig. 3.8) and V-LADRC (Fig. 3.9), applied to the outer loop is made in order to observe the behavior of the systems when facing to a change of target or a grid disturbance.

About methodology

For this study, simulations made in Matlab Simulink will be compared to theoretical computations. Indeed, the whole analytical model, including the inner loops, the RLC filter, and LADRCs, has also been expressed. Equations for the V-LADRC model are written in Appendix C. For the comparison, equations are solved in time domain by using the *RK45* method in Python.

The example is made in an intermediate case, which parameters are written in Table 3.3. Q - V droop coefficient $D_q = 5\%$ is chosen (in (3.1)), as it is a mean value of standards requirements indications (Section 3.1). The external droop coefficient σ_b , as defined in Figs. 3.8 and 3.9, is chosen to be same as the internal droop coefficient D_q , in a *Grid-Forming philosophy*. The outer loop filter has a small time constant $\tau_f = 0.001$ [s] (in (3.1)), and this choice will be discussed later in Section 3.4.2.

P-LADRC (Fig. 3.7) is enabled and its parameters are similar as those used in [16], without external droop ($\sigma_a \rightarrow \infty$). Thus it is a *Grid-Following philosophy*, since the constant target power P^{**} will be reached in steady-state whatever the frequency.

Q- and V-LADRC are parametrized with $b_0 = b$. When V-LADRC is considered (Fig. 3.9), the loop gain b can be identified in (3.3): $b_V = 1/\tau_f$. However, since $\tau_f \ll \tau_{v,inner}$, the filter dynamics can be considered quasi-instantaneous compared to the voltage inner loop speed. Hence $b_V = 1/(\tau_{v,inner}) = 1/(10 \cdot \tau_i) = 100$ is considered. When Q-LADRC is considered (Fig. 3.8), the loop gain b must instead be identified in the transfer function related to the Q response. It can be calculated²:

$$\frac{\partial Q}{\partial Q^*}(s) = \frac{\frac{K_{grid}D_q}{1+K_{grid}D_q}}{\frac{\tau_f}{1+K_{grid}D_q}s + 1} \quad (3.4)$$

$$\text{Where } K_{grid} = \frac{X_g}{R_g^2 + X_g^2} \approx \frac{1}{X_g}.$$

$$\text{Hence it can be identified: } b_Q = \frac{K_{grid}D_q}{\tau_f} = \frac{X_g}{R_g^2 + X_g^2} \frac{D_q}{\tau_f} \approx \frac{D_q}{X_g \tau_f}$$

However, since $\tau_f \ll \tau_{v,inner}$, the filter dynamics can be considered quasi-instantaneous compared to the voltage inner loop speed. Hence $b_Q \approx \frac{D_q}{X_g \cdot 0.01}$ should be considered instead.

Desired response is a first-order low-pass filter with $\tau = 0.02$ [s] time constant, as asked by the standards requirements (Section 3.1). The related proportional gain $K_{p,Q}$ or $K_{p,V}$ used in the LADRC parametrization depends on the system. When V-LADRC is considered (Fig. 3.9), external droop effect on the $\partial V_{PCC}/\partial V_{target}$ dynamics is negligible (σ_b is small). In this case, (A.13) indicates simply using $K_{p,V} = 1/\tau$. However, when Q-LADRC is considered (Fig. 3.8), external droop effect on the $\partial V_{PCC}/\partial V_{target}$ dynamics is not negligible ($1/\sigma_b$ is large). Starting from the $\partial Q/\partial Q^{**}$ dynamics given by (A.13), voltage response can be calculated:

$$\frac{\partial V_{PCC}}{\partial V_{target}}(s) = \frac{\frac{1}{K_{grid}\sigma_b + 1}}{\underbrace{\frac{1}{K_{p,Q} K_{grid}\sigma_b + 1}}_{\tau} s + 1} \approx \frac{\frac{X_g}{\sigma_b + X_g}}{\underbrace{\frac{1}{K_{p,Q} \sigma_b + X_g}}_{\tau} s + 1} \quad (3.5)$$

$$\text{Hence } K_{p,Q} = \frac{1}{\tau} \frac{K_{grid}\sigma_b}{K_{grid}\sigma_b + 1} \approx \frac{1}{\tau} \frac{\sigma_b}{\sigma_b + X_g}.$$

To summarize, parameters used in each cases are shown in Table 3.4.

²Eq. (3.4) does not depend on the filter impedance Z_f because the considered reactive power Q is the one flowing through the grid equivalent impedance at the PCC level.

3.4. Q-LADRC vs V-LADRC

Parameter P-LADRC	Value	Parameter Q-LADRC	Value	Parameter V-LADRC	Value
$\omega_{0,P}$ [p.u.]	1	$\omega_{0,Q}$ [p.u.]	1	$\omega_{0,V}$ [p.u.]	1
$b_{0,P}$	800	$b_{0,Q}$	120.2	$b_{0,V}$	100
$K_{p,P}$	200	$K_{p,Q}$	5.36	$K_{p,V}$	50
$K_{d,P}$	40				
σ_a	∞	σ_b	0.05	σ_b	0.05

Table 3.4: Parameters for the comparison of Q-LADRC and V-LADRC, relatively to Figs. 3.7, 3.8 and 3.9.

Reaction to a step of voltage target

In Fig. 3.10a are compared the responses of PCC voltage to a step of voltage target from 1 [p.u.] to 1.1 [p.u.], with Q-LADRC or V-LADRC applied to the Q - V outer loop. Since in steady-state $V_{PCC} > V_g$, the converter will produce reactive power Q . Thus because of the droop control, the new operating point is expected lower than 1.1 [p.u.].

Simulation results fit to theoretical computations, which cross-validates both the Simulink and Python model implementations. Small differences may be attributed to implementation-specific elements and numerical artifacts.

For the step of voltage target, the responses are close to the desired response, though they are slower. Increasing Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$ may help reducing this error. Q-LADRC response seems generally more oscillating than the V-LADRC response. However V-LADRC corrects the initial voltage peak faster.

Reaction to a grid voltage drop

Comparing responses on a step of voltage target is interesting to observe the dynamics of the systems. However, it is not the most relevant situation in practice because as mentioned earlier, the TSO should ask for a slow rate-limited ramp as target. Hence it is also interesting to compare the behavior of the various systems when facing a grid disturbance.

In Fig. 3.10b are compared the responses of PCC voltage to a grid voltage drop, here modeled by a step of infinite grid voltage V_g from the nominal 1 [p.u.] to 0.66 [p.u.]. Since in steady-state $V_{PCC} > V_g$, the converter will produce reactive power Q . Thus because of the droop control, the new operating point is expected lower than 1 [p.u.]. The previous comment regarding the systems dynamics for the case of a step of target also apply in this situation. However, it can be seen that the voltage converges much slower to the new operating point with Q-LADRC than with V-LADRC.

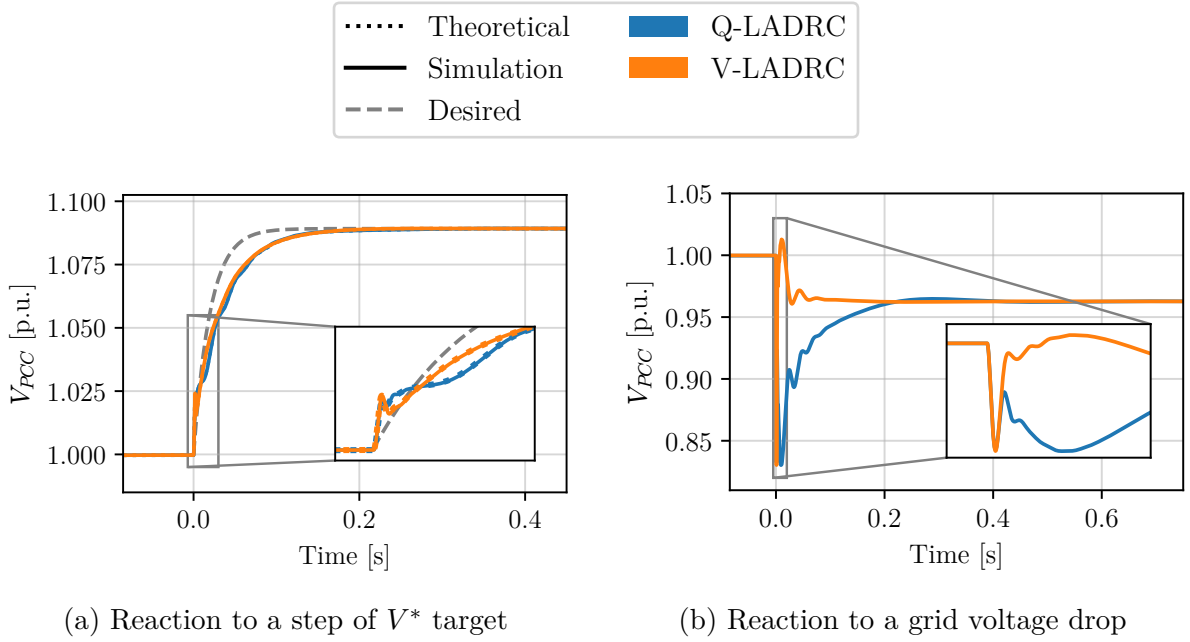


Figure 3.10: PCC voltage response to (a) a step of voltage target from 1 [p.u.] to 1.1 [p.u.], and (b) to a grid voltage drop (V_g step from 1 [p.u.] to 0.66 [p.u.]). Comparison Q-LADRC vs V-LADRC, applied to the Q - V outer loop.

(a) Responses are similar. With Q-LADRC, the response seems slightly more oscillating.
(b) Voltage drops instantaneously then recovers quickly. Response with V-LADRC stabilizes faster to the new operational voltage point.

3.4.2 Q-LADRC vs V-LADRC, small-signal stability

Another way to observe the dynamics of the systems is to analyze their stability, which is also an important criterion that may help with the decision to use Q-LADRC or V-LADRC.

Modal analysis is realized by computing the poles (eigenvalues) of the complete system modeled in Python. These poles inform on the dynamical behavior of the system around an operating point. The real part of a pole represents the attenuation of the corresponding state. Hence the real part of every poles should be negative for the system to be stable *in small-signal*, i.e. linearized around the operating point. The imaginary part of a pole represents the natural frequency of the corresponding state oscillation [13][16][39][56].

More information on how these poles are computed is available in Appendix E.

The modal analysis will be made with the same parameters as the time domain analysis, summarized by Tables 3.3 and 3.4, except for mentioned deviations.

How to read a pole map?

In the following figures, parametric pole maps will be presented to observe how the system oscillates (frequency ω on the y-axis, with per-unit base $\omega_B = 2\pi \cdot 50$ [rad/s]) and how these oscillations are attenuated (attenuation σ on the x-axis, with the same per-unit base as the frequency).

As a reminder, the poles of an LTI system are conjugate complexes, because the ODEs are made of real coefficients. Hence only the positive values of ω are represented, and the negative values can be deduced by symmetry.

Moreover, the values of σ are focused on values between -1 and 0 to represent the *dominant poles* ([56]). Poles with $\sigma \ll 0$ are strongly attenuated (so little important) and poles with $\sigma > 0$ are responsible for the system instability (which must be avoided).

In the following interpretations, a "low-frequency" pole designates a pole with $\omega < 1$ while a "high-frequency" pole designates a pole with $\omega \gg 1$. A "weakly attenuated" pole designates a pole with $\sigma \approx 0 < 0$.

In Fig. 3.11 are represented the pole maps for varying the Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$. The results confirm the observations in time domain: Q-LADRC systems have weakly attenuated low-frequency oscillations, while V-LADRC systems have a higher frequency pole. When the observer bandwidth $\omega_{0,V}$ increases, high-frequency oscillations are less and less attenuated, until the system becomes unstable.

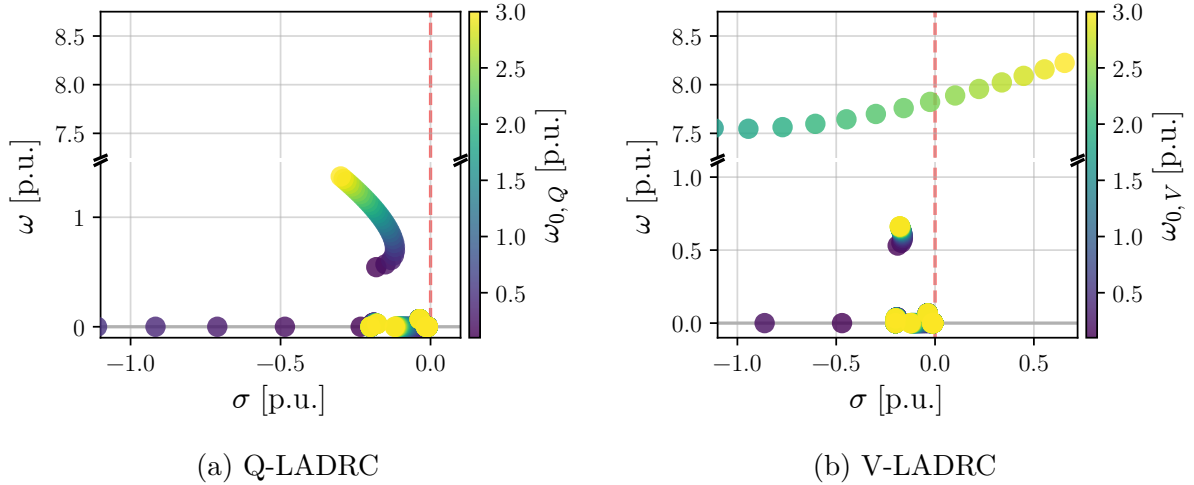


Figure 3.11: Pole map with Q- or V-LADRC on the Q - V outer loop. Parametric small-signal stability analysis for varying the Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$. Using V-LADRC may lead to high frequency oscillations and instability when $\omega_{0,V}$ is too high.

In Fig. 3.12 are represented the pole maps for varying the low-pass filter time constant τ_f of the outer loop (3.1). For the time-domain example, $\tau_f = 0.001$ [s] was considered

short compared to the voltage inner loop time constant ($\tau_{v,inner} = 0.01$ [s]), hence LADRC have been parametrized by considering that the estimated state was linked to the first order voltage inner loop. When this approximation is not true anymore (i.e. when $\tau_f \not\ll \tau_{v,inner}$), the LADRC must be parametrized by considering that the estimated state is mostly linked to the integral part of the first-order filter. Hence for this parametric analysis, a global $\tau = \tau_f + \tau_{v,inner}$ has been considered when computing the K_p and b_0 gains of the LADRC.

With Q-LADRC, the low-frequency oscillation is less and less attenuated when increasing the filter time constant τ_f , until the system becomes unstable when τ_f is too long. With V-LADRC, this effect also exists but is less pronounced. It can be seen that the filter allows rejecting the high frequency pole of V-LADRC even with very short time constants τ_f .

In conclusion, the filter of the outer loop is useful to reject high-frequency oscillations, but its time constant should be kept short to avoid low-frequency oscillations to cause stability issues.

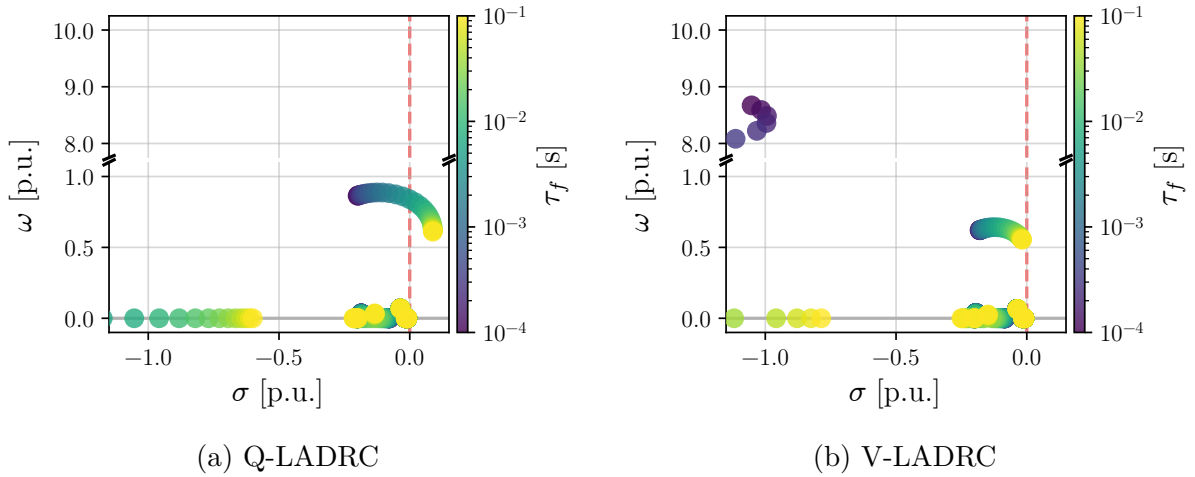


Figure 3.12: Pole map with Q- or V-LADRC on the Q - V outer loop. Parametric small-signal stability analysis for varying the outer loop filter time constant τ_f . Weakly damped oscillations or instability may occur with Q-LADRC or V-LADRC when the filter dynamics is too slow.

In Fig. 3.13 are represented the pole maps for varying the external droop coefficient σ_b . As expected, the ability of the system with Q-LADRC to regulate the voltage strongly depends on σ_b . This coefficient should be *small* such that the voltage remains near the target whatever the reactive power Q (Grid-Forming philosophy). However as can be seen, when σ_b is decreasing, a high-frequency oscillation is less and less attenuated, until the system becomes unstable when σ_b is too small. Referring to the block schematic (Fig. 3.8), the feedback on the voltage is proportional to $1/\sigma_b$. Thus when this amplification is too extreme, the control becomes unstable. This problem does not occur with V-LADRC: the regulation of the voltage does not rely on σ_b , because the external droop is only there to deviate slightly from the target following the reactive power Q . Referring to the block schematic (Fig. 3.9), the feedback on Q is proportional to σ_b . Thus when this attenuation

is very low, no undesirable effect is expected regarding voltage regulation.

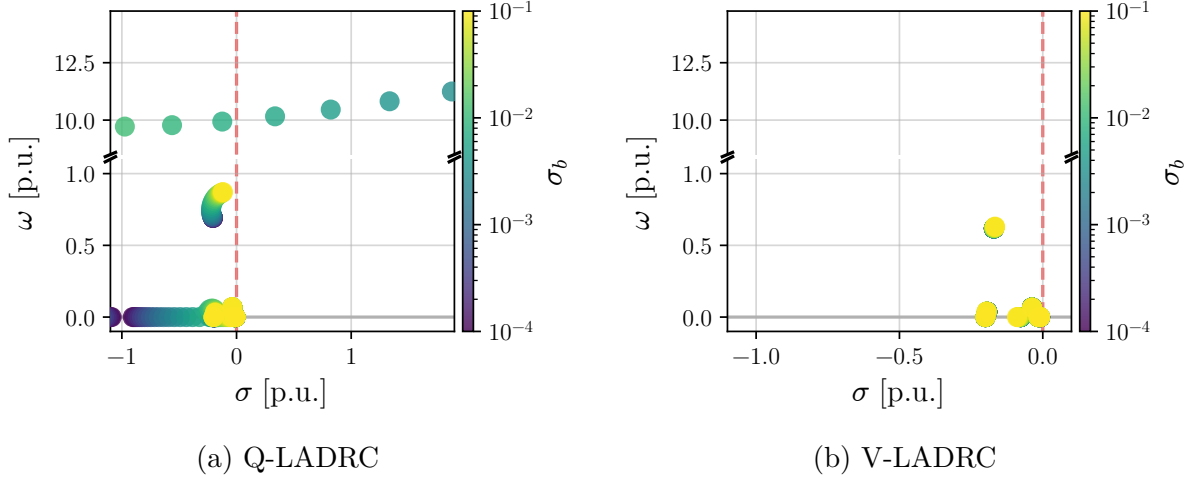


Figure 3.13: Pole map with Q- or V-LADRC on the Q - V outer loop. Parametric small-signal stability analysis for varying the external Q - V droop coefficient σ_b . Using Q-LADRC may lead to high frequency oscillations and instability when σ_b is too low (meaning too strong voltage feedback on Q^*).

3.4.3 Q-LADRC vs V-LADRC: conclusions

In conclusion, both Q-LADRC and V-LADRC based systems have advantages and disadvantages.

Q-LADRC systems small-signal stability is less sensitive to high observer bandwidths $\omega_{0,Q}$, which may be useful to get precisely the desired response to a change of target. However, the response to a grid voltage drop is much slower than with V-LADRC.

V-LADRC systems small-signal stability is less sensitive to the filter time constant τ_f and the external droop coefficient σ_b . However, it becomes quickly unstable when increasing the observer bandwidth $\omega_{0,V}$, which reduces the possibilities to precisely replace the existing system dynamics by fast desired dynamics.

Since the response to a grid disturbance is in practice more relevant than the response to a step of target, and because the precision of the response is not very important as long as it is fast, which is the case with the moderate observer bandwidth $\omega_{0,V}$, the V-LADRC is selected for the rest of this work.

There is a trade-off to find with the filter time constant: τ_f should be short enough to avoid slowing down the control (which would lead to weakly attenuated low-frequency oscillations), but should also be long enough to attenuate the high-frequency oscillations.

3.5 P-V system model, filter matching

In this section

In a similar way the (P, Q) system has been linearized in function of $(\delta, \Delta V)$, the linearization of the (P, V_{PCC}) system in function of $(\delta, \Delta V)$ will be attempted. The goal is to experience how the filter and grid impedances impact the control of the PCC voltage.

To summarize, it will be shown:

- V_{PCC} cannot be linearized as a linear combination of δ and ΔV
- dV_{PCC} can be linearized around the operating point as a linear combination of $d\delta$ and $d\Delta V$.
- When the filter and the grid impedances have the same time constant, dependency of dV_{PCC} on $d\delta$ (cross-coupling) cancels.

From the linearized system (1.5), it is clearly seen the relationship between the control inputs $(\delta, \Delta V)$ and the controlled outputs (P, Q) , which allowed to model a simple control system in Chapter 2. However, as discussed in Section 3.4, the Grid-Forming goal is to control the frequency (via control of P) and the PCC voltage (not Q). Hence it would be useful to analyze the relationship between the control inputs $(\delta, \Delta V)$ and the controlled outputs (P, V_{PCC}) , for the electrical system in Fig. 3.3.

Mathematical details of this development is available in Appendix G.

On the contrary of P and Q , V_{PCC} cannot be linearized under the form of a linear combination of δ and ΔV . As could be expected, the PCC voltage does not only depend on ΔV (and δ), but also on the value itself of V_c (or V_g). A non-linear cross-coupling term due to the multiplication by $V_c\delta$ also appears. Consequently, a small-signal dV_{PCC} around the operating point is derived to analyze the impact of the filter and grid impedances:

$$dV_{PCC} = \frac{R_g X_f - X_g R_f}{(R_f + R_g)^2 + (X_f + X_g)^2} d\delta + \frac{R_g(R_f + R_g) + X_g(X_f + X_g)}{(R_f + R_g)^2 + (X_f + X_g)^2} dV_c \quad (3.6)$$

In (3.6), the first term is an undesirable cross-coupling term (because a change of phase angle should not impact the voltage magnitude). It can be seen that this term cancels when $\frac{X_f}{R_f} = \frac{X_g}{R_g}$: no cross-coupling for the voltage response when the filter time constant is matched with the equivalent grid impedance time constant! This is an important information also regarding the transient dynamics that were neglected in Section 3.2. For the design of the filter, R_f and X_f might be chosen based on expected grid characteristics to avoid undesirable transients and coupling at the PCC due to impedance mismatching.

It can also be seen that the second (and main) term is maximal ($= 1$) when there is no filter ($R_f = X_f = 0$). This is quite logical, because in this case V_c is also V_{PCC} . In the opposite, this term is minimal ($= 0$) when the grid is extremely strong ($R_g = X_g = 0$). In

this case, changing the PCC voltage becomes nearly impossible, because it would require an extreme (infinite) value of V_c , which is unrealistic.

The complete linearized (P, V_{PCC}) system can be written:

$$\begin{bmatrix} dP \\ dV_{PCC} \end{bmatrix} = \begin{bmatrix} \frac{X_f + X_g}{(R_f + R_g)^2 + (X_f + X_g)^2} & \frac{R_f + R_g}{(R_f + R_g)^2 + (X_f + X_g)^2} \\ \frac{R_g X_f - X_g R_f}{(R_f + R_g)^2 + (X_f + X_g)^2} & \frac{R_g(R_f + R_g) + X_g(X_f + X_g)}{(R_f + R_g)^2 + (X_f + X_g)^2} \end{bmatrix} \begin{bmatrix} d\delta \\ dV_c \end{bmatrix} \quad (3.7)$$

When the typical *inductive grid* assumption is used, the system further simplifies:

$$\begin{bmatrix} dP \\ dV_{PCC} \end{bmatrix} \approx \begin{bmatrix} \frac{1}{X_f + X_g} & 0 \\ 0 & \frac{X_g}{X_f + X_g} \end{bmatrix} \begin{bmatrix} d\delta \\ dV_c \end{bmatrix} \quad (3.8)$$

Observation of cross-coupling and dynamics linked to the filter mismatch with the grid impedance are made in Figs. 3.14 (no control) and 3.15 (inner loops and VSG). The parameters of the considered intermediate system are shown in Table 3.3. R_f is the degree of freedom chosen to obtain the three represented cases.

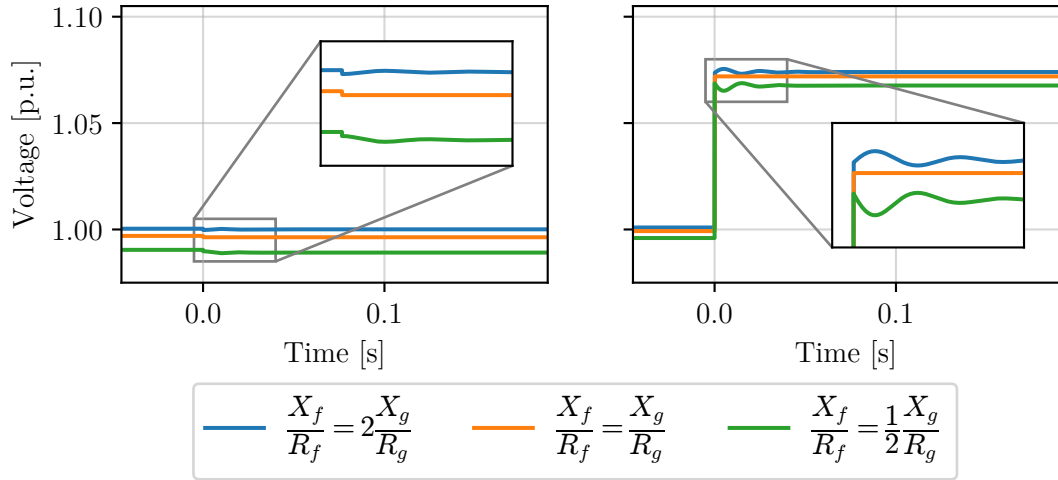


Figure 3.14: Cross-coupling action of $d\delta$ on V_{PCC} (left) and direct action of dV_c on V_{PCC} (right). Simulation in open loop (without control, system in Fig. G.1). A +10% step of δ from 10° has little effect on V_{PCC} . A +10% step of V_c from 1 [p.u.] has a significant effect on V_{PCC} . Filter mismatch with grid impedance lead to oscillations.

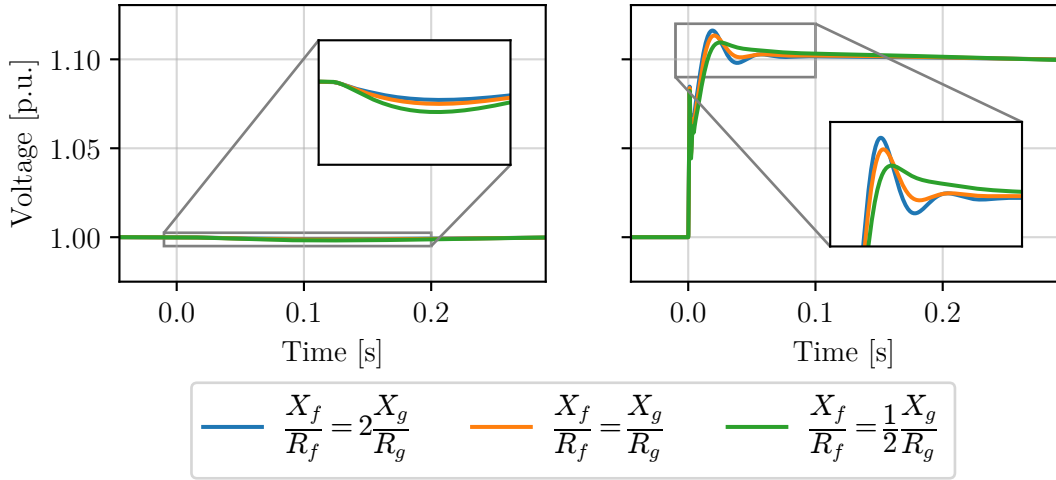


Figure 3.15: Cross-coupling action of $d\delta$ on V_{PCC} (left) and direct action of dV_c on V_{PCC} (right). Simulation with inner and outer loops ($D_q = 0$), and VSG. A +10% step of P^* from 1 [p.u.] has little effect on V_{PCC} . A +10% step of V_{ref} from 1 [p.u.] has a noticeable effect on V_{PCC} . Filter mismatch with grid impedance influences the dynamics.

3.6 Final system overview and analysis: verification of LADRC interests and additional modal analysis

In this section

Now that the entire final system has been chosen, it is possible to analyze more widely the dependencies to parameters and the interests of using LADRC. The three LADRC interests identified in Chapter 1 and analyzed in the frequency domain in Chapter 2 are now analyzed in time domain. Complementary small-signal stability analyses are also provided.

To summarize,

- With high but limited observer bandwidths, LADRCs allow making the response independent from system characteristics, including loops decoupling, but only when reacting to a change of target, not when facing to external disturbances. Though external disturbances are more attenuated. With low observer bandwidths ω_0 , LADRCs lead to the rejection of the input target change, while still decoupling the two loops.
- A distinct change of behavior in function of $\omega_{0,P}$ is observed for the P-LADRC when facing external disturbances. However for V-LADRC, the response is about the same whatever $\omega_{0,V}$.
- P-LADRC may become unstable in strong grids. P-LADRC and V-LADRC may become unstable in highly inductive grids. V-LADRC may become unstable in case of loop gain b_V under-estimation.

3.6. Final system overview and analysis: verification of LADRC interests and additional modal analysis

To recap, the chosen system is composed of:

- The power flow electrical system (Fig. 3.3)
- The Virtual Synchronous Generator (Fig. 1.8)
- The voltage and current inner loops in dq Park's frame, and the transient virtual resistance (Fig. 3.4)
- The Q - V voltage droop outer loop *feedforward with filter on $Q^* - Q$ and V^** (3.1)
- The P-LADRC (for a second-order system) and V-LADRC (for a first-order system) from Sections 1.6 and Appendix A.

The block schematic implemented in Matlab Simulink is represented in Appendix H.

As explained in Section 3.5, the electrical system can be linearized, assuming quasi-static approximation (phasor quantities) and small-signal, with a new ELEC matrix (referring to the notation used in (2.27) and Fig. 2.6). The Q - V loop in Section 2.2, that was at this point quite unclear, has been in purpose analyzed with a general first-order control based on a PI controller. Hence it is expected that the conclusion of the Section regarding P-LADRC and Q-LADRC behaviors still applies to the chosen system, by swapping the ELEC matrix and using V-LADRC instead of Q-LADRC.

However, several elements distinguish the system considered in Section 2.2, from the new linearized system in Section 3.5, and the new system with its non-linearities (already seen in Section 3.4). For instance, the new system includes intricate inner loops with feed-forward dq decoupling actions, multiple PI controllers, and the transient virtual resistance, that has not been considered in the (P,Q) system in Section 2.2. Moreover, the RL circuit dynamics introduces new states that are neglected in a quasi-static phasor approximation (Sections 2.2 and 3.5). However, [16] showed that this dynamics could not be neglected when assessing for the stability of the system when including P-LADRC. The consequence is that the observer bandwidths ω_0 must be limited to avoid instability. This may have already been observed in Section 3.4.2, where high $\omega_{0,V}$ might lead to small-signal stability issues.

For that reason, the conclusions on the interests of LADRC studied in frequency domain in Section 2.2, must be confirmed with simulations of the complete (P,V) system. This section aims to study independence of the control to the system characteristics, behavior change in function of the observer bandwidth ω_0 and decoupling of the control loops, in time domain simulations made in Matlab Simulink. Except mentioned deviations, system parameters are the intermediate shown in Table 3.3. LADRC parameters are those shown in Table 3.4, except a higher $\omega_{0,P} = 3$ [p.u.] has been considered since small-signal stability allowed it.

3.6.1 Interest 1: independence of the control to the grid characteristics

For this analysis, grid impedance Z_g has been varied by proportionally adapting grid resistance R_g and reactance X_g , in order to conserve the same ratio.

Reaction to steps of targets

The active power P and PCC voltage V_{PCC} responses to a step of targets P_{ref} then V_{ref} for varying the grid impedance Z_g are shown in Fig. 3.16. As expected, using LADRC allows reducing the response dependence on Z_g for the quantity corresponding to the step of target. Cross-coupling effects (i.e. variation of P when changing V_{ref} and variation of V_{PCC} when changing P_{ref}) are shortened in time. However, in the case of a strong (low impedance) grid, LADRC introduces heavy oscillations of power when changing the voltage. Without LADRC, power also increases instantly but without such oscillations. The difference of Z_g is responsible for a difference of reactive power Q , hence due to the non-zero droop coefficients D_q and σ_b , the voltage point is also different.

Reaction to disturbances from the grid

The active power P and PCC voltage V_{PCC} responses to a shift of grid angle (i.e. relatively sudden increase of the leading phase angle δ of the converter), then to a drop of grid infinite voltage V_g , for varying grid impedance Z_g , are shown in Fig. 3.17. In all the cases, LADRC shortens as expected the impact of both disturbances, but the responses are not independent from grid characteristics. Heavy oscillations may also appear with strong (low-impedance) grids.

3.6. Final system overview and analysis: verification of LADRC interests and additional modal analysis

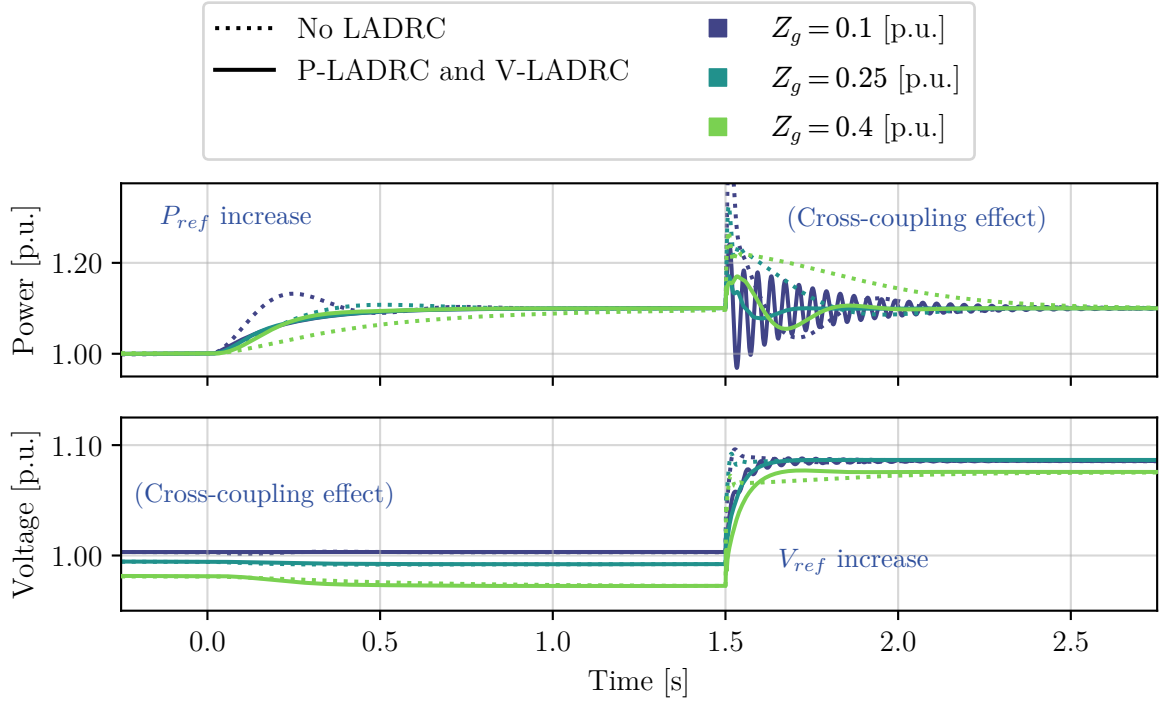


Figure 3.16: Active power P response to a $+0.1$ [p.u.] step of target P_{ref} ($t = 0$ [s]) then to a $+0.1$ [p.u.] step of target V_{ref} ($t = 1.5$ [s]), for varying grid impedance Z_g . (Left) LADRC reduces response dependence on grid characteristics for the desired change of P . Cross-coupling effect is weakly visible for the voltage. (Right) Cross-coupling effect is also shortened in time, but heavy oscillations may appear with strong (low-impedance) grids. LADRC reduces response dependence on grid characteristics for the desired response of V_{PCC} , but small oscillations may appear with strong (low-impedance) grids.

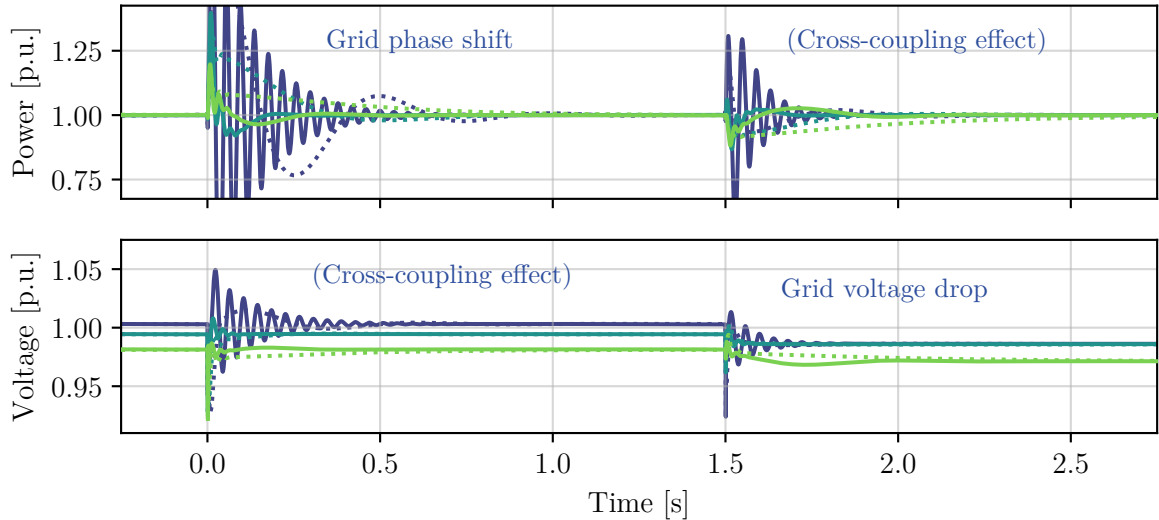


Figure 3.17: Active power P response to a -10° drop of grid phase angle ($t = 0$ [s]) then to a -0.1 [p.u.] drop of grid voltage V_g ($t = 1.5$ [s]), for varying grid impedance Z_g . (Left and right) LADRC shortens the impact of both disturbances, but the responses are not independent from grid characteristics, and heavy oscillations may appear with strong (low-impedance) grids.

3.6. Final system overview and analysis: verification of LADRC interests and additional modal analysis

3.6.2 Interest 2: behavior change in function of the observer bandwidth ω_0

For this analysis, P-LADRC and V-LADRC observer bandwidths $\omega_{0,P}$ and $\omega_{0,Q}$ have been simultaneously varied. The *low bandwidth* case has been arbitrarily chosen to be $\omega_{0,P} = \omega_{0,V} = 0.02$ [p.u.] ($= 2\pi \cdot 1 = 6.28$ [rad/s]), and the *high bandwidth* case is the default values $\omega_{0,P} = 3$ [p.u.] and $\omega_{0,V} = 1$ [p.u.] for small-signal stability reasons. An intermediate case has been considered for a third of these values.

Reaction to steps of targets

The active power P and PCC voltage V_{PCC} responses to a step of targets P_{ref} then V_{ref} for varying the LADRC observer bandwidths $\omega_{0,P}$ and $\omega_{0,V}$ are shown in Fig. 3.18. As expected, LADRC with low ω_0 responds slowly to a change of target. This *input rejection* would be total if $\omega_0 = 0$. Nevertheless, this low bandwidth does not prevent LADRC from quickly rejecting cross-coupling effects, with even less oscillations than with higher bandwidths. High ω_0 allows a faster response to the change of target, as expected.

Reaction to disturbances from the grid

The active power P and PCC voltage V_{PCC} responses to a shift of grid angle (i.e. relatively sudden increase of the leading phase angle δ of the converter), then to a drop of grid infinite voltage V_g , for varying $\omega_{0,P}$ and $\omega_{0,V}$, are shown in Fig. 3.19.

As expected, LADRC with low ω_0 reacts to the disturbances similarly as the system without LADRC. The response of P is quite long (virtual inertia), which is the Grid-Forming behavior. Oppositely, LADRC with high ω_0 reacts very fast to the disturbances. This is closer to a Grid-Following behavior: the system adapts quicker its angle such that the disturbance is dissolved with few P (hence current) deviation.

Regarding the voltage response to the disturbances, the interpretation must be nuanced. High ω_0 LADRC allows fast disturbance rejection. But the low ω_0 LADRC response, similar to the case without LADRC, is also very fast. In fact, in all cases the voltage response has a Grid-Forming behavior. This could be predicted, since voltage disturbance rejection was expected with or without LADRC.

For the P - δ loop, the situation was different: the VSG GFM has a Grid-Forming behavior, i.e. the *frequency* is maintained as soon as possible, so power disturbance rejection is not expected. With a high σ_a , P-LADRC brings this unexpected rejection, which translates into a Grid-Following behavior. The results are summarized in Table 3.5.

	Outer control	LADRC configuration	Behavior with low ω_0	Behavior with high ω_0
P - f loop	VSG Grid-Forming behavior	P-LADRC with $\sigma_a \gg 1$ Grid-Following philosophy	Grid-Forming	Grid-Following
Q - V loop	Outer Q-V loop Grid-Forming behavior	V-LADRC with $\sigma_b \ll 1$ Grid-Forming philosophy	Grid-Forming	Grid-Forming

Table 3.5: Synthetic summary of results concerning the system behavior in function of ω_0 .

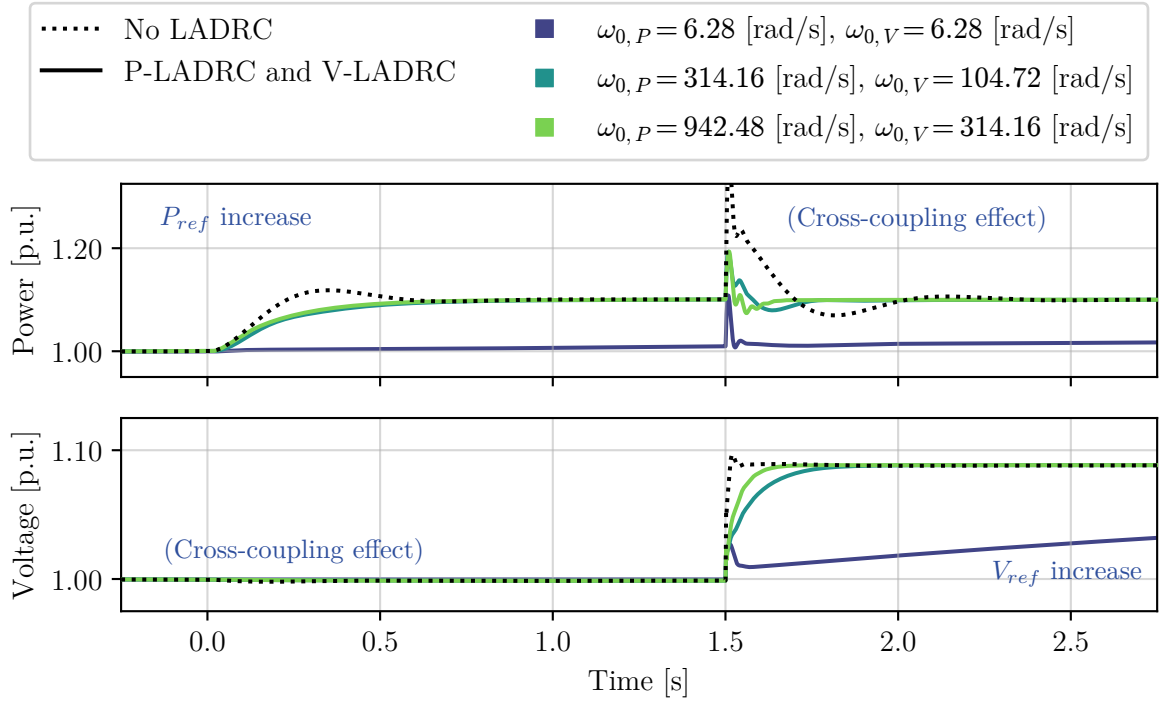


Figure 3.18: Response to a +0.1 [p.u.] step of target P_{ref} ($t = 0$ [s]) then to a +0.1 [p.u.] step of target V_{ref} ($t = 1.5$ [s]), for varying LADRCs observer bandwidths $\omega_{0,P}$ and $\omega_{0,V}$. (Left) LADRC with low observer bandwidths reacts slowly to the change of target (*input rejection*). Cross-coupling effect is weakly visible for the voltage. (Right) the cross-coupling effect is rejected, also with low ω_0 . High LADRC observer bandwidths allows high precision dynamics replacement. LADRC with low observer bandwidths reacts slowly to the change of target (*input rejection*).

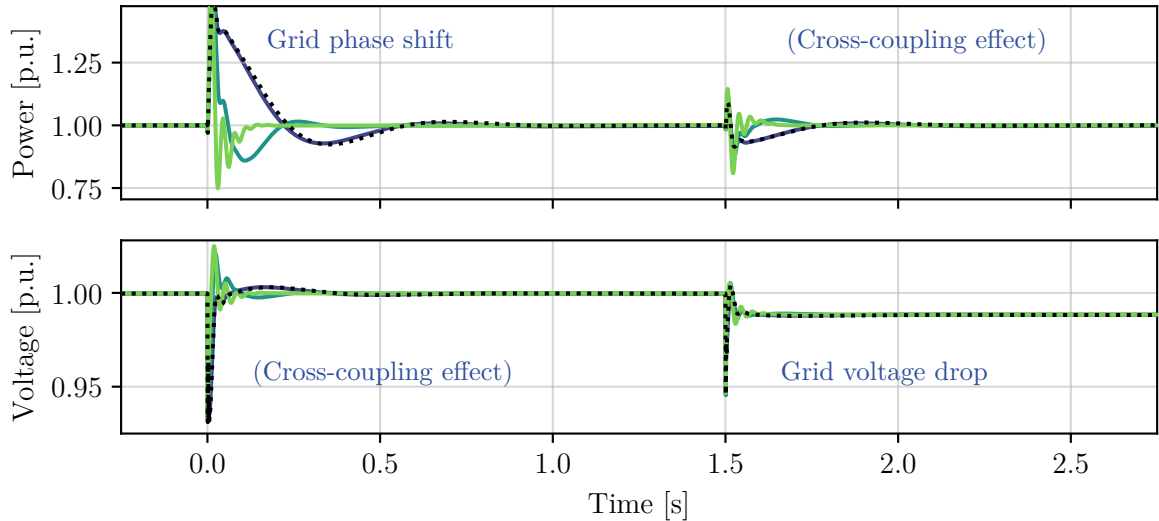


Figure 3.19: Response to a -10° drop of grid phase angle ($t = 0$ [s]) then to a -0.1 [p.u.] drop of grid voltage V_g ($t = 1.5$ [s]), for varying LADRCs observer bandwidths. (Power) LADRC with low observer bandwidths rejects both the disturbances similarly to the Grid-Forming system without LADRC. LADRC with high observer bandwidths rejects the disturbances faster, which is more a Grid-Following behavior. (Voltage) LADRC with low observer bandwidths rejects both the disturbances similarly to the system without LADRC. LADRC with high observer bandwidths rejects the disturbances stronger, but the response without LADRC is about as fast, giving a Grid-Forming behavior in all cases.

3.6.3 Interest 3: decoupling of the control loops

For this analysis, the grid equivalent resistance R_g has been varied. As a reminder (3.7), the resistive part of the electrical system is directly responsible of an undesired variation of P when changing V_c , and also takes part in an undesired variation of V_{PCC} when changing δ , when the filter and the grid impedances do not have the same time constant.

Reaction to steps of targets

The active power P and PCC voltage V_{PCC} responses to a step of targets P_{ref} then V_{ref} for varying the grid equivalent resistance R_g , are shown in Fig. 3.20. As already shown in Fig. 3.16, LADRC allows reducing the response dependence on R_g for the quantity corresponding to the step of target. As expected, LADRC reduces the effect of the resistive cross-coupling, but oscillations may increase in inductive (low R_g) grids. As already shown in Fig. 3.15, the effect of filter mismatching (cross-coupling for the voltage) is negligible for these values.

Reaction to disturbances from the grid

The active power P and PCC voltage V_{PCC} responses to a shift of grid angle (i.e. relatively sudden increase of the leading phase angle δ of the converter), then to a drop of grid infinite voltage V_g , for varying the grid resistance R_g , is shown in Fig. 3.21. As expected, LADRC rejects disturbances faster, but the cross-coupling effect linked to these disturbances is still present (no decoupling): the grid angle shift impacts P and V_{PCC} , as well as the grid voltage drop.

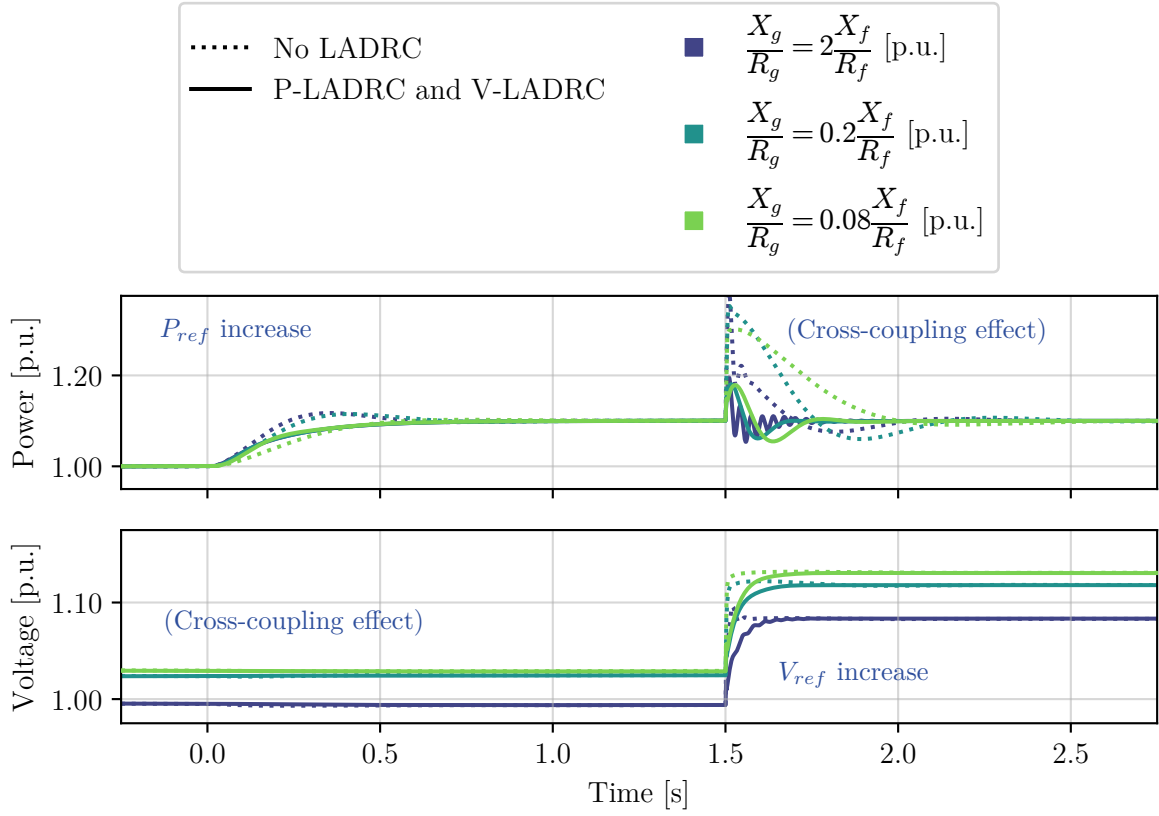


Figure 3.20: System response to a +0.1 [p.u.] step of target P^{**} ($t = 0$ [s]) then to a +0.1 [p.u.] step of target V^{**} ($t = 1.5$ [s]), for varying grid resistance R_g . (Left) LADRC allows independence of the response on the resistive cross-coupling. Cross-coupling effect is weakly visible for the voltage. (Right) LADRC reduces the effect of the resistive cross-coupling, but oscillations may increase in inductive grids. LADRC allows independence of the response on the resistive cross-coupling, but oscillations may increase in inductive grids.

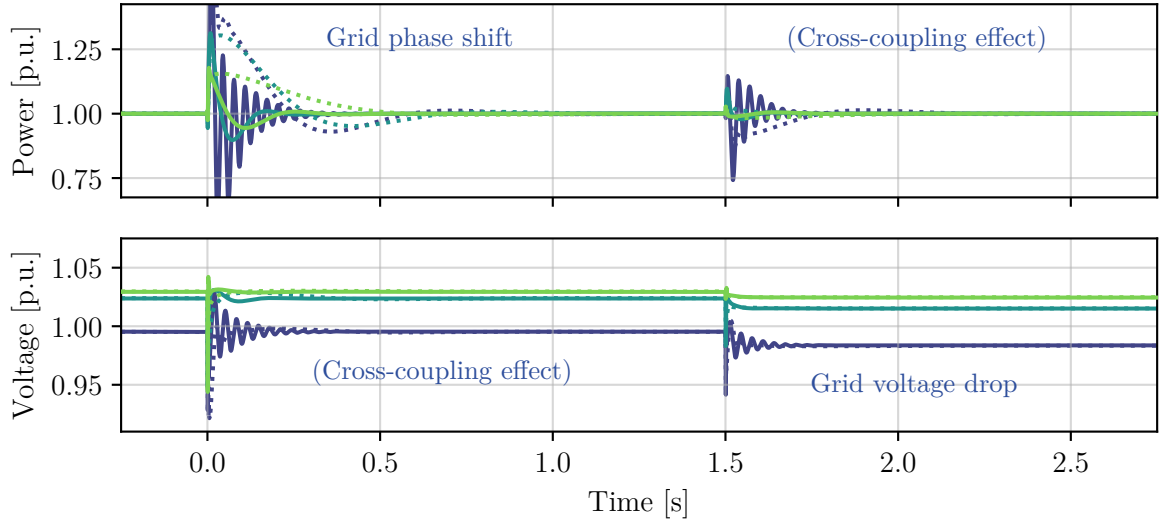


Figure 3.21: System response to a -10° drop of grid phase angle ($t = 0$ [s]) then to a -0.1 [p.u.] drop of grid voltage V_g ($t = 1.5$ [s]), for varying grid resistance R_g . (Power) LADRC rejects both disturbances faster, but heavy oscillations may appear in inductive grids. (Voltage) LADRC rejects both disturbances stronger, but response without LADRC is about as fast. Heavy oscillations may appear in inductive grids.

3.6.4 Conclusions on time domain analysis of the LADRC interests

The observations made in frequency domain in Chapter 2 for the P-Q-LADRC still apply for this P-V-LADRC system.

- With high observer bandwidths ω_0 , LADRCs allow making the response to a change of target independent of the system characteristics and decouple the P - δ loop from the Q - V loop.
- However when facing to grid disturbances, LADRC response is not independent of the system characteristics and the two loops are not decoupled. Nevertheless external disturbances impact on the power are strongly attenuated.
- With low observer bandwidths ω_0 , LADRCs lead to the rejection of the input target change, while still decoupling the two loops.
- With low observer bandwidths ω_0 , LADRCs facing grid disturbances lead to the same response as the Grid-Forming system without LADRC. With high observer bandwidths ω_0 , LADRC quickly compensates for the disturbance on P , which can be assimilated to a Grid-Following behavior. However, with or without LADRC, the voltage response to grid disturbances is fast, and is always typical of a Grid-Forming behavior.

A possible area of development is to use Q-LADRC (or maybe the V-LADRC) with a high external droop coefficient σ_b (regulation of reactive power Q , Grid-Following philosophy) instead of V-LADRC with a low σ_b (regulation of voltage V). It is likely that using such a Q-LADRC with a high $\omega_{0,Q}$ would give a Grid-Following behavior, just like the P-LADRC does. Switching for a low $\omega_{0,Q}$ would retrieve the Grid-Forming behavior.

However, the voltage being a local variable, soften the voltage response in favor of Q regulation seems to have less interest than soften the frequency response in favor of P regulation, justified by reasons of stability because frequency is a global variable.

3.6.5 Additional stability analyses

As seen previously in this section, oscillations and instabilities may occur under certain conditions. Small-signal stability and modal analysis have already been discussed in Section 3.4.2 for design-relevant parameters of the system. However, it would also be interesting to complement this analysis with situation-dependent variables to asses the robustness of the solution. The objective is also to distinguish whether only one of the two LADRCs is problematic.

The methodology is the same as described in Section 3.4.2. The default values of parameters are also the same, except for the P-LADRC observer bandwidth set to $\omega_{0,P} = 3$ [p.u.] like previously in this section. When changing grid characteristics, gain estimates $b_{0,P}$ and $b_{0,V}$ have not been changed.

In Fig. 3.22a it can be seen that the system with P-LADRC and V-LADRC becomes unstable for strong (low impedance) grids, as expected from Figs. 3.16 and 3.17. However

3.6. Final system overview and analysis: verification of LADRC interests and additional modal analysis

in Fig. 3.22b it can be seen that V-LADRC alone does not lead to such an instability issue.

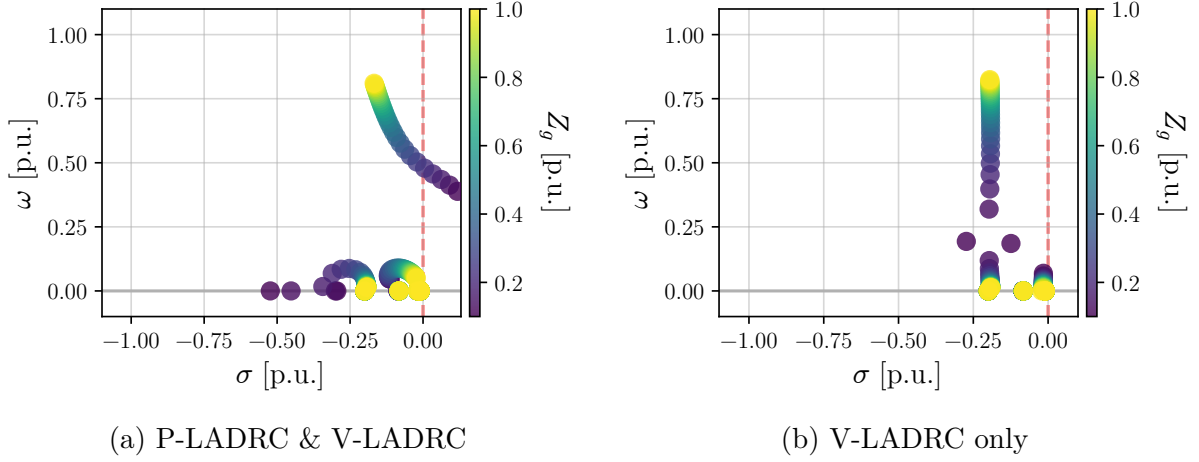


Figure 3.22: Pole map with P-LADRC and V-LADRC, or V-LADRC only, for varying the grid equivalent impedance Z_g . P-LADRC is responsible for the instability encountered in strong (low impedance) grids.

In Fig. 3.23a it can be seen that the system becomes unstable for highly inductive grids (i.e. low R_g/X_g), as expected from Figs. 3.20 and 3.21. With V-LADRC alone (Fig. 3.23b), the instability occurs for higher values of R_g/X_g , but the evolution of the problematic pole is similar. Hence it can be concluded that both P-LADRC and V-LADRC are leading to the instability.

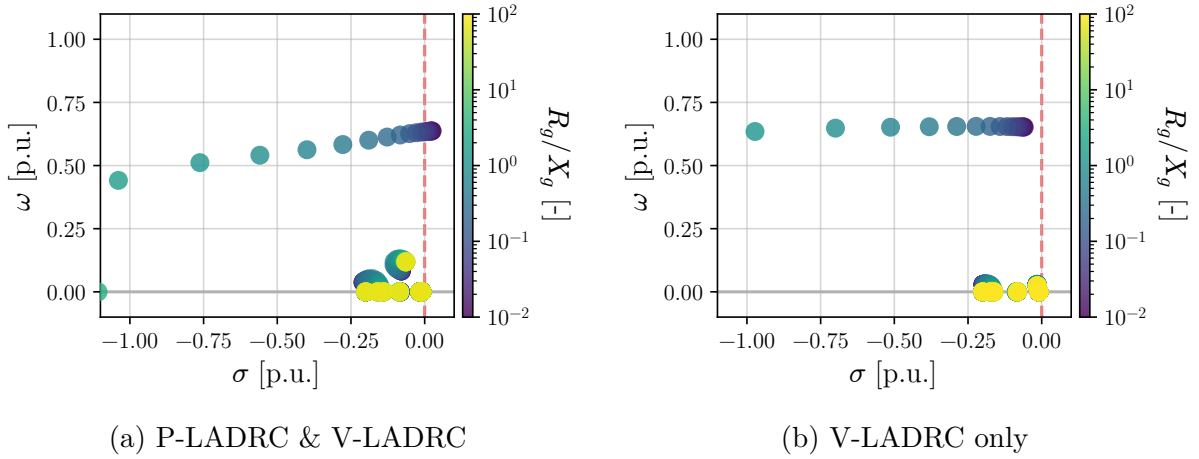


Figure 3.23: Pole map with P-LADRC and V-LADRC, or V-LADRC only, for varying the grid equivalent resistance-to-reactance ratio R_g/X_g (resulting impedance Z_g is kept constant). P-LADRC and V-LADRC are both responsible for the instability encountered in highly inductive grids.

In Fig. 3.24 it can be seen that the dominant poles evolve similarly for a variation of the gain estimate $b_{0,V}$ with P-LADRC and V-LADRC, or V-LADRC alone. Instability may occur when this gain is under-estimated. This result is coherent with the same

observation regarding P-LADRC and $b_{0,P}$ in [16]. However the consequence of this analysis must be nuanced: as discussed in Section 3.4.1, $b_{0,V}$ estimate does not depend on the grid characteristics, hence it should be quite accurate in practice.

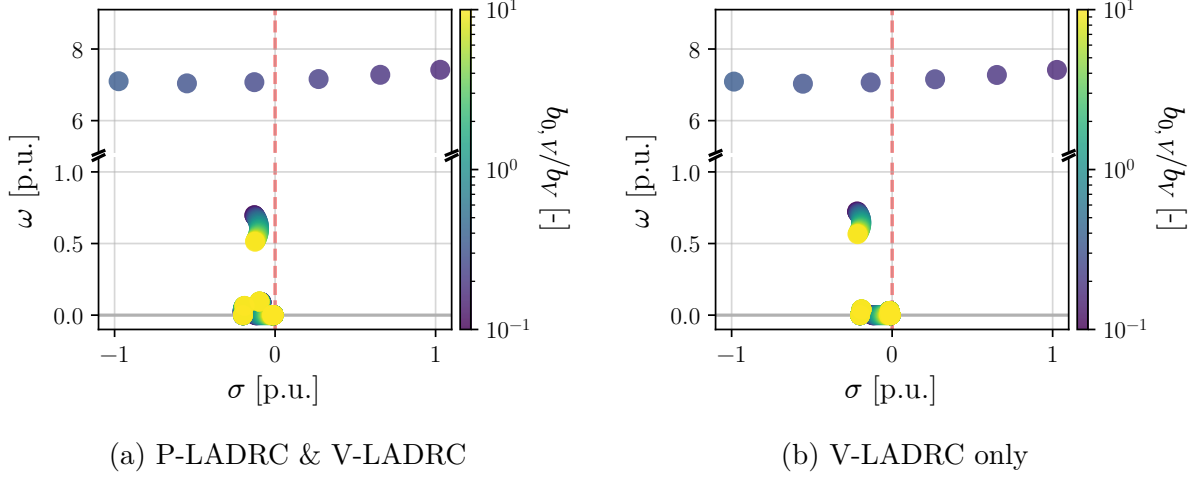


Figure 3.24: Pole map with P-LADRC and V-LADRC, or V-LADRC only, for varying the V-LADRC gain estimate $b_{0,V}$. V-LADRC is responsible for the instability encountered in case of b_V gain under-estimation.

3.7 Fault Ride Through and current limiter

In this section

A simple current limiter method will be implemented for the base GFM system with the chosen outer voltage loop and the VSG, then the behavior of the solution is analyzed when LADRC is added.

To summarize,

- When using P-LADRC and/or V-LADRC with low observer bandwidths, the Fault Ride Through capability is the same as the base GFM system.
- When using V-LADRC with a high observer bandwidth, the system does not recover by itself.
- When using P-LADRC alone with a high observer bandwidth, the system recovers by itself, but slower than the base GFM system.

Faults mostly come from irregular events occurring in the grid, like a line connection or disconnection, or a short-circuit. It leads to a sudden change of voltage magnitude and/or phase angle. Faults can be categorized following multiple criteria, like their (non)-symmetry, duration, origin (short-circuit, open-circuit), etc. [22][25][57]. In this work, a *fault* is defined as a *large disturbance* of the phase angle difference $\delta = \theta_c - \theta_{grid}$ or voltage magnitude difference $\Delta V = V_c - V_{grid}$ coming from the grid. To simplify, only symmetrical faults will be considered, in order to stay with the single-phase equivalent

circuit in a balanced three-phase case. Symmetrical faults are the most severe, even though unsymmetrical faults are more common in practice [57].

Power electronics converters are particularly sensitive to faults, because their transistors made of semi-conductor materials cannot stand high overcurrents like traditional synchronous generators. About 20% to 40% overcurrent is allowed without over-sizing, compared to 600% to 700% for synchronous machines [23].

As a reminder, active and reactive power flows can be written in function of voltage and current components in dq Park's frame, and linked *approximately* to a phase angle difference and a voltage difference at the terminals of the considered equivalent impedance for the power flow (1.6):

$$P = v_d i_d + v_q i_q \approx \frac{1}{X} \delta \quad (3.9)$$

$$Q = v_q i_d - v_d i_q \approx \frac{1}{X} \Delta V \quad (3.10)$$

For an ideal Grid-Following converter, V_{grid} and θ_{grid} are instantaneously measured (notably thanks to a PLL), and the current I_c is quickly controlled regarding the power set-point. Thus the risk of overcurrent is low.

For an ideal droop-based Grid-Forming converter, θ_c is quickly controlled regarding the active power P set-point while V is kept constant. Thus the risk of overcurrent is also low.

For an ideal VSG Grid-Forming however, θ_c control is deliberately slow regarding P set-point in order to provide inertia, while V is also kept constant. From (3.9), it can be immediately seen that the current magnitude $I = \sqrt{i_d^2 + i_q^2}$ will instantaneously increase when there is a sudden increase of δ (i.e. a grid angle retraction) and P is maintained temporarily constant. Thus the risk of overcurrent is high.

To avoid destroying the converter during a severe fault, current protections must be implemented. Several solutions have already been studied in the literature. The most common method is to use a *Current Saturation Algorithm* in the inner loops to avoid reaching excessive overcurrent. However, some difficulties occur regarding stability [23]. Temporary virtual impedance is another method to reduce the voltage more softly during faults. as mentioned in Chapter 1, this allows keeping the voltage source behavior [23][50].

Standards requirements presented in Section 3.1 give important information for the Fault Ride Through (FRT) and the design of a current limiter.

A current saturator block is introduced between the output of the inner voltage loop and the input of the inner current loop. Its role is to saturate the current components references, such that the inner current loop can quickly adapt the converter voltage to avoid high overcurrent. The saturation of the dq components is made *proportionally*, as asked by the standards. A safe limit of 1.2 [p.u.] overcurrent is considered. When the current limit is reached, the block applies (3.11).

$$i_{d,ref,sat} = i_{d,ref} \cdot \frac{I_{measured}}{I_{limit,sat}} \quad i_{q,ref,sat} = i_{q,ref} \cdot \frac{I_{measured}}{I_{limit,sat}} \quad (3.11)$$

When the current saturator is active, the (excessive) reference current components asked by the inner voltage loops are never reached, hence the voltage reference is not either reached. Consequently, the integrators in the PI controllers of the voltage inner loops are continuously integrating this error, which prevents the control from recovering safely and softly. Hence, an anti-windup method needs to be implemented [37]. In this work, an additional block compares the current magnitude to a desired limit. When this limit is reached, $k_{i,v}$ gains are set to 0, which freezes the integrators while still allowing a partial voltage regulation with the proportional gains $k_{p,v}$.

The current saturator is known to make the converter having more a Grid-Following behavior [23]. Moreover, as discussed in Section 3.1 (Standards requirements), the current clipping should be limited in time. Hence another action is necessary to get the converter out of saturation and retrieve the Grid-Forming behavior as soon as possible. For that reason, the active power P set-point should be adapted such that it would not lead to an overcurrent in steady-state. This specific limit, is in purpose set a little lower than the *clipping* limit of the current saturator, at 1.05 [p.u.] for instance. At this level, priority can be given to reactive power, as recommended for HVDC converters in the standards. This set-point adapter follows (3.12).

$$\begin{aligned} S_{limit} &= V_{PCC,meas} I_{limit,adapt} \\ P_{limit} &= \sqrt{S_{limit}^2 - Q_{meas}^2} \\ P_{sat} &= \text{sign}(P^*) \cdot \min(|P^*|, P_{limit}) \end{aligned} \quad (3.12)$$

The complete system implemented in Matlab Simulink is shown in Appendix I.

The system is analyzed on two examples of faults. The parameters correspond to the intermediate case of Table 3.3. Parameters of the outer voltage loop are those used in Section 3.4.1. LADRC parameters are also those in Table 3.4, excepted for $\omega_{0,P} = 3$ [p.u.] just like in the previous section, because small-signal stability allows such a high value.

3.7.1 Fault 1: three-phase ground fault at the PCC

A severe three-phase ground fault is made at the PCC during 0.2 [s], corresponding to the reference duration of the FRT profile in the standards requirements (Fig. 3.2).

FRT without LADRC

The proper functioning of the system is shown in Fig. 3.25. Individual results of the current limiter blocks are found in Appendix J, Fig. J.1.

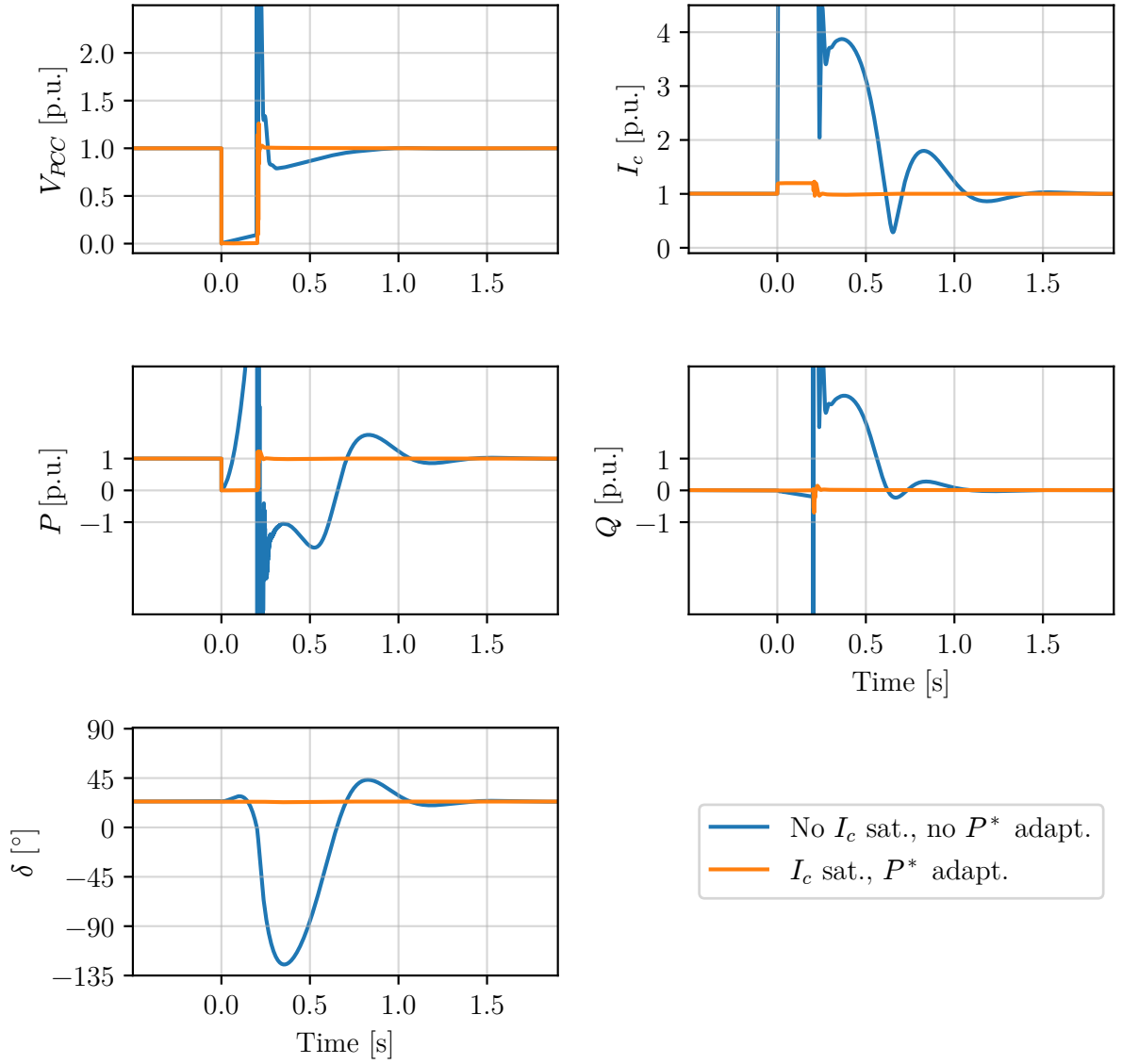


Figure 3.25: Main electrical quantities reaction to a 3-ph fault at the PCC, with and without the FRT system (without LADRC). By saturating the current and adapting the active power target P^* , voltage and powers recovers quickly, and fault current is limited. Converter phase angle keeps stable.

FRT with high observer bandwidth ω_0

P-LADRC and V-LADRC with high observer bandwidths ($\omega_{0,P} = 3$ [p.u.] and $\omega_{0,V} = 1$ [p.u.]) are successively applied to the system. Results are shown in Fig. 3.26. It can be seen that none of the cases with V-LADRC allows proper Fault Ride Through: the current remains clipped, while voltage also stabilizes to an excessive value, and P stabilizes at 0 [p.u.] (all the converter current is dedicated to the reactive power Q). With P-LADRC alone, the system recovers correctly, but slower than without LADRC.

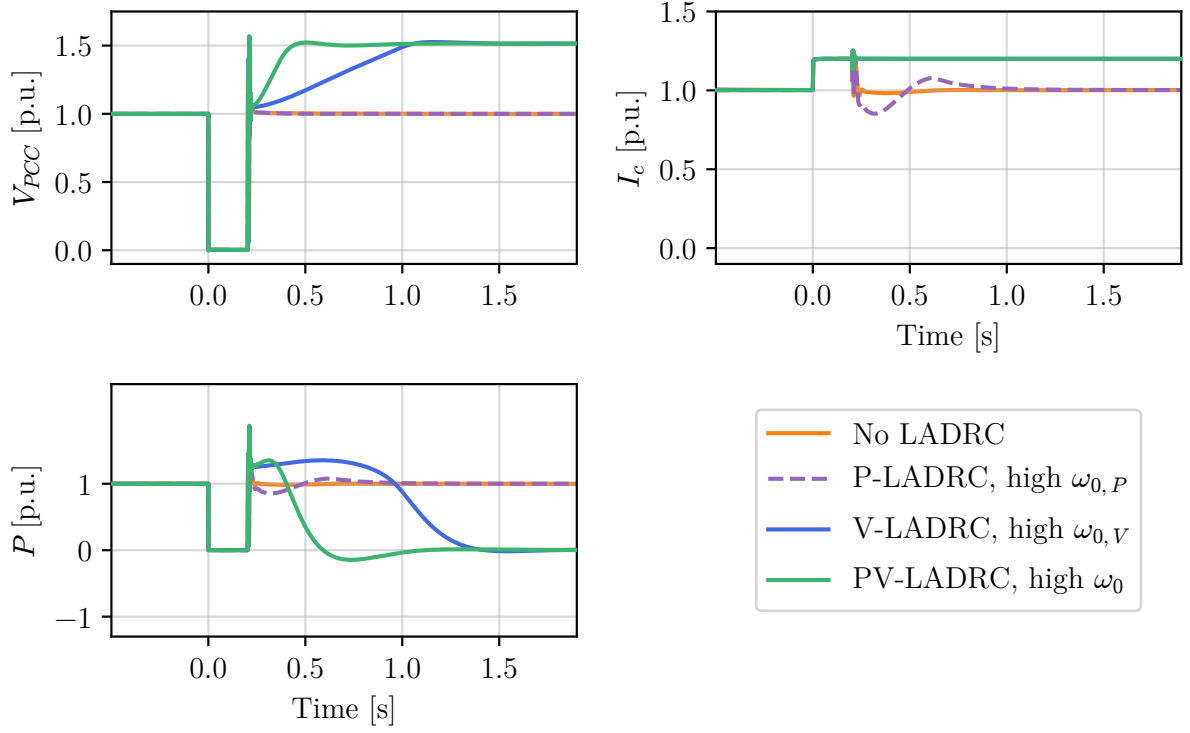


Figure 3.26: Main electrical quantities reaction to a 3-ph fault at the PCC, with or without LADRCs, with high observer bandwidths ω_0 . When V-LADRC is used, the system keeps saturated and does not recover by itself.

FRT with low observer bandwidth ω_0

As a reminder, Figs. 3.19 and 3.19 showed that LADRC with low observer bandwidth gave the same response to a grid disturbance than the base system without LADRC. Hence, P-LADRC and V-LADRC with low observer bandwidths ($\omega_{0,P} = \omega_{0,V} = 0$ [p.u.]) are successively applied to the system. Results are shown in Fig. 3.27. As expected, systems with low observer bandwidths LADRCs give the same Fault Ride Through capability as the base system without LADRC.

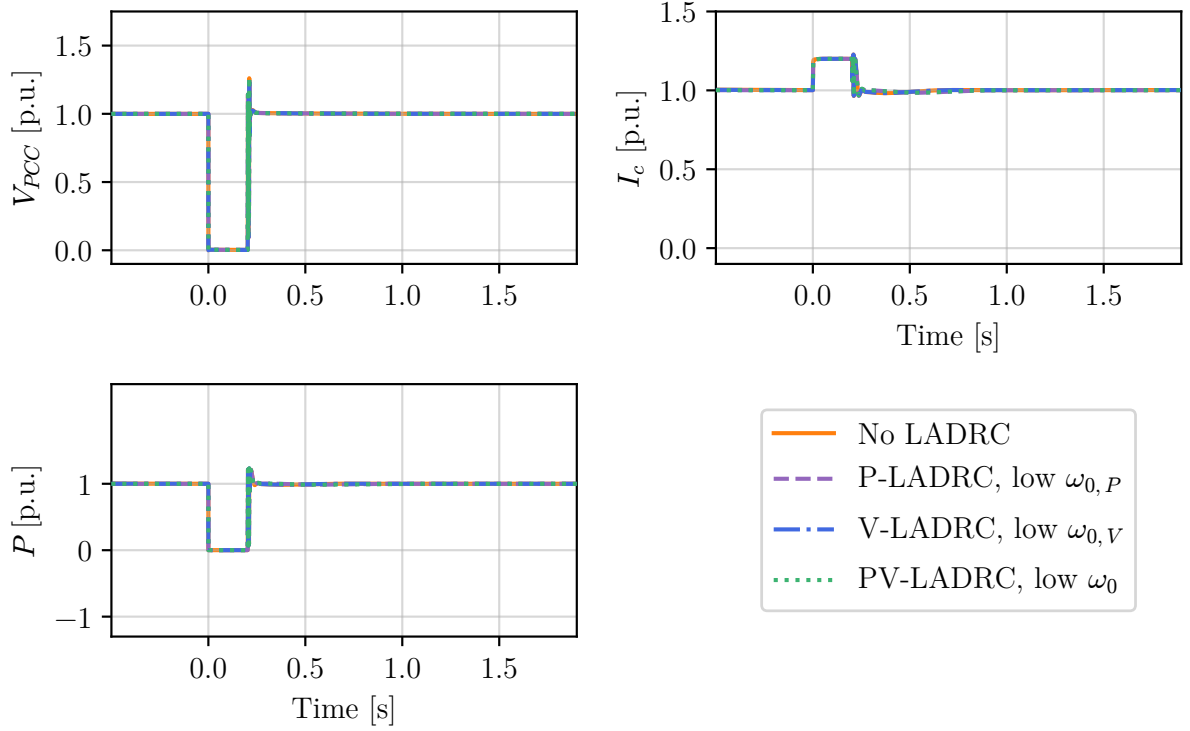


Figure 3.27: Main electrical quantities reaction to a 3-ph fault at the PCC, with or without LADRCs, with low observer bandwidths $\omega_0 = 0$. When V-LADRC is used alone, the system keeps saturated and does not recover by itself. Using P-LADRC (along or not with V-LADRC) gives the same recovery as the case without LADRC.

3.7.2 Fault 2: $\pm 45^\circ$ phase shift at the PCC

Standards (Section 3.1) require the capability to withstand a $\pm 45^\circ$ phase angle shift at the PCC. In the case where the grid is strong (low X reactance), such a phase angle shift leads to enormous values of active power P and hence of current, referring to (3.12).

The analysis of this fault is available in Appendix J. The implemented system also demonstrates its operation in the case without LADRC, and the behavior with LADRC is similar to that discussed previously.

3.7.3 Conclusion on Fault Ride Through with LADRC

The simple current limiter implemented is working as expected on the base system without LADRC, for both the three-phase ground fault and the $\pm 45^\circ$ phase angle shift at the PCC.

When using V-LADRC with high observer bandwidth $\omega_{0,V}$, the system does not recover automatically. The priority given to the reactive power Q , permitted in the adaptation of the active power set-point, is used such that Q and V_{PCC} are maximized.

However when using P-LADRC and/or V-LADRC with low observer bandwidths $\omega_{0,P} = \omega_{0,V} = 0$ [p.u.], the Fault Ride Through capability is the same as the base

system without LADRC. It is likely that keeping a low observer bandwidth when the system is in steady-state would be a recommended parametrization to prepare the fault events.

It has been seen that when a large phase angle shift occurs, the controller may adapt the converter angle θ_c such that the angle difference δ makes an entire turn to recover the equilibrium point while respecting the limitations. This process is slow, because of the virtual inertia provided by the VSG. More than 1 [s] has been necessary under the studied parameters, while maximum 0.2 [s] was indicated by early HVDC standards requirements. As suggested in the end of Section 3.1, it may be interesting to temporarily decrease the inertia constant H when a fault that does not require FCR occurs. The associated results are presented in Appendix J, Fig. J.5.

Finally, it is still important to remind that the results of this section have been obtained from the perspective of controlling an ideal system. In practice however, technological considerations should also be considered. For instance, real systems might have other technical specifications (delays, bandwidth, voltage limits, etc.). Moreover, it has been assumed that the converters could also absorb active power ($P < 0$ should be allowed). The need of energy storage systems, over-sizing, and energy buffers for Grid-Forming control are highlighted in the literature [10][18][23][57][58].

Chapter 4

More realistic situations

In this chapter

Having described the system, it is now possible to examine its application in more advanced situations. First, the parallel operation of Grid-Forming converters will be studied with and without LADRC. Second, operation in a standardized 9-bus network will be analyzed.

To summarize,

1. Strong interactions are possible with P-LADRC when the converters are too close electrically.
2. Observer bandwidth should be decreased when using multiple LADRCs. Using multiple V-LADRCs is not particularly useful.

4.1 Parallel operation

In this section

To make multiple generators provide power from the same location on the grid, they must be connected on the same bus. Such a parallel operation raises questions concerning stability: is the system stable when multiple controllers aim to control the same electrical node ?

To summarize, parallel operation of multiple converters is possible when the controlled nodes are distinct. Strong interactions are possible with P-LADRC when the converters are too close electrically.

Common connection through impedances

Multiple converters cannot be directly connected and controlled on the same node. Intuitively, this would indeed break the feedback loops for the voltage regulation, which would make the system unstable. An attempt was made to see if the LADRC would allow this type of operation, but without success. The results can be found in Appendix K.

4.1. Parallel operation

In practice, the controlled points (Points of Common Coupling, PCC) should be separated from the unique Point of Connection (PoC). ENTSO-E standard [46] suggests using a *Power Collection System* (PCS) that is an internal grid to centralize the power production of several Grid-Forming converters. Thus each PCC is controlled separately, and the voltage magnitudes may not exactly be equal to the unique PoC voltage magnitude. However since $V_g \approx V_c \approx 1$ [p.u.], $V_{PoC} \approx 1$ [p.u.] is also expected. For the TSOs, the most important is that "the PCS design maintains a voltage source behind an impedance behavior at the PoC" [46, p. 14]. By using impedances to separate each PCC from the PoC, this requirement is met. This impedance should be large enough for the controllers to be stable, but small enough to avoid an important voltage drop from the PCC to the PoC.

The considered electrical circuit with two converters is represented in Fig. 4.1. Impedances are chosen to be $\bar{Z}_1 = \bar{Z}_2 = \frac{0.1}{5} + j0.1$ [p.u.]. These impedances respect the standards requirements ([46]) and have the same $\frac{L}{R}$ time constant as the other impedances in the circuit, which is advantageous regarding the dynamics, as stated in Section 3.5.

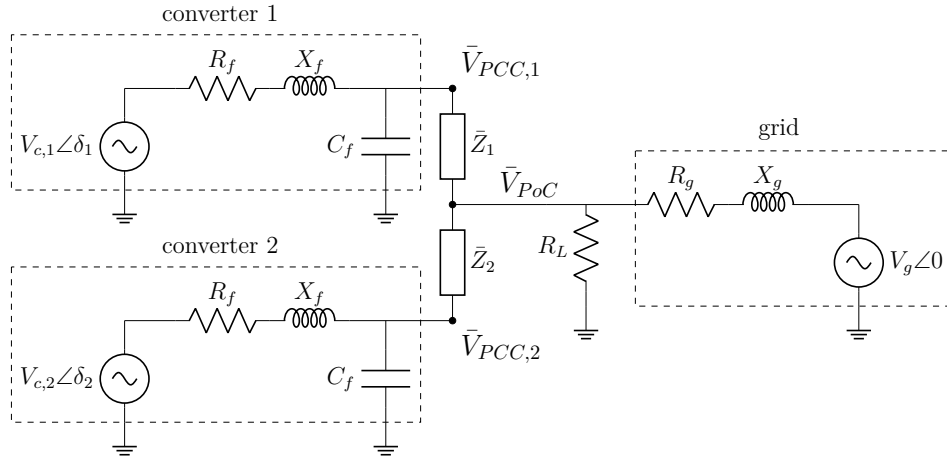


Figure 4.1: Equivalent circuit for the two converters controlling their own PCC, separated from the common PoC by an impedance

As the goal here is to simulate more realistic situations, a more realistic model of the grid is used.

In the grid Thévenin equivalent circuit, instead of using a pure 50 [Hz] voltage source, effects of grid inertia and droop are emulated by a dedicated loop. Model and parameters are from [50] and are shown in Fig. 4.2 and Table 4.1.

When $P > P_{ref,grid}$, it means that the converters inject excessive power to the grid. Consequently, grid frequency ω_g increases, which is the expected behavior. On the contrary, when $P < P_{ref,grid}$, it means that the converters inject less power than planned. Consequently, grid frequency ω_g decreases. The grid equivalent has an inertia constant H_g [s], which physical meaning is the same as for the synchronous generator (cf. Section 1.2). The grid P - f droop is implemented with the R_{SG} coefficient, and a first-order transfer function mimics the turbine dynamics associated with grid generators, with T_N [s] and T_D [s] coefficients.

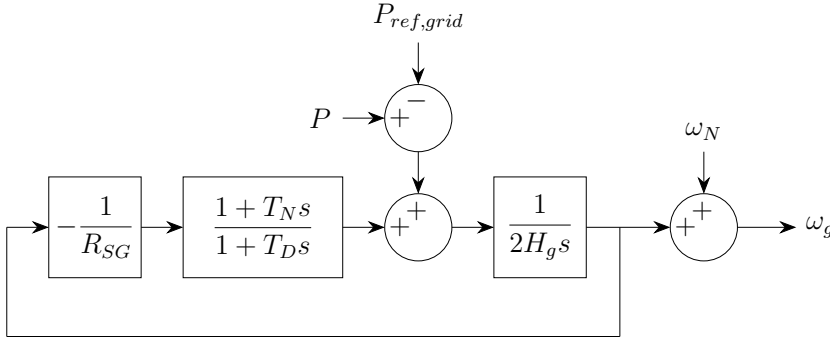


Figure 4.2: Inertial grid model, adapted from [50].

Parameter	Value
H_g [s]	5
R_{SG}	0.04
T_N [s]	1
T_D [s]	6

Table 4.1:

Parameters of the inertial grid model, adapted from [50].

For this analysis, a 1 [p.u.] resistive load R_L is connected directly on the bus (with voltage $\bar{V}_{PoC}$). The converters are chosen to be the same, with parameters being the same as in Section 3.6. Both converters power target is $P^{**} = 0.5$ [p.u.]. Hence it is expected that few active power is exchanged with the grid. Thus in the grid model, $P_{ref,grid} = 0$ [p.u.] is considered, and the grid mainly serves to FCR and voltage support.

Simulations are made in three steps: first ($t < 0$ [s]), the system is observed in steady-state. Second, at $t = 0$ [s], the grid is disconnected, and the two converters operate in islanded mode (micro-grid) with the resistive load. Third, at $t = 1$ [s], the converter C2 disconnects, leaving C1 alone with the load. All along the simulation, system balance is ensured thanks to droop controls, and no capability limit is expected to be exceeded.

Reaction with V-LADRC only

In Fig. 4.3 are shown the active power P_1 from converter C1 and voltage magnitude at the unique Point of Connection (PoC), with applying V-LADRC on C2 only, or on both C1 and C2. Observer bandwidth is either high ($\omega_{0,V} = 1$ [p.u.]) or low ($\omega_{0,V} = 0$ [p.u.]). All along the simulation, the systems are stable, and behaviors with only V-LADRC are similar to the case without LADRC.

When the grid is disconnected at $t = 0$ [s], little impact can be observed, because the exchanged active power was low. No disturbing interactions are observed before or after isolating.

When the converter C2 is lost at $t = 1$ [s], P_1 increases to nearly 1 [p.u.] almost instantaneously. Virtual inertia does not slow down the response, because the power consumed by the resistive load only depends on the value of V_{PoC} that is quickly regulated ($P_L = \frac{V_{PoC}^2}{R_L}$). The load voltage ($\bar{V}_{PoC}$) phase angle consequently shifts immediately such that the phase angle difference with C1 output changes, without requiring C1 to change its phase angle. Nevertheless, such an instant power response is only possible provided that the used technology allows it in practice.

It can be observed that applying V-LADRC on both C1 and C2 with high observer bandwidth leads to a slight overreaction to the second event, which suggests a stronger but controlled interaction between the controllers.

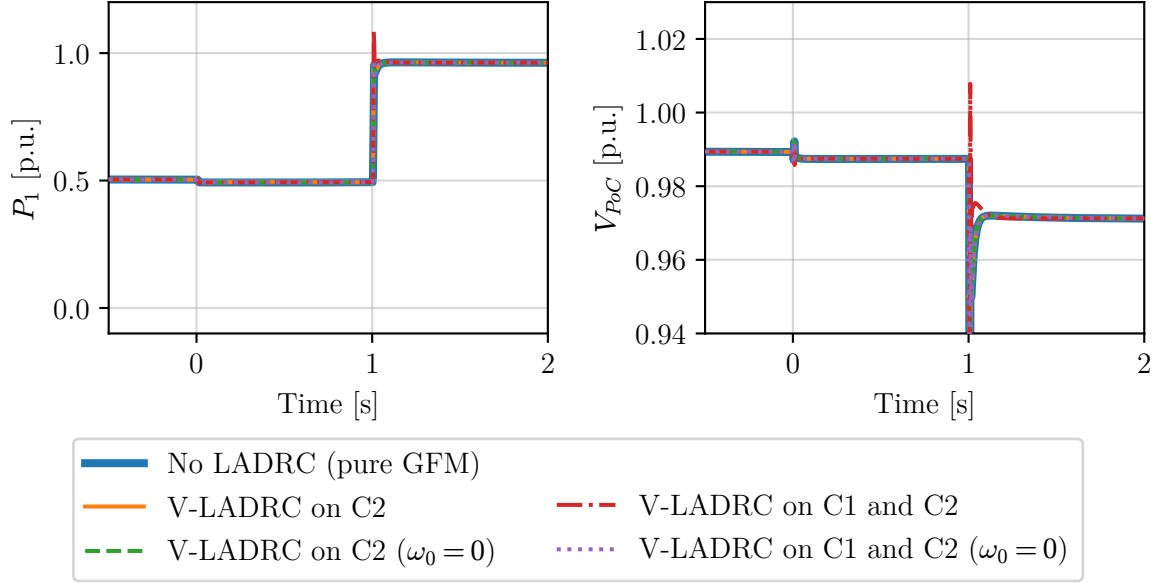


Figure 4.3: Parallel operation with impedances separating the controlled PCCs from the unique PoC. Application of V-LADRC on one or both converters, with high or low observer bandwidth. The systems are stable, and power and voltage behaviors with only V-LADRC are similar to the case without LADRC. Disconnection of the grid ($t = 0$ [s]) has little impact. Loss of converter C2 ($t = 1$ [s]) results in an almost immediate P_1 increase to nearly 1 [p.u.], and V_{poc} is less supported.

Reaction with P-LADRC only or along with and V-LADRC

In Fig. 4.4a is shown the active power P_1 from converter C1, with high LADRC observer bandwidths ($\omega_{0,P} = 3$ [p.u.], $\omega_{0,V} = 1$ [p.u.]). Using multiple P-LADRCs ($t < 1$ [s]) leads to instabilities. Strong interaction appears when P-LADRC is applied to both C1 and C2. The system oscillates without V-LADRC, or triggers the current limiter system with V-LADRC. When applied to C2 only, P-LADRC also leads to oscillations, which are lower with V-LADRC. Oscillations are centered around the expected $P_1 = 0.5$ [p.u.] value, but are not attenuated with time. Amplitude increases in islanded mode ($0 < t < 1$ [s]).

The encountered oscillations have a quite low frequency of about 6 [Hz] (≈ 0.12 [p.u.]). An hypothesis of such oscillations is the smallness of the impedances Z_1 and Z_2 . If those impedances are too small, each converter sees a quite strong system, similarly to a low Z_g value in Section 3.6. As a reminder, Fig. 3.22a showed the possibility of instability when the PCC is *too close* (electrically) to the grid. This hypothesis is confirmed in Fig. 4.5 where the impedances Z_1 and Z_2 have been varied.

In Fig. 4.4b is shown the active power P_1 from converter C1, when applying P-LADRC alone or with V-LADRC on C2 or both C1 and C2, with low observer bandwidths ($\omega_{0,P} = \omega_{0,V} = 0$ [p.u.]). Strong interaction appears when P-LADRC is applied to both C1 and C2, giving incorrect values and triggering the current limiter system. When applied to C2 only, P-LADRC (with or without V-LADRC) leads to the expected power when grid is still connected for $t < 0$ [s] (though with small oscillations without V-LADRC), but incorrect values when grid is disconnected for $0 < t < 1$ [s].

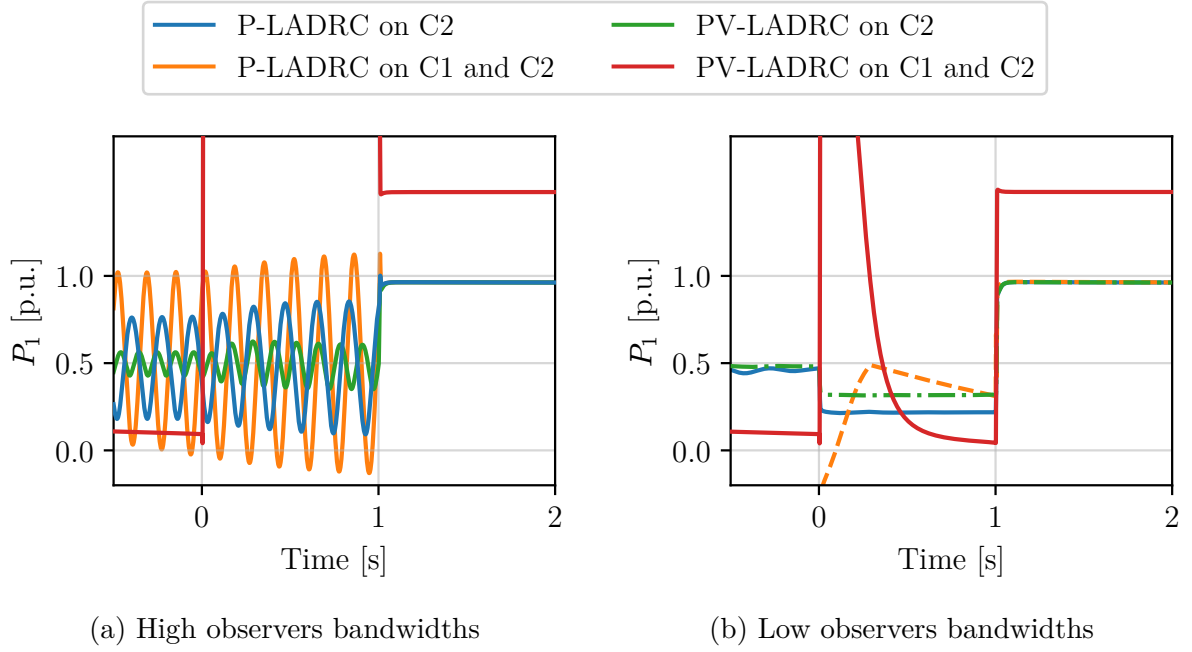


Figure 4.4: Parallel operation with impedances separating the controlled PCCs from the unique PoC. Application of P-LADRC alone or with V-LADRC on one or both converters. (a) Using multiple P-LADRCs leads to instabilities. Strong interaction appears when P-LADRC is applied to both C1 and C2, making the system strongly oscillating without V-LADRC, or triggering the current limiter system with V-LADRC. When applied to C2 only, P-LADRC leads to oscillations, which are attenuated with V-LADRC. (b) Strong interaction appears when P-LADRC is applied to both C1 and C2, giving incorrect values and triggering the current limiter system. When applied to C2 only, P-LADRC (with or without V-LADRC) leads to the expected power when grid is connected, but incorrect values when grid is disconnected.

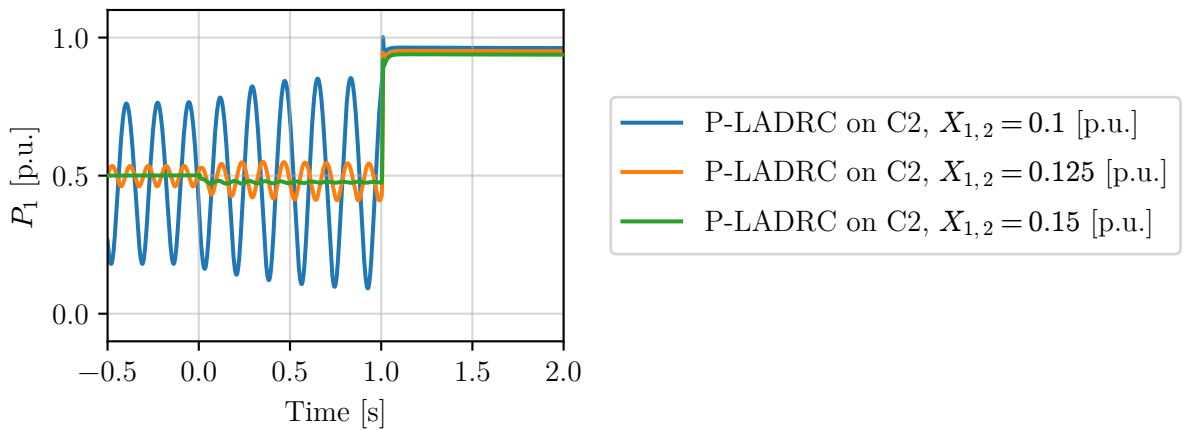


Figure 4.5: Parallel operation with impedances separating the controlled PCCs from the unique PoC. Application of P-LADRC alone on C2. Instability and oscillations occur when the impedance is too small, meaning that the converters are electrically *too close* to each other.

4.1.1 Conclusions on parallel operation

By separating each PCC from the PoC, parallel operation of multiple converters is possible. Based on simulations of a typical situation, V-LADRC alone does not cause interaction issues, no matter the observer bandwidth and if it is applied to one or both converters.

However, P-LADRC is likely to bring interaction issues when operating converters in parallel. With a high observer bandwidth, oscillations may appear if the separating impedances are too small. The oscillations may be attenuated with V-LADRC. However when multiple converters use P-LADRC, interactions are even stronger and are not solved by V-LADRC. By using low observer bandwidths, oscillations mainly disappear, but the results do not meet expectations when the two converters are placed in islanded mode with the load.

To allow for a symmetrical representation of the results, both converters have been parametrized identically. However, further experimentation showed that the undesired effects presented in this section may be much worse with two converters with different parameters. This does not however invalidate the results of this particular case with two identical converters. Further research is necessary to study in detail the interactions and the stability of converters placed in parallel using P-LADRC.

4.2 In-grid operation

In this section

Finally, it is worth taking a step back by looking at the situation on the scale of the electrical grid. High penetration of Grid-Forming converters with or without LADRCs is analyzed empirically based on a European adaption of the IEEE 9-bus grid model.

To summarize,

- Using multiple P-LADRCs in a system may lead to instabilities when the observer bandwidth $\omega_{0,P}$ is excessive.
- Using multiple V-LADRCs with a high observer bandwidth $\omega_{0,V}$ increases the system sensitivity to noise disturbances.
- Using multiple V-LADRCs is not particularly useful.

Up to now in this work, quite simplified models have been considered to better highlight the fundamentals of LADRC on Grid-Forming converters. Notably, transmission lines have been modeled by simple series impedances. By doing it this way, possible phenomena of resonance with real lines distributed capacitance are neglected. Moreover, the grid was initially considered as an ideal voltage source behind an equivalent impedance, and later with a more realistic inertial equivalent associated with the dynamics of traditional synchronous generators. Therefore, it is still interesting to see whether Grid-Forming converters with LADRC are a viable solution with a high penetration in the grid.

4.2. In-grid operation

In this section, a simple grid is modeled based on the IEEE 9-bus benchmark model. Since this model is inspired by the Western North American grid in the 70's, it may not be appropriate as such for a study in the contemporary context of power converters in the European grid. For that reason, the model has recently been adapted to the European transmission grid standards in [59]. The main changes concern the frequency (50 [Hz] instead of 60 [Hz]), the high-voltage magnitude (400 [kV] instead of 230 [kV]), the length of the transmission lines, and the power of the sources and the loads. The considered grid model is represented in Fig. 4.6. Converters nominal powers are 600 [MVA] for C1 and C3, and 1200 [MVA] for C2. Associated transformers have YNd11 configuration, $x_s = 0.2$ [p.u.] reactance, and $p_{copper} = 0.015$ [p.u.] copper losses represented by an equivalent resistive part.

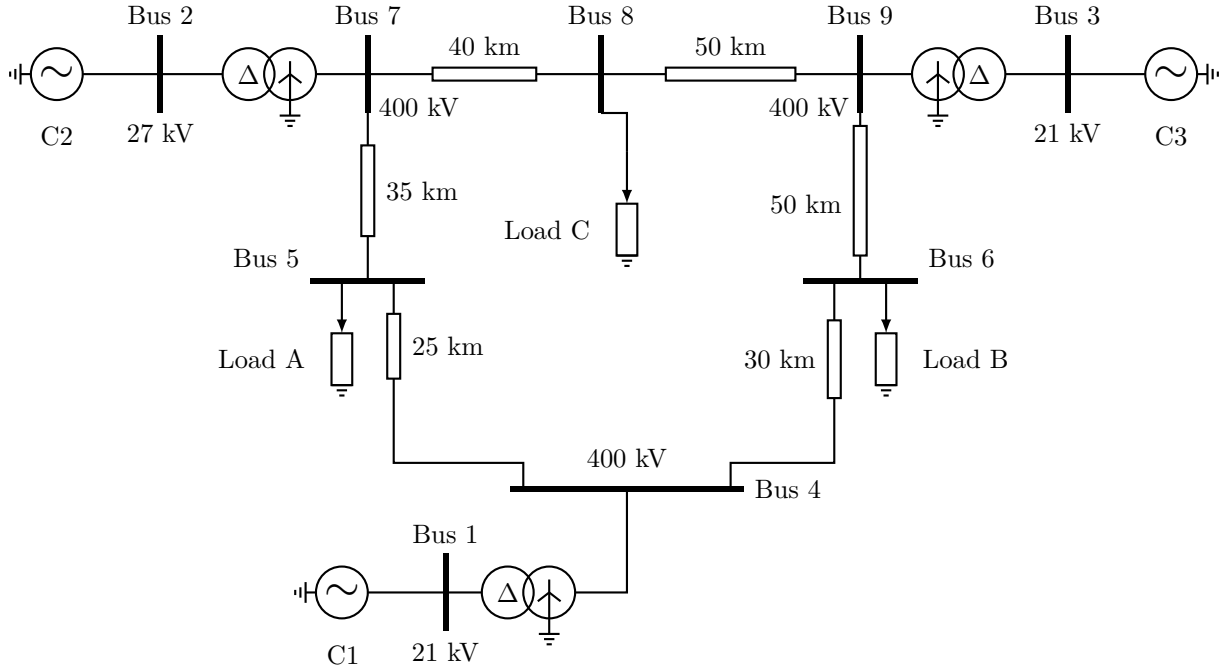


Figure 4.6: European adaptation of the IEEE 9-bus grid model, adapted from [59].

Bus	P [MW]	Q [MVar]	V [p.u.]	θ
1	361	207	1.080	0.0°
2	908	363.5	1.075	2.87°
3	471	153.5	1.049	-1.32°
4			1.021	-36.23°
5	-687.5	-275	1.016	-36.55°
6	-495	-165	1.017	-36.74°
7			1.027	-34.99°
8	-550	-192.5	1.019	-36.24°
9			1.026	-35.51°

Table 4.2: Operating point of the grid model, from [59].

The operating point calculated in [59] is summarized in Table 4.2. The values of this load flow are used as is in this work, and slight deviations due to implementation differences are considered to be managed by droop controls of the loads and the sources.

The lines are simulated with the *Distributed Parameters Line* model in Matlab Simulink. Parameters are found with the *Line Parameter Calculator* tool based on physical data of existing wires and tower geometries, in accordance to the "German standard for overhead line conductors" [59][60]. Three-phase lines are considered continuously transposed, meaning that the positive and negative sequences of R, L and C elements are equal. The computed positive and zero sequence elements are the following:

$$\begin{aligned} R_1 &= 0.02760 \text{ } [\Omega/\text{km}] & L_1 &= 0.00086 \text{ } [\text{H}/\text{km}] & C_1 &= 1.34059 \cdot 10^{-8} \text{ } [\text{F}/\text{km}] \\ R_0 &= 0.13130 \text{ } [\Omega/\text{km}] & L_0 &= 0.00293 \text{ } [\text{H}/\text{km}] & C_0 &= 7.09705 \cdot 10^{-9} \text{ } [\text{F}/\text{km}] \end{aligned}$$

To get an idea for the comparison with values previously used in this work, for the intermediate 35 [km] line: $R_1 = 0.006$ [p.u.], $X_1 = 0.059$ [p.u.].

In [59], considered loads are constant impedances sized in the operating conditions. In practice, the loads notably vary in function of the frequency and the voltage [26]. In this work, operating point of dynamic loads are given by (4.1) [61].

$$P = P_0 \left(1 + D_{p,load} \frac{f - f_N}{f_N} \right) \left(\frac{V}{V_0} \right)^\alpha \quad Q = Q_0 \left(1 + D_{q,load} \frac{f - f_N}{f_N} \right) \left(\frac{V}{V_0} \right)^\beta \quad (4.1)$$

Where P_0 , Q_0 and V_0 are the load operating powers and voltage in the standard $f = 50$ [Hz] and $V = 1$ [p.u.] conditions. Coefficients $D_{p,load}$, $D_{q,load}$, α , β depend on the nature of the load. Typical values are found in [61] and are arbitrarily attributed to the system loads¹ as summarized in Table 4.3.

	α	β	$D_{p,load}$	$D_{q,load}$	Category
Load A	0.2	6	2.6	1.6	Industrial
Load B	1.2	2.9	0.8	-2.2	Residential (summer)
Load C	1.0	3.5	1.2	-1.6	Commercial (summer)

Table 4.3: Parameters for the frequency and voltage dependencies of the loads, from [61].

4.2.1 System stability with LADRCs

Previous results (Sections 3.6 and 4.1) showed that interactions between P-LADRC and V-LADRC, as well as between multiple converters, are possible and may lead to instabilities. Hence in order to use LADRC as a common solution in future power systems, it is crucial to know whether widespread use of LADRC in the grid can have consequences for the system stability.

Stability is here stated empirically based on the single example of the 9-bus model. The reference case without any LADRC (pure GFM converters) gave simulation results

¹Load power factors are kept the same as the load flow in [59], and have not been matched with categorical values of [61].

4.2. In-grid operation

close to the expected load flow (Table 4.2) and showed no stability issues. All the combinations of applying P-LADRC/V-LADRC/PV-LADRC on converters C1, C2, and C3, with high observer bandwidths ($\omega_{0,P} = 3$ [p.u.], $\omega_{0,V} = 1$ [p.u.]) or low observer bandwidths ($\omega_{0,P} = \omega_{0,V} = 0$ [p.u.]) have been simulated. When LADRC is not used, classic GFM controls (VSG and Q - V outer loop) are applied.

The system is considered *stable* when the expected operating point can be maintained in steady-state. To avoid numerical instabilities as much as possible, efforts have been made to gently bring the system to the desired point (by ramping all the quantities separately from a black start). In practice, procedures should be developed to connect loads and LADRCs on an existing functional grid. When the system is considered *unstable*, supplementary trials have been made to identified the cause of the instability. To that end, observer bandwidths have been reduced to $\omega_{0,P} = 1$ [p.u.] and/or the loads have been changed to constant impedances (equivalent in nominal conditions).

Results are synthetically presented in Table 4.4.

	P-LADRC (high ω_0)	V-LADRC (high ω_0)	PV-LADRC (low ω_0)	PV-LADRC (high ω_0)
C1	✓	✓	✓	✓
C2	✓	✓	✓	✓
C3	✓	✓	✓	✓
C1 & C2	✓	✗	✓	✗
C1 & C3	✓	✓	✓	✗
C2 & C3	✓	✗	✓	✗
C1 & C2 & C3	✓	✗	✓	✗

Legend:

✓ : Stable

✗ : Unstable due to the loads dynamics

✗ : Unstable due to the loads dynamics and excessive $\omega_{0,P}$ value

Table 4.4: Stability at the operating point when using LADRCs in the 9-bus model. When LADRC is not used, classic GFM controls (VSG and Q - V outer loop) are applied. System is stable with any usage of P-LADRC without V-LADRC. Systems with a single V-LADRC (without P-LADRC) are stable, but multiple V-LADRC may lead to instability when using high $\omega_{0,V}$. Using both P-LADRC and V-LADRC with low observer bandwidths ($\omega_{0,P} = \omega_{0,V} = 0$ [p.u.]) is safe in all the cases. Using multiple PV-LADRCs with high observer bandwidths ($\omega_{0,P} = 3$ [p.u.], $\omega_{0,V} = 1$ [p.u.]) leads to instability.

System is stable with any usage of P-LADRC without V-LADRC. Stability statement was the same for high and low $\omega_{0,P}$. Supplementary analysis are however necessary to state on the particular dynamics differences when using more than one single P-LADRC converter.

The systems with a single V-LADRC (without P-LADRC) are stable, but multiple V-LADRCs may lead to instability. Low $\omega_{0,V}$ allowed stability in every cases. The instabilities do not occur when the dynamic loads (Tables 4.2 and 4.3) are replaced by constant impedances. Other tests made with $\alpha = \beta = 2$ and $D_{p,load} = D_{q,load} = 0$, which should have given the same results as with the constant impedances, also show the instabilities, which origin is therefore probably numerical. Specifically, the "dynamic load" blocks use an internal PLL which is likely to interact with the V-LADRCs dynamics. The stability observed when V-LADRC is applied to C1 and C3 is likely to be a coincidence, however more tests are necessary (e.g. with different converter parameters) to confirm this hypothesis.

Using both P-LADRC and V-LADRC with low ω_0 is safe in all the cases. Using multiple PV-LADRCs with high ω_0 leads to instabilities. Varying $\omega_{0,P}$ did not directly solve the issues, further confirming the numerical origin of the instabilities. However, the systems were still unstable even with constant impedances. In this case, decreasing $\omega_{0,P}$ from 3 [p.u.] to 1 [p.u.] allowed the systems to be stable.

4.2.2 System reaction to events with LADRCs

From the perspective of the TSO, GFM converters must improve grid stability compared to the present-day situation, in terms of frequency and voltage stability. Beyond theoretical considerations, the widespread use of LADRC as an additional control layer must be verified and justified operationally.

Inertial behavior of P-LADRC has already been studied in [15]. Behavior change of P-LADRC with the observer bandwidth $\omega_{0,P}$ has also been discussed in [41]. It is shown that it is possible to switch from a Grid-Forming behavior to Grid-Following by varying $\omega_{0,P}$. This has also been observed in this work (Sections 2.2 and 3.6).

From the point of view of the energy supplier (who operates the converter), using high bandwidth P-LADRC allows meeting the requirements while contributing less when facing to a frequency disturbance, in the first instants. The grid code effectively evaluates the inertia based only on a steady-state transient response (*frequency ramp method*) [15]. Consequently, using P-LADRC may be economically advantageous for the supplier.

For the TSO however, these first instants of the transient may be in practice very important in case of disturbance, thus the use of high bandwidth P-LADRC may be detrimental for the frequency stability. As discussed in [15], "the frequency ramp test may not be the best method to compare the inertia" [p.9]. Other metrics should probably be included in the next grid code evolutions.

Nevertheless, since frequency is a global variable, the possibility of switching between Grid-Following and Grid-Forming behaviors may justify the use of P-LADRC for the TSO. This is beneficial if an excessive use of pure GFM had consequences that could be avoided by bringing more Grid-Following behavior in the system [31]. For example, excessive inertia "reduces damping ratio, delays power adjustments and prolongs frequency recovery" [62, p. 2]. Then the dynamics of P-LADRC may be interesting as well from the TSO stance.

Regarding the V-LADRC, Section 3.6 showed that a single V-LADRC has nearly a Grid-Forming behavior whatever its observer bandwidth $\omega_{0,V}$. In Section 3.4.1, Q-LADRC voltage response to a disturbance led to its disqualification due to the Grid-Forming objectives. Since voltage is a local variable, it is likely that using Q-LADRC for a Grid-Following behavior on the voltage would not make sense. In Section 3.5, it has been calculated that interactions of the active power P on the voltage V is small for the considered controlled system. Moreover, in case of faults, Section 3.7 has shown that using V-LADRC with a high bandwidth $\omega_{0,V}$ may prevent the system from recovering by itself. Thus the interest of using V-LADRC in practice must still be evaluated.

In this last section, a prevalent use of LADRC is observed with the 9-bus grid model, with the aim of assessing its practical interest and possible interactions between the converters scattered in the grid (not concentrated like in Section 4.1). The parameters are the same as those previously used in this chapter. To avoid instabilities summarized in Table 4.4, and to keep consistent with previous results in Section 3.6, $\omega_{0,P} = \omega_{0,V} = 0.02$ [p.u.] = 6.28 [rad/s] have been considered for the cases of *low observer bandwidth*, and $\omega_{0,P} = \omega_{0,V} = 1$ [p.u.] = 314.15 [rad/s] have been considered for the cases of *high observer bandwidth*.

The scenario is the following: at time $t = 0$ [s], the 30 [km] line L46 opens at bus 6. At $t = 1$ [s], load A drops to $P = Q = 0$ [p.u.]. At $t = 2$ [s], line L46 reconnects.

LADRC on all the converters

First, all the converters (C1, C2 and C3) have been used with both P-LADRC and V-LADRC. Frequency is shown in Fig. 4.7. Because of the parametrization of the P-LADRC (with the external droop $\sigma_a = 40$, Fig. 3.7), all the converters with P-LADRC reached the steady-state operating point with an excessive frequency of 1.05 [p.u.] due to a slight imbalance in the load flow. Indeed with this configuration, P-LADRC with a high $\omega_{0,P}$ prioritizes power injection rather than frequency regulation (Grid-Following philosophy). An other interesting situation would be using a small value for σ_a , which would have led to prioritizing frequency regulation rather than power injection (Grid-Forming philosophy). In this case, the results would probably have been close to the pure GFM case, based on observations of [15].

In the cases with low $\omega_{0,P}$, the initial frequency value is also excessive, because $\omega_{0,P}$ has only been decreased from the high value once the system reached the steady state. However, the response to the events is similar to the case without LADRC.

Without P-LADRC, the VSG is on the contrary parametrized with $\sigma_p = 1/40$, meaning that the frequency regulation is prioritized over power injection (Grid-Forming philosophy). As can be seen, line disconnection ($t = 0$ [s]) and reconnection ($t = 2$ [s]) have few impact on the frequency. However the load disconnection ($t = 1$ [s]) significantly increases the frequency, as expected from the droop control of the converters. The power limiter along with LADRC dynamics is responsible for the progressive frequency drop at $t \approx 1.7$ [s].

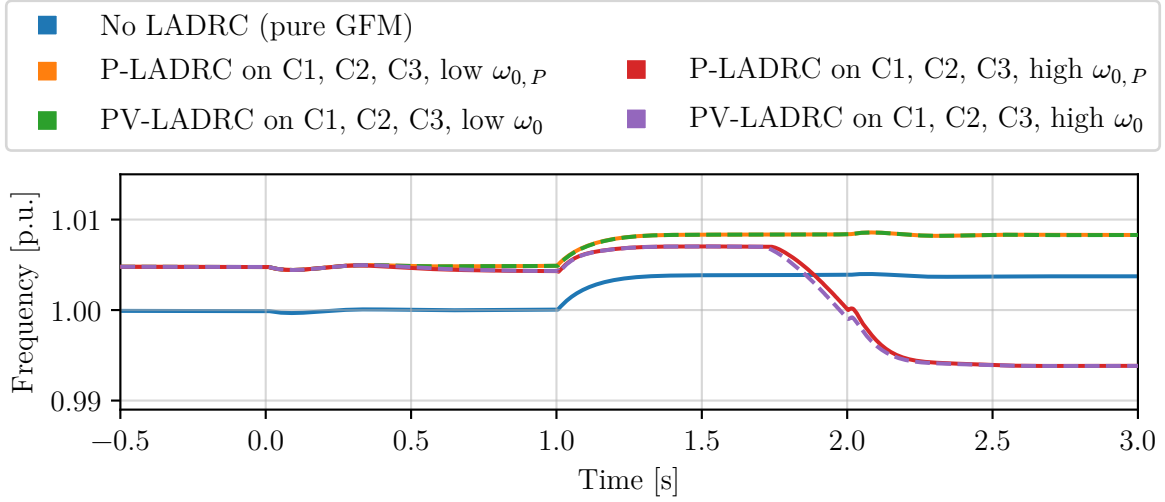


Figure 4.7: Frequency of the system. Using P-LADRC on all the converters leads to an excessive frequency in steady-state before the events, because of excessive droop coefficient σ_a on all the converters. Frequency is weakly disturbed with the line disconnection ($t = 0$ [s]). The load disconnection ($t = 1$ [s]) increases the frequency significantly. The power limiter along with LADRC dynamics is responsible for the progressive frequency drop at $t \approx 1.7$ [s]. Line reconnection ($t = 2$ [s]) weakly impacts the frequency.

LADRC on C1 and C2, low $\omega_{0,V}$

To analyze a more realistic situation where simple GFM converters would still remain in the grid, converter C3 will be left without LADRC (pure GFM) for the next results.

The detail of the three converters power is shown in Fig. 4.8. Powers and frequency are weakly disturbed by the line disconnection ($t = 0$ [s]). As for the previous analysis, the load disconnection ($t = 1$ [s]) increases the frequency significantly. It is interesting to see that the only pure GFM converter C3 decreases its power whereas it is the furthest source from the disconnected load. Leaving C3 without LADRC makes it act like a *slack source*: it adapts to the other sources to maintain the frequency near the desired value of 1 [p.u.], thanks to its low droop coefficient $\sigma_p = 1/40$ (Fig. 1.8). Converters C1 and C2 with high $\omega_{0,P}$ P-LADRC try to inject power as planned, due to high droop coefficient $\sigma_a = 40$ (Fig. 3.7). Line reconnection ($t = 2$ [s]) has a more significant impact on the powers than the disconnection near the nominal operating point. With low $\omega_{0,P}$ bandwidth, the responses are identical to the pure GFM case without LADRC, as expected from Section 3.6. No undesired interactions can be observed between the converters. After reacting to the events, power responses are quite slow, which is typical when using virtual inertia.

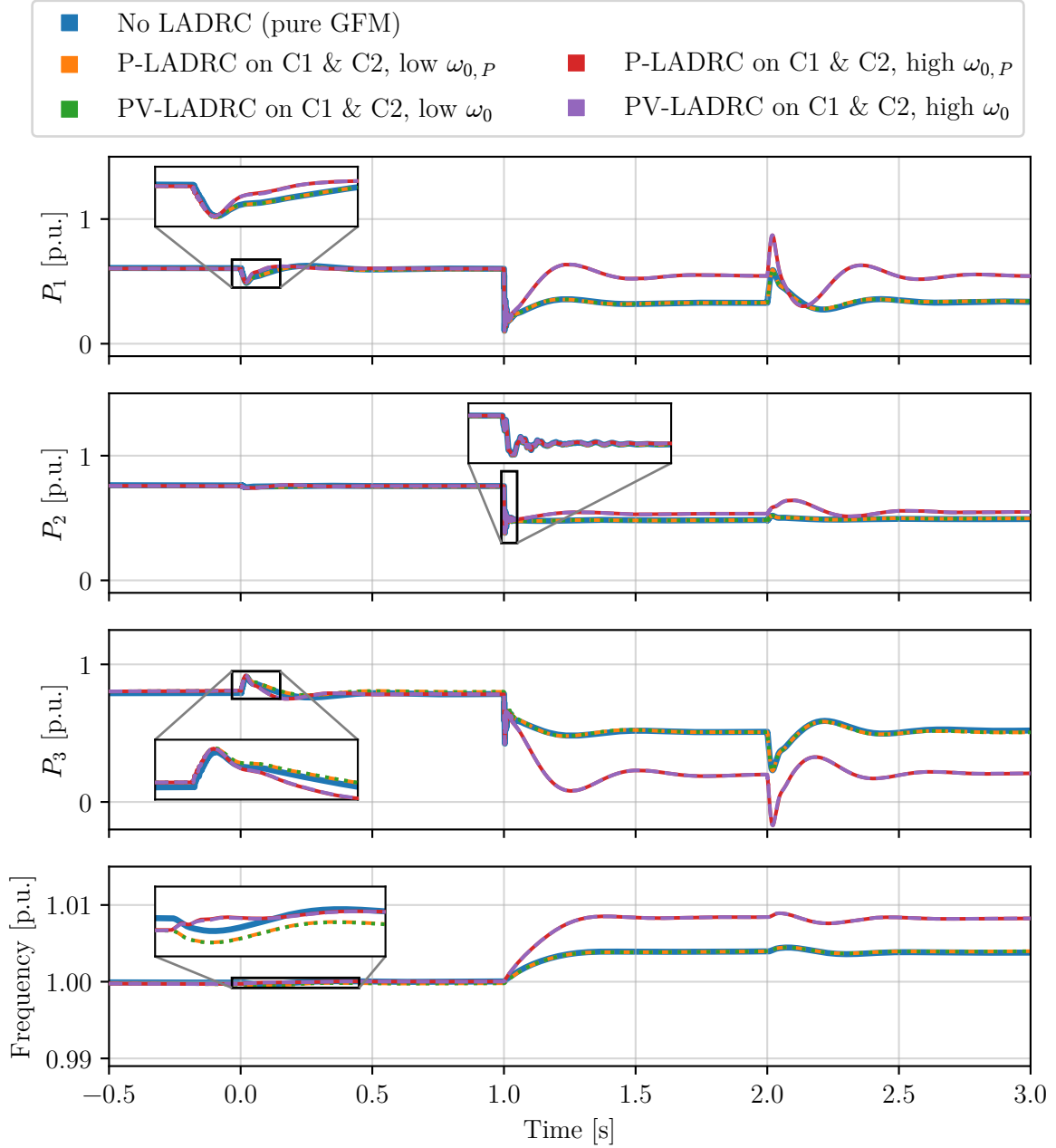


Figure 4.8: Power of converters C1, C2 and C3, and frequency of the system. Powers and frequency are weakly disturbed by the line disconnection ($t = 0$ [s]). The load disconnection ($t = 1$ [s]) increases the frequency significantly. Pure GFM converter C3 decreases its power whereas it is the furthest source from the disconnected load. Converters C1 and C2 with high $\omega_{0,P}$ P-LADRC try to inject power as planned, due to high droop coefficient σ_a . Line reconnection ($t = 2$ [s]) has a significant impact on the powers. With low $\omega_{0,P}$ bandwidth, the responses are identical to the pure GFM case without LADRC.

4.2. In-grid operation

High voltage magnitudes at buses 4, 7 and 9 (400 [kV] side of the transformers) are represented in Fig. 4.9. Line disconnection (at $t = 0$ [s]) and reconnection (at $t = 2$ [s]) lead to small high frequency oscillations and a change of operating point. V_4 increases, V_7 keeps stable, and V_9 decreases, which can be understood quite logically with Q - V droop controls of the converters: C1 near the bus 4 stops feeding reactive load B and C3 near the bus 9 must now feed reactive load B almost alone.

The sudden load disconnection ($t = 1$ [s]) resulted in high oscillations (between 0.8 [p.u.] and 1.8 [p.u.]) everywhere in the circuit. The operating point also changes, with significantly higher voltages in the system, due to lower currents flowing from the sources through the system impedances.

There is no significant difference in voltage response with or without LADRC (here with considering low $\omega_{0,V}$ only). It can be concluded that there are no undesired interactions between P-LADRC and V-LADRC, nor between the converters.

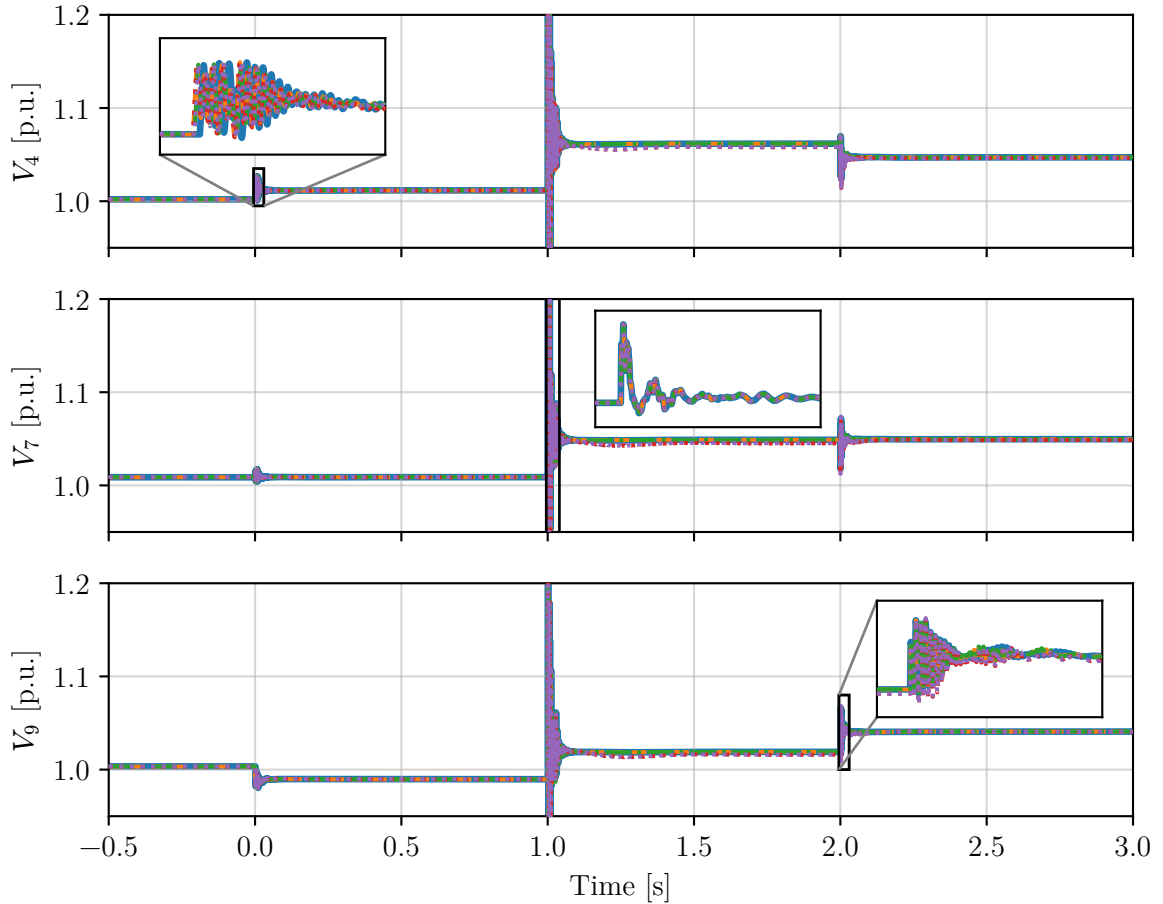


Figure 4.9: Voltage magnitude at the HV side of the transformers. Line disconnection ($t = 0$ [s]) and reconnection ($t = 2$ [s]) lead to small high frequency oscillations and a change of operating point. The sudden load disconnection ($t = 1$ [s]) resulted in high oscillations (between 0.8 [p.u.] and 1.8 [p.u.]). The operating point also changes, with significantly higher voltages in the system, due to lower currents flowing from the sources through the system impedances. There is no significant differences in voltage response with or without LADRC.

LADRC on all the converters, high $\omega_{0,V}$, constant impedance loads

Because of the numerical instability encountered with the dynamic loads (cf. Table 4.4), it has not been possible to include comparisons with high observer bandwidth $\omega_{0,V}$ V-LADRC in the previous results. For that reason and for the sake of completeness, the same scenario has been applied to the 9-bus system where dynamic loads have been replaced by constant impedances. For the next results, V-LADRC has been applied to all the converters (C1, C2, C3). No undesired effect of droop (like with P-LADRC) is expected, nor strong interactions between the converters because voltage is a local variable.

The detail of the three converters power is shown in Fig. 4.10. About the same responses to the events as the pure GFM case of Fig. 4.8 are observed. As expected from Sections 3.6, V-LADRC does not significantly impact the power response of the system.

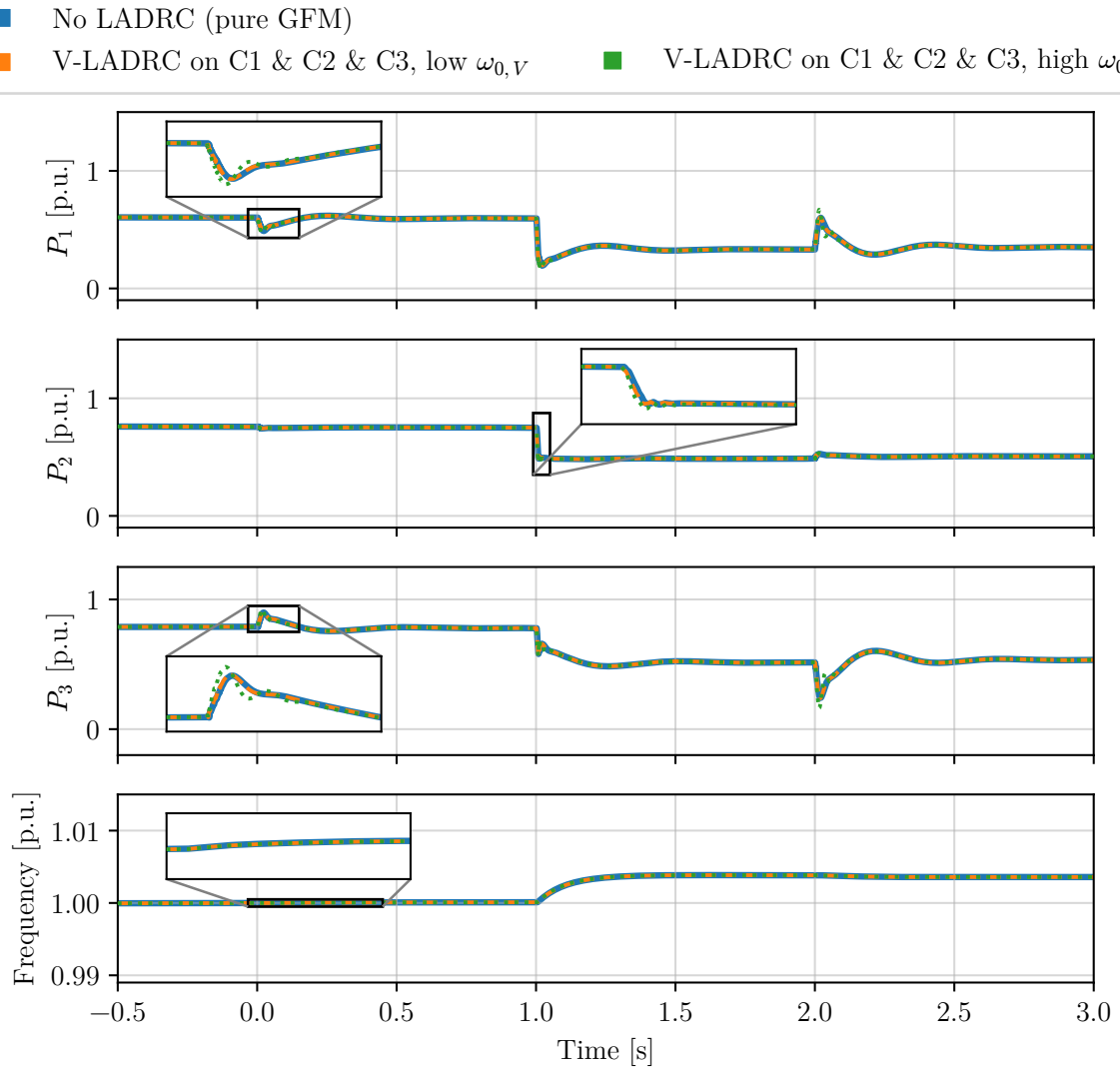


Figure 4.10: Power of converters C1, C2 and C3, and frequency of the system (with constant impedances as loads). The responses are similar to the case without LADRC with the dynamic loads (Fig. 4.8). V-LADRC does not significantly impact the power response of the system.

High voltage magnitudes at buses 4, 7 and 9 (400 [kV] side of the transformers) are represented in Fig. 4.11. The responses are similar to the case without LADRC with the dynamic loads (Fig. 4.9), except the high voltage peaks after the load disconnection ($t = 1$ [s]) that is here lower than 1.15 [p.u.]. Neither with a low nor a high observer bandwidth $\omega_{0,V}$, using V-LADRC does not significantly change the voltage response of the systems, that behaves similarly to the pure GFM system in both cases, as expected from Section 3.6. No undesired interactions are observed between the converters.

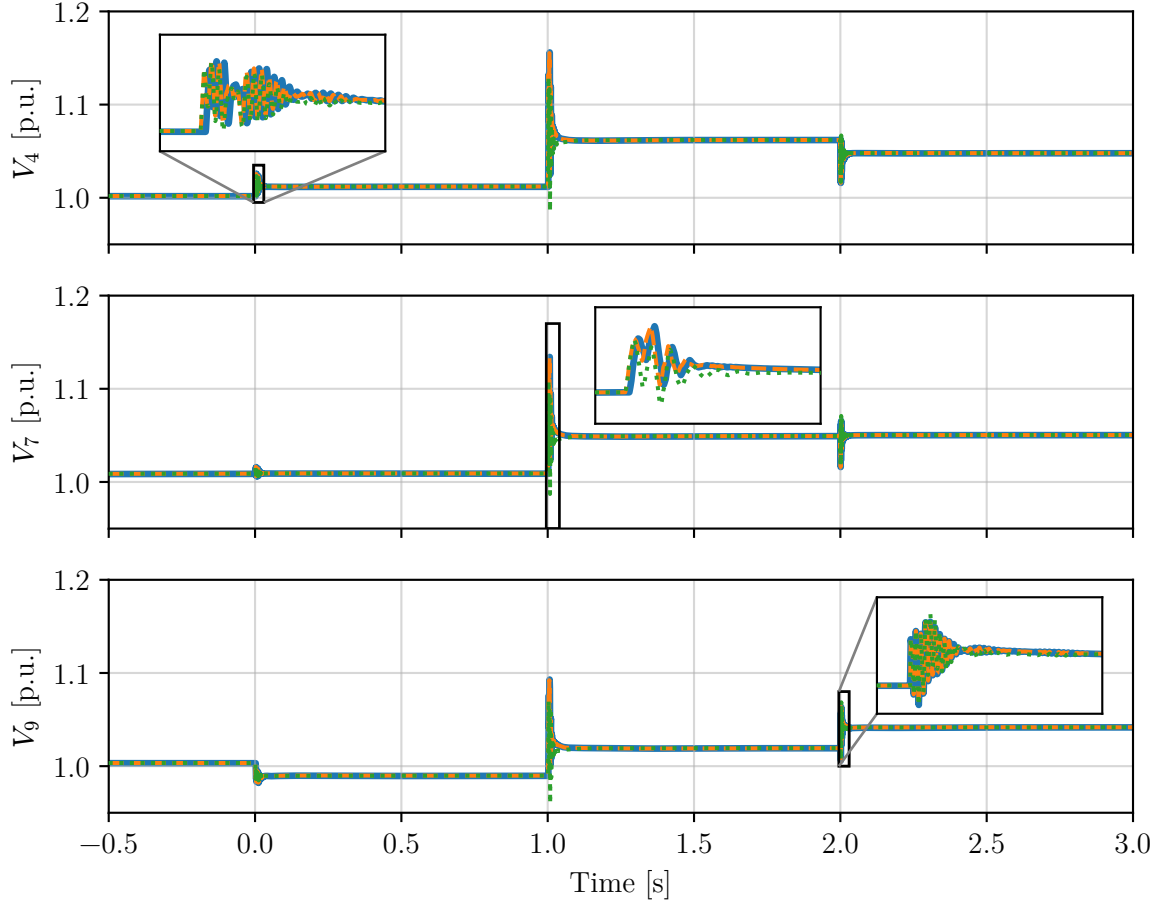


Figure 4.11: Voltage magnitude at the HV side of the transformers (with constant impedances as loads). The responses are similar to the case without LADRC with the dynamic loads (Fig. 4.9), except the high voltage peak after the load disconnection ($t = 1$ [s]) that is here much lower. V-LADRC does not significantly impact the power response of the system.

4.2.3 Conclusions on in-grid operations

A more advanced grid model with distributed parameters lines and dynamic loads has been considered, based on an adaptation of the IEEE 9-bus model for the European standards.

When using V-LADRC with a high observer bandwidth $\omega_{0,V}$, numerical instabilities occurred due to the dynamic loads. These instabilities disappeared when using constant impedances instead. When using both P-LADRC and V-LADRC, stability condition further requires to decrease the P-LADRC observer bandwidth $\omega_{0,P}$.

With these stability conditions being fulfilled, an example of scenario with classic events showed a proper system functioning, with no undesired interaction between P-LADRC and V-LADRC, or between the converters scattered in the grid.

By using P-LADRC with high $\omega_{0,P}$ and high external droop coefficient σ_a , the converter has more a Grid-Following behavior, as expected. This means that under these conditions, the frequency may be quite far from 1 [p.u.] when P-LADRC is applied to all the generators. By using at least one classic GFM without LADRC, this problem is solved because this converter acts like a slack source. No obvious benefit of using P-LADRC could be identified from the TSO's point of view thanks to this single example. More research is necessary to show whether the dynamics of P-LADRC with high $\omega_{0,P}$ could be useful from the perspective of the TSO relatively to events management.

As expected, using V-LADRC does not change the system response significantly, and the voltage behavior remains close to the one of the base Grid-Forming converter. With a high observer bandwidth $\omega_{0,V}$, V-LADRC seems more sensitive to high frequency disturbances (like numerical noise) than the base system. No benefit of using V-LADRC could be identified from the perspective of the TSO nor the operator thanks to this single example.

Conclusion

As shown in this work, using the LADRC provides more flexibility in the field of system control.

With a semi-analytical approach in frequency domain, it has been possible to confirm the correct operation of the control with two LADRCs in Chapter 2. Based on a simple first-order Two-Input Two-Output system (Section 2.1), it has been theoretically established that the observer bandwidth ω_0 is a key parameter to choose the behavior of the system. When applied to a simplified Grid-Forming control of converters (Section 2.2), using two LADRCs helped making the control independent from grid characteristics for a change of target, including the reduction of cross-coupling of the loops due to the resistive part of the lines.

After the Q - V loop design was discussed based on standards requirements, two ways of applying the second LADRC (Q-LADRC vs V-LADRC) have been presented in Chapter 3. Time-domain simulations and small-signal analyses allowed to make a choice, concluding that V-LADRC had stronger advantages in a Grid-Forming perspective. However, linearized system equations and time-domain simulations with the complete system showed that the voltage response with the base system (without V-LADRC) already met the Grid-Forming objectives. Moreover, simulations with a particular FRT solution showed that the system failed to recover by itself when V-LADRC is used with a high $\omega_{0,V}$, further questioning the practical usefulness of using V-LADRC.

Finally, particular situations with more realistic models have been analyzed in Chapter 4 to attempt to justify the use of a second LADRC for the Q - V loop. The use of two V-LADRCs with converters operating in parallel has been verified. Multiple V-LADRCs with converters scattered in a grid have been possible with constant impedance loads, but not with the dynamic load model, highlighting V-LADRC difficulties with high-frequency noise, when $\omega_{0,V}$ is high.

In conclusion, the opportunities offered by the P-LADRC are promising in the context of the energy transition. However, V-LADRC failed to demonstrate a significant advantage compared to the base Grid-Forming system, within the framework of the parameters and simplifying assumptions considered in this work (notably the model of the converter as a perfect three-phase voltage source).

Areas for further research and improvements

As a direct logical continuation of this research work, further study of the P-LADRC should be able to show interesting results on the common interests of suppliers and TSOs.

First, by including P-LADRC converters in a grid model (such as the adapted 9-bus model considered in this work), much more situations could be analyzed. In particular, varying the inertia and the damping coefficients of the converters and the other sources may provide key results. As explained in this work, adapting the observer bandwidth $\omega_{0,P}$ while considering a high external droop coefficient $\sigma_a \gg 1$ changes significantly the behavior of the converter. Further analyses can also be made regarding the operation of Grid-Forming converters in resistive grids (typically the distribution grid), based on results of Sections 2.2 and 3.6.

Second, if interest is more focused on the independence to the grid characteristics, the consideration of a low $\sigma_a \ll 1$ is likely to keep a Grid-Forming behavior while still using a high $\omega_{0,P}$, based on this work results.

Other combinations of controls and parameters can be deduced, and further research is necessary to confirm and study the potential interests of those, summarized in Table 4.5.

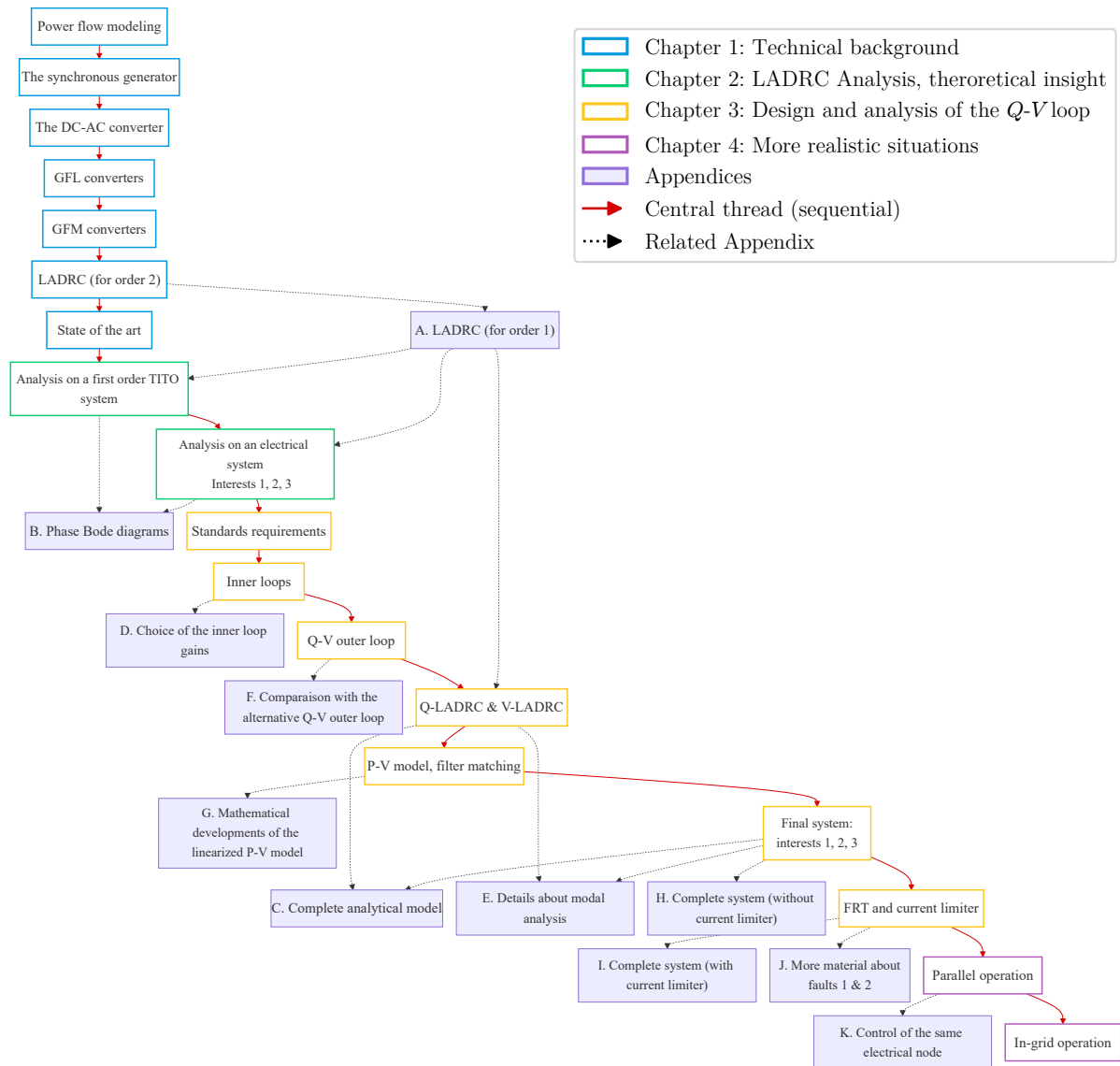
	Outer control	LADRC configuration	Behavior with low ω_0	Behavior with high ω_0
P - f loop	VSG Grid-Forming behavior	P-LADRC with $\sigma_a \gg 1$ Grid-Following philosophy (Sections 2.2, 3.6)	Grid-Forming	Grid-Following
		P-LADRC with $\sigma_a \ll 1$ Grid-Forming philosophy (Not encountered)	Grid-Forming	Grid-Forming
Q - V loop	Outer Q - V loop Grid-Forming behavior	V-LADRC with $\sigma_b \gg 1$ Grid-Following philosophy (Not encountered)	Grid-Forming	Grid-Following
		V-LADRC with $\sigma_b \ll 1$ Grid-Forming philosophy (Sections 3.4, 3.6)	Grid-Forming	Grid-Forming
		Q-LADRC with $\sigma_b \gg 1$ Grid-Following philosophy (Section 2.2)	Grid-Forming	Grid-Following
		Q-LADRC with $\sigma_b \ll 1$ Grid-Forming philosophy (Section 3.4)	Grid-Forming	Grid-Forming

Table 4.5: Summary of behaviors with LADRC, encountered in this work or logically deduced for the cases not encountered (further research is necessary for confirmation).

Third, using an LADRC on the Q - V loop may be justified if it enhances the control of the voltage in less ideal cases. For instance, it would be interesting to use V-LADRC on a detailed model of converter (instead of a perfect three-phase voltage source). Notably, the management of voltage harmonics by the LADRC would be intriguing.

Appendices

Numerous appendices have been proposed throughout this work. These are linked to the different sections as shown in the structure below.



A LADRC theory for a first-order system (second-order ESO)

If the GFM process is of the first-order instead of a second-order, the LADRC must be adapted (simplified). If not, the algorithm would try to estimate an inexistent second-order component and try to put all the divergence in the generalized disturbance, making the estimated first-order component not accurate.

Let us consider a first-order process $G(s)$ with a DC gain K and a time constant T . The Laplace equation is given by:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{Ts + 1} \quad (\text{A.1})$$

In time domain, the equation is written: $T\dot{y}(t) + y(t) = Ku(t)$ Let $b = \frac{K}{T}$ and let us add an input disturbance $d(t)$.

$$T\dot{y}(t) + y(t) = Tbu(t) + d(t) \quad (\text{A.2})$$

Let us split b into a known and unknown part $b = b_0 + \Delta b$, and isolate the first-order term:

$$\dot{y}(t) = \underbrace{-\frac{1}{T}y(t) + \frac{1}{T}d(t) + \Delta bu(t) + b_0u(t)}_{\text{generalized disturbance}} \quad (\text{A.3})$$

$$= f(t) + b_0u(t) \quad (\text{A.4})$$

The *Extended State Observer* (ESO) is designed to give estimations $\hat{x}_1 = \hat{y}(t)$ and $\hat{x}_2 = \hat{f}(t)$.

$$\begin{bmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} + \begin{bmatrix} b_0 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} (y(t) - \hat{x}_1(t)) \quad (\text{A.5})$$

$$= \underbrace{\begin{bmatrix} -l_1 & 1 \\ -l_2 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix}}_{A'} + \begin{bmatrix} b_0 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} y(t) \quad (\text{A.6})$$

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{bmatrix} \quad (\text{A.7})$$

With l_1, l_2 the observer gains (to be determined).

The stability of the system depends on matrix A' eigenvalues. Those are solutions of equation:

$$\det(s\mathbf{I} - \mathbf{A}') = 0 \quad (\text{A.8})$$

$$= s^2 + l_1s + l_2 \quad (\text{A.9})$$

It is common to design the ESO such that it has only one multiple pole ω_0 .

$$0 = s^2 + l_1 s + l_2 = (s + \omega_0)^2 = s^2 + 2\omega_0 s + \omega_0^2 \quad (\text{A.10})$$

By identification it is shown that a double pole $s_0 = -\omega_0$ is only possible with:

$$l_1 = 2\omega_0 \quad l_2 = \omega_0^2 \quad (\text{A.11})$$

The angular frequency ω_0 is named the *observer bandwidth*.

The process $G(s)$, from which the generalized disturbance estimated by the ESO $\hat{f} = \hat{x}_2$ is deduced, can now be controlled by a more classic P control, thanks to the state $\hat{y} = \hat{x}_1$ estimation.

Assuming a perfect ESO and b_0 of the process is known, the system response is:

$$\dot{y} = u_0 \quad (\text{A.12})$$

With the LADRC controller, the transfer function of the control loop becomes:

$$\frac{y}{y^{**}} = \frac{K_p}{s + K_p} = \frac{1}{\frac{1}{K_p}s + 1} \quad (\text{A.13})$$

Hence K_p gain can be chosen to have any desired second-order response with unity DC gain (which is not problematic from a control perspective). Time constant is $\tau = \frac{1}{K_p}$.

B Phase parts of the Bode plots

About Bode plot in phase

Although mathematically important, phase plots are not analyzed in this work. In open loop, phase plots with the amplitude plots are useful to assess the stability of the system (stability criterion based on *Gain Margin* (GM) and *Phase Margin* (PM)). In closed loop however, the phase plot mainly informs on the delay of the response. Regarding the presented interests, provided information is similar to the one brought by the amplitudes plots.

B.1 Phase parts of the Bode plots - Two-Input Two-Output system

Behavior change in function of the observer bandwidth ω_0

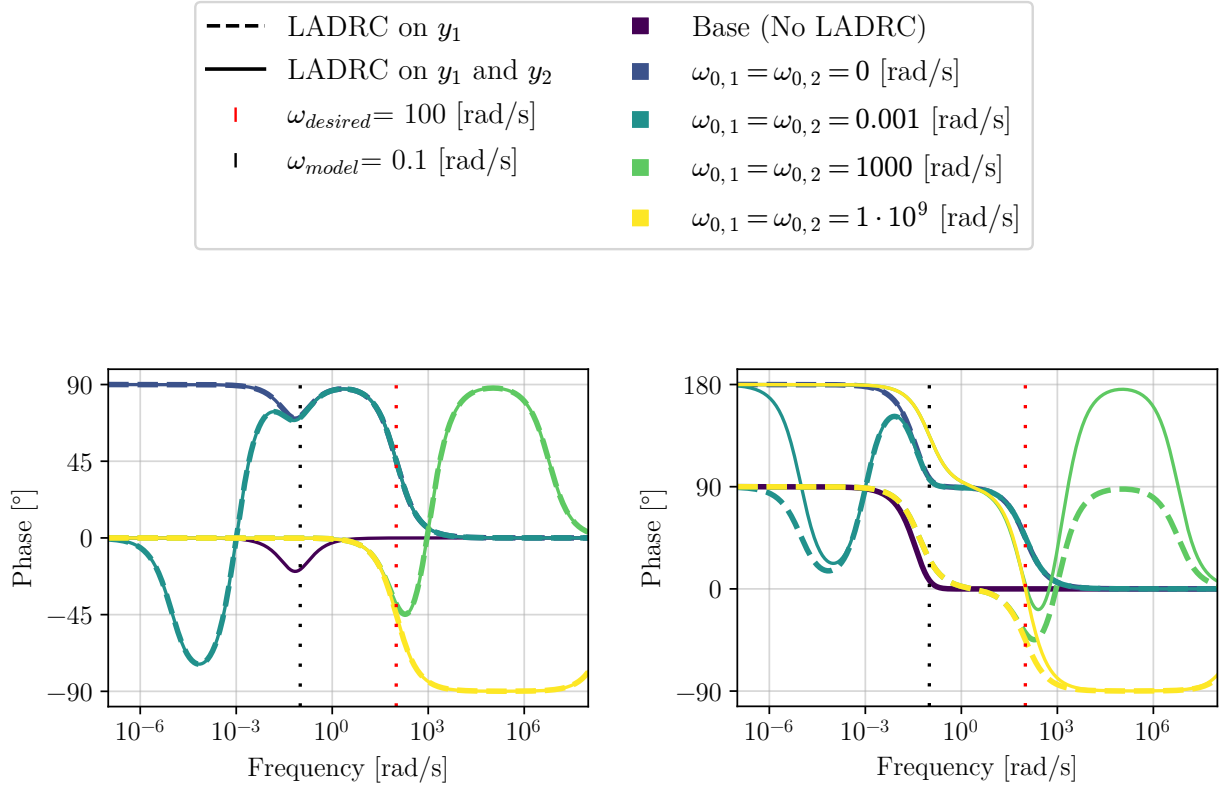


Figure B.1: Phase of dy_1/dy_1^{**} for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$.

Figure B.2: Phase of dy_2/dy_1^{**} for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$.

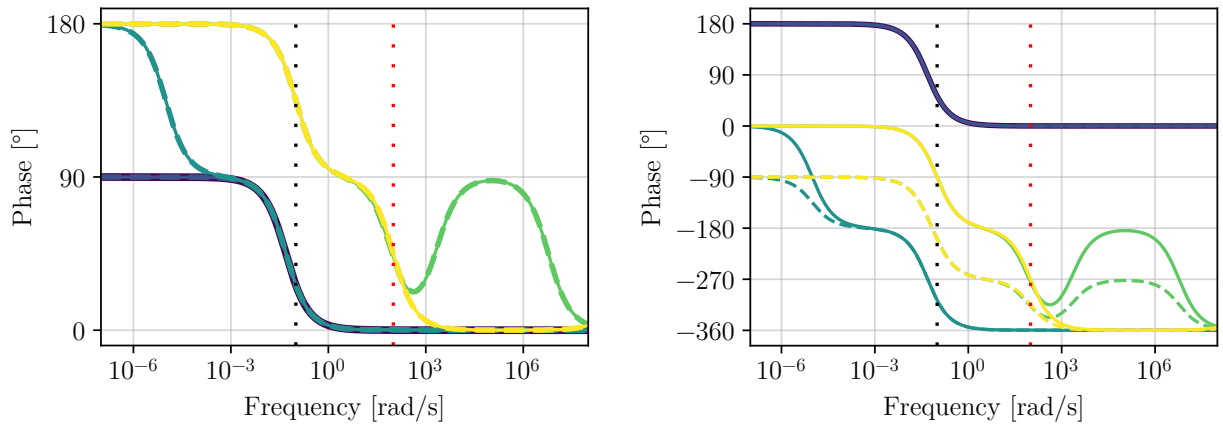


Figure B.3: Phase of $dy_1/\Delta du_1$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$.

Figure B.4: Phase of $dy_2/\Delta du_1$ for varying observers bandwidth $\omega_{0,1} = \omega_{0,2}$.

B.2 Phase parts of the Bode plots - Electrical P - δ and Q - V system

Interest 1: independence of the control to the grid characteristics

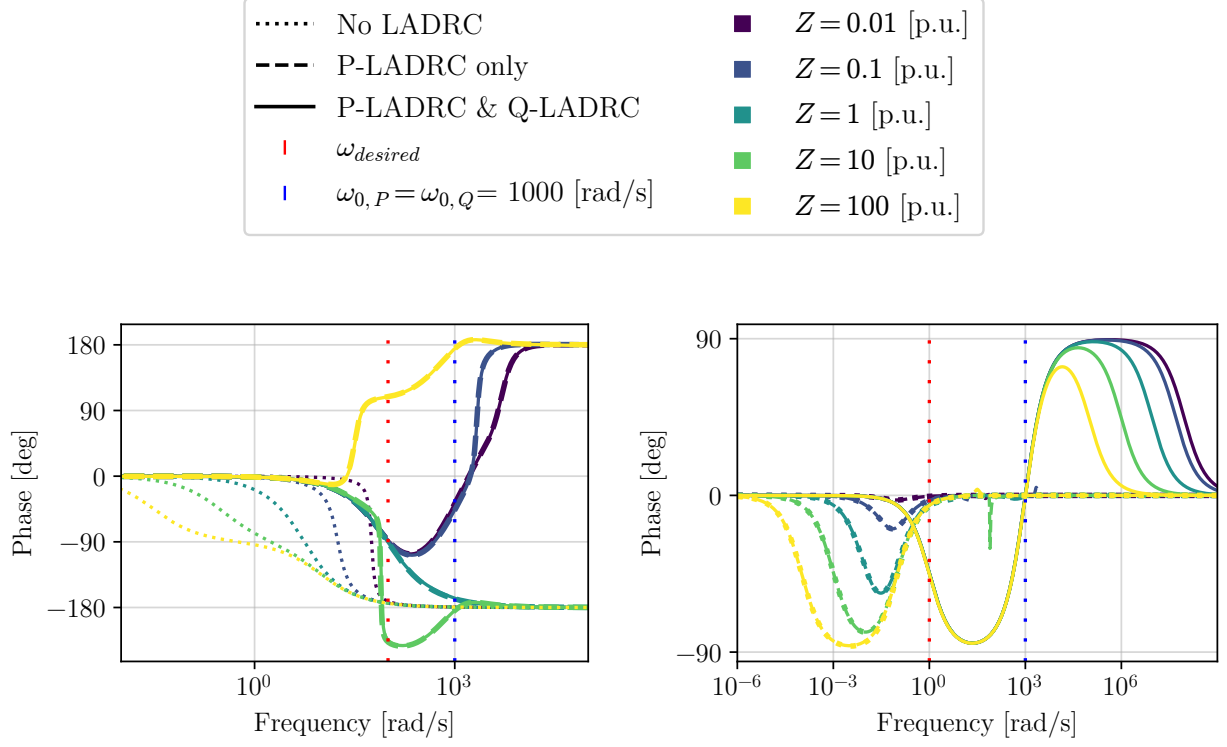


Figure B.5: Magnitude of dP/dP^{**} for varying grid impedance Z .

Figure B.6: Magnitude of dQ/dQ^{**} for varying grid impedance Z .

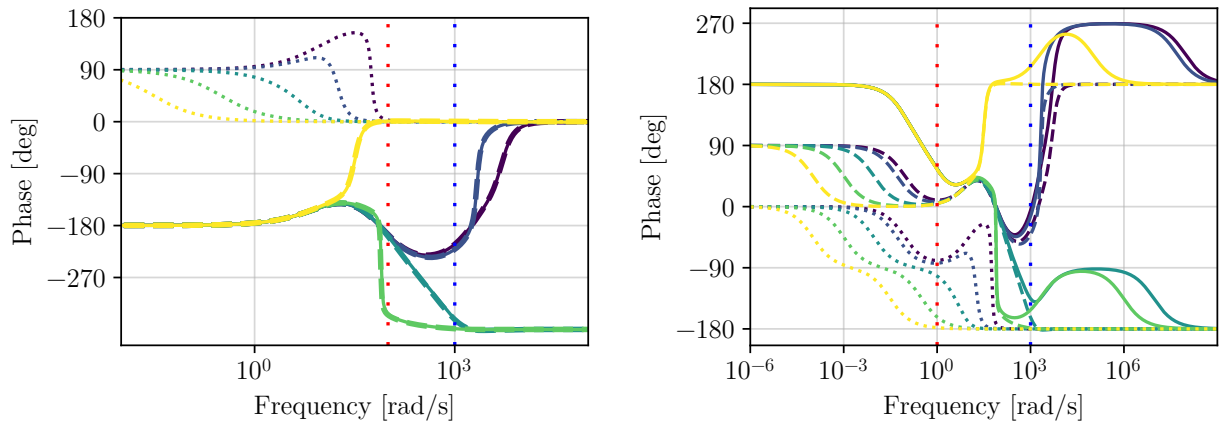


Figure B.7: Magnitude of $dP/d\Delta\delta$ for varying grid impedance Z .

Figure B.8: Magnitude of $dQ/d\Delta\delta$ for varying grid impedance Z .

Interest 2: behavior change in function of the observer bandwidth ω_0

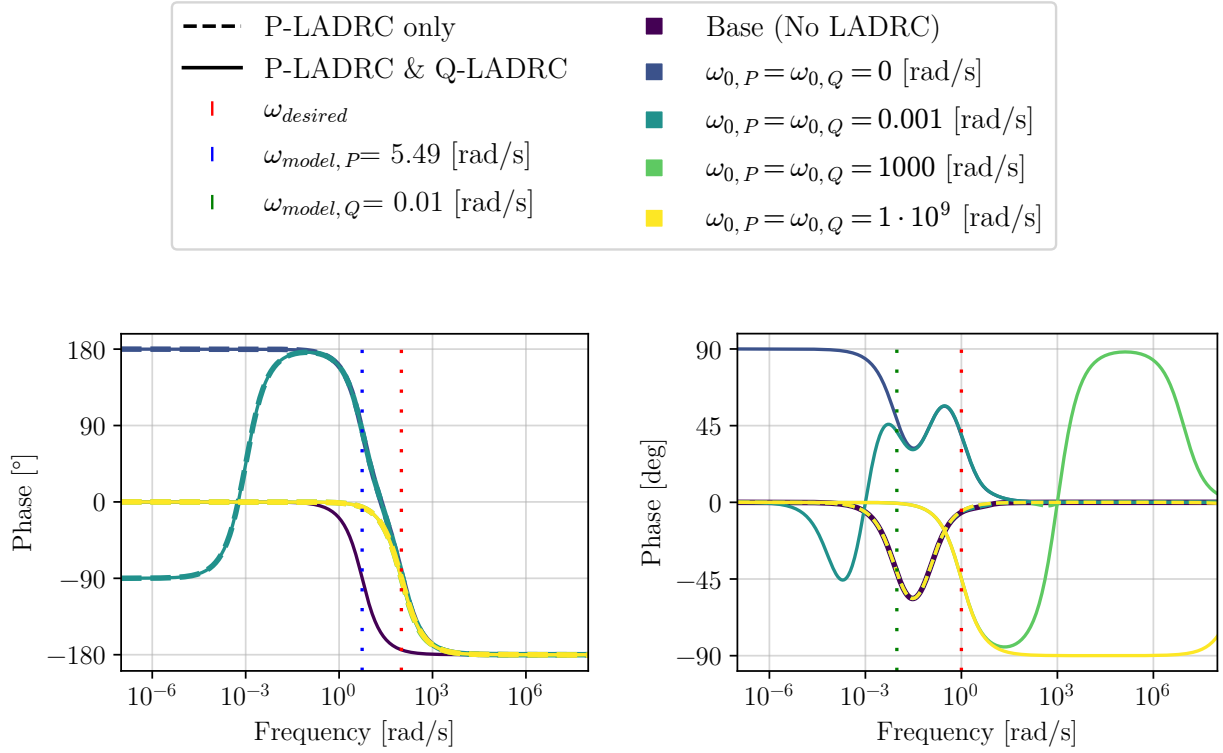


Figure B.9: Magnitude of dP/dP^{**} for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$.

Figure B.10: Magnitude of dQ/dQ^{**} for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$.

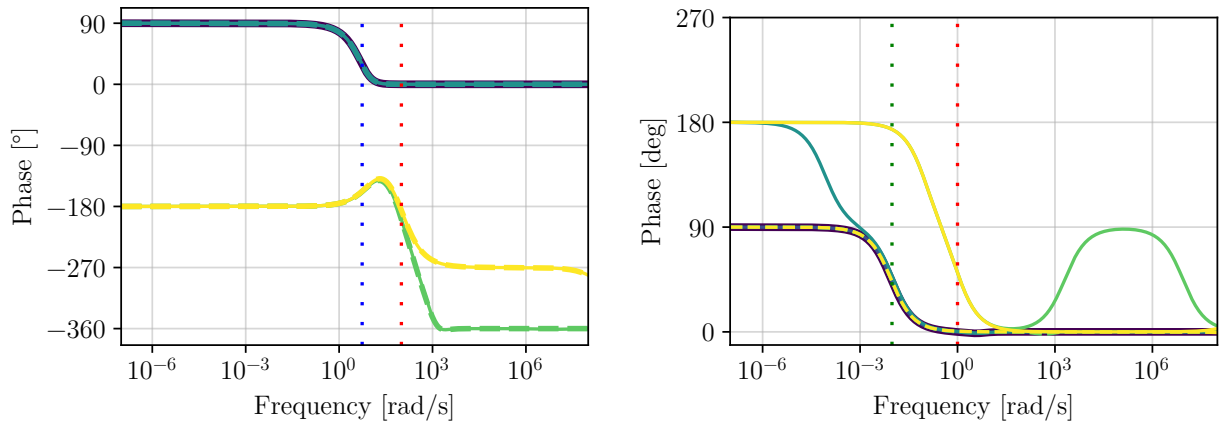


Figure B.11: Magnitude of $dP/d\Delta\delta$ for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$.

Figure B.12: Magnitude of $dQ/d\Delta\Delta V$ for varying observers bandwidth $\omega_{0,P} = \omega_{0,Q}$.

Interest 3: decoupling of the control loops

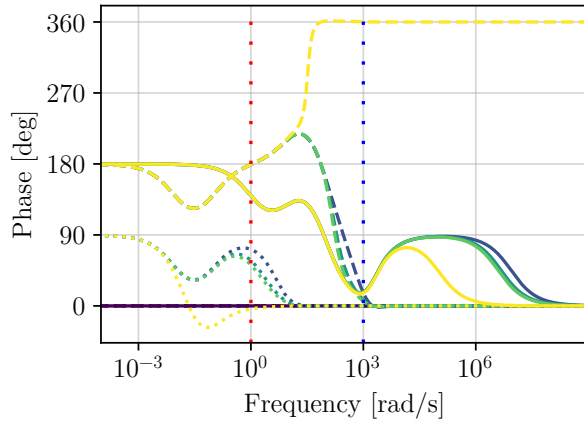
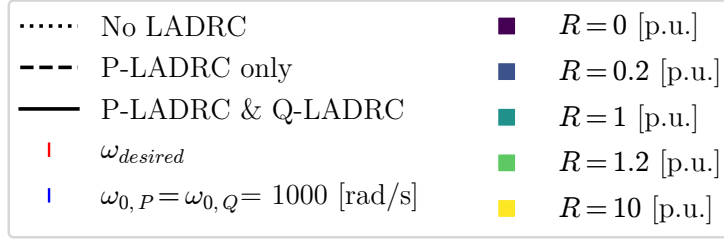


Figure B.13: Magnitude of dP/dQ^{**} for varying the resistive part R .

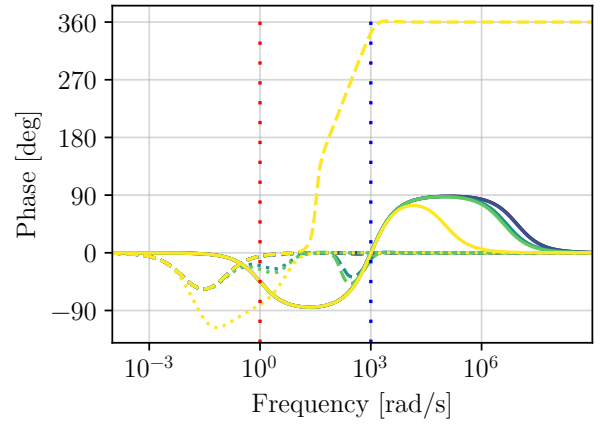


Figure B.14: Magnitude of dQ/dQ^{**} for varying the resistive part R .

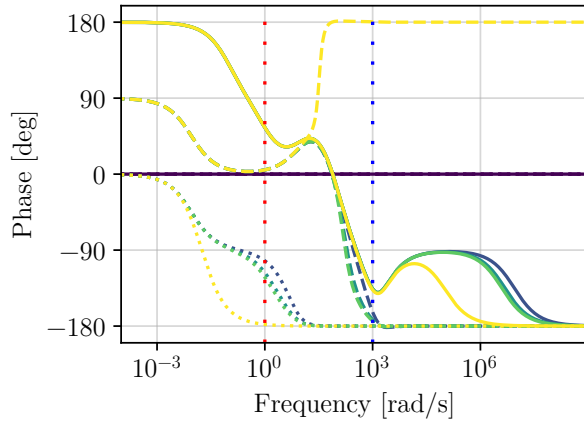


Figure B.15: Magnitude of $dQ/d\Delta\delta$ for varying the resistive part R .

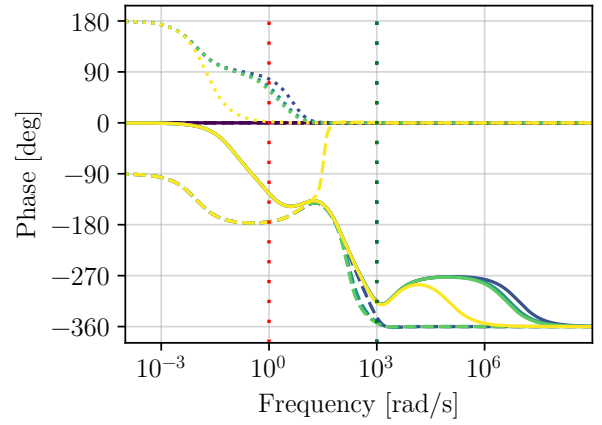


Figure B.16: Magnitude of $dP/d\Delta V$ for varying the resistive part R .

C Complete analytical model

1. VSG

$$\frac{d\omega_{GFM}}{dt} = \frac{1}{2H} \left(\frac{1}{\sigma_p} (\omega_n - \omega_{GFM}) + D (\omega_g - \omega_{GFM}) - P + P^* \right) \quad (C.1)$$

$$\frac{d\delta}{dt} = \omega_B (\omega_{GFM} - \omega_g) \quad (C.2)$$

2. Powers

$$P = V_{PCC,d} I_d + V_{PCC,q} I_q \quad (C.3)$$

$$Q = V_{PCC,q} I_d - V_{PCC,d} I_q \quad (C.4)$$

3. Filter and grid

$$\frac{dI_{c,d}}{dt} = \frac{\omega_B}{X_f} (V_{c,d} - V_{PCC,d} - R_f I_{c,d}) + \omega_{GFM} \omega_B I_{c,q} \quad (C.5)$$

$$\frac{dI_{c,q}}{dt} = \frac{\omega_B}{X_f} (V_{c,q} - V_{PCC,q} - R_f I_{c,q}) - \omega_{GFM} \omega_B I_{c,d} \quad (C.6)$$

$$\frac{dV_{PCC,d}}{dt} = \frac{\omega_B}{C_f} (I_{c,d} - I_d) + \omega_{GFM} \omega_B V_{PCC,q} \quad (C.7)$$

$$\frac{dV_{PCC,q}}{dt} = \frac{\omega_B}{C_f} (I_{c,q} - I_q) - \omega_{GFM} \omega_B V_{PCC,d} \quad (C.8)$$

$$\frac{dI_d}{dt} = \frac{\omega_B}{X_g} (V_{PCC,d} - V_{g,d} - R_g I_d) + \omega_{GFM} \omega_B I_q \quad (C.9)$$

$$\frac{dI_q}{dt} = \frac{\omega_B}{X_g} (V_{PCC,q} - V_{g,q} - R_g I_q) - \omega_{GFM} \omega_B I_d \quad (C.10)$$

4. Grid voltage in the converter frame

$$V_{g,d} = V_g \cdot \cos(-\delta) \quad (C.11)$$

$$V_{g,q} = V_g \cdot \sin(-\delta) \quad (C.12)$$

5. Q-V droop

$$\frac{dV_{ref,int,d}}{dt} = \frac{1}{\tau_f} (D_q (Q_{ref} - Q) - V_{ref,int,d} + V^*) \quad (C.13)$$

$$V_{ref,base,d} = V_{ref,int,d} \quad (C.14)$$

$$V_{ref,base,q} = 0 \quad (C.15)$$

6. Transient virtual resistance

$$\frac{dx_{v,d}}{dt} = \omega_v (R_v I_{c,d,meas} - x_{v,d}) \quad (C.16)$$

$$\frac{dx_{v,q}}{dt} = \omega_v (R_v I_{c,q,meas} - x_{v,q}) \quad (C.17)$$

$$\Delta V_{v,d} = R_v I_{c,d,meas} - x_{v,d} \quad (C.18)$$

$$\Delta V_{v,q} = R_v I_{c,q,meas} - x_{v,q} \quad (C.19)$$

$$V_{PCC,d,ref} = V_{ref,base,d} - \Delta V_{v,d} \quad (C.20)$$

$$V_{PCC,q,ref} = V_{ref,base,q} - \Delta V_{v,q} \quad (C.21)$$

7. Inner loops

$$\frac{di_{ref,int,d}}{dt} = k_{i,v} (V_{PCC,d,ref} - V_{PCC,d,meas}) \quad (C.22)$$

$$\frac{di_{ref,int,q}}{dt} = k_{i,v} (V_{PCC,q,ref} - V_{PCC,q,meas}) \quad (C.23)$$

$$I_{d,ref} = k_{p,v} (V_{PCC,d,ref} - V_{PCC,d,meas}) + i_{ref,int,d} + I_{d,meas} \quad (C.24)$$

$$I_{q,ref} = k_{p,v} (V_{PCC,q,ref} - V_{PCC,q,meas}) + i_{ref,int,q} + I_{q,meas} \quad (C.25)$$

$$\frac{dV_{int,d}}{dt} = k_{i,i} (I_{d,ref} - I_{c,d}) \quad (C.26)$$

$$\frac{dV_{int,q}}{dt} = k_{i,i} (I_{q,ref} - I_{c,q}) \quad (C.27)$$

$$V_{c,d} = k_{p,i} (I_{d,ref} - I_{c,d}) + V_{int,d} + V_{PCC,d,meas} - \omega_{GFM} X_f I_{c,q,meas} \quad (C.28)$$

$$V_{c,q} = k_{p,i} (I_{q,ref} - I_{c,q}) + V_{int,q} + V_{PCC,q,meas} + \omega_{GFM} X_f I_{c,d,meas} \quad (C.29)$$

8. Measurement filter

Impact of measurement delay has not been studied in this work and is hence considered very short.

In the Simulink implementation, measurement delay is simply ensured by a discrete delay block z^{-1} .

In the Python implementation, each measured quantity is filtered with a very fast first-order low-pass filter:

$$\frac{dy_{meas}}{dt} = \frac{1}{\tau_{meas}} (y - y_{meas}) \quad (C.30)$$

For $y \in (V_{PCC,d}, V_{PCC,q}, I_{c,d}, I_{c,q}, I_d, I_q)$

9. P-LADRC

$$\frac{d\hat{y}_P}{dt} = 3\omega_{0,P} (P - \hat{y}_P) + \hat{y}_P \quad (C.31)$$

$$\frac{d\hat{\dot{y}}_P}{dt} = 3\omega_{0,P}^2 (P - \hat{y}_P) + \hat{\dot{y}}_P + b_{0,P} P^* \quad (C.32)$$

$$\frac{d\hat{\ddot{y}}_P}{dt} = \omega_{0,P}^3 (P - \hat{y}_P) \quad (C.33)$$

$$P^* = \frac{1}{b_{0,P}} \left(K_{p,P}(P^{**} - \hat{y}_P) - K_{d,P}\hat{y}_P - \hat{d}_P \right) \quad (C.34)$$

$$P^{**} = P_{ref} + \frac{1}{\sigma_a}(\omega_n - \omega_{GFM}) \quad (C.35)$$

10. V-LADRC

$$\frac{d\hat{y}_V}{dt} = 2\omega_{0,V} (V_{PCC,d,meas} - \hat{y}_V) + \hat{d}_V + b_{0,V}V^* \quad (C.36)$$

$$\frac{d\hat{d}_V}{dt} = \omega_{0,V}^2 (V_{PCC,d,meas} - \hat{y}_V) \quad (C.37)$$

$$V^* = \frac{1}{b_{0,V}} \left(K_{p,V}(V^{**} - \hat{y}_V) - \hat{d}_V \right) \quad (C.38)$$

$$V^{**} = V_{PCC,ref} + \sigma_b(Q_{ref} - Q) \quad (C.39)$$

Variables:

ω_{GFM}, δ	frequency (p.u.) and angle [rad] generated by the VSG
H [s]	virtual inertia constant
D	damping coefficient
σ_p	P - f droop coefficient
$\omega_n = \omega_g = 1$ [p.u.]	nominal grid frequency
ω_B [rad/s]	base frequency ($=2\pi \cdot 50$ [rad/s])
P, Q [p.u.]	active and reactive power
P_{ref}, Q_{ref} [p.u.]	power set-points (reached in case of nominal frequency and voltage)
D_q	Q - V droop coefficient
τ_f [s]	Q - V droop low-pass filter time constant
X_f, R_f [p.u.]	reactance and resistance of the filter
C_f [s]	normalized capacitance of the filter
X_g, R_g [p.u.]	reactance and resistance of the grid
V_c [p.u.]	converter output voltage
V_{PCC} [p.u.]	voltage at PCC
$V_g = 1$ [p.u.]	infinite grid voltage
I_c [p.u.]	current flowing in the converter (and R_f, X_f)
I [p.u.]	current flowing through the grid
$k_{p,v}, k_{i,v}$	proportional and integral gains of the inner voltage loop
$k_{p,i}, k_{i,i}$	proportional and integral gains of the inner current loop
$i_{ref,int}, V_{int}$	state variables (integral parts) of inner loops
R_v [p.u.]	damping virtual resistance

C. Complete analytical model

ω_v [rad/s]	cutoff frequency of transient virtual resistance high-pass filter
x_v	state variable (integral part) of the transient virtual resistance high-pass filter
$\omega_{0,P}$	observer bandwidth of the P-LADRC ESO
$\hat{y}_P$	estimate of the active power by the P-LADRC ESO
$\hat{\dot{y}}_P$	estimate of the derivative of the active power by the P-LADRC ESO
$\hat{d}_P$	estimate of the disturbance of the active power by the P-LADRC ESO
P^*	main output of the P-LADRC controller, active power target for the VSG
P^{**}	main input of the P-LADRC controller, active power target
$b_{0,P}$	estimate of the internal loop for the active power
$K_{p,P}$ and $K_{d,P}$	proportional and derivative gains for the P-LADRC PD controller
σ_a	external droop coefficient for the frequency
$\omega_{0,V}$	observer bandwidth of the V-LADRC ESO
$\hat{y}_V$	estimate of the voltage by the V-LADRC ESO
$\hat{d}_V$	estimate of the disturbance of the voltage by the V-LADRC ESO
V^*	main output of the V-LADRC controller, voltage target for the Q - V loop
V^{**}	main input of the V-LADRC controller, voltage target
$V_{PCC,ref}$	reference voltage set-point
$b_{0,V}$	estimate of the internal loop for the voltage
$K_{p,V}$	proportional gain for the V-LADRC P controller
σ_b	external droop coefficient for the voltage

D Choice of the inner loops gains

Several solutions exist to determine gains for these controllers. The most classical method, that is used in this work, is to design the inner current loop with a fast time constant τ_i and to design the inner voltage loop with a slower time constant in order to avoid undesired interactions between the two cascaded loops. However as explained in Section 3.1, the inner voltage loop should be kept as fast as possible for a Grid-Forming converter. A typical choice is $\tau_{v,inner} = 10 \cdot \tau_i$. As proposed in [33] and [25], the inner current loop gains can be calculated to make a pole-zero canceling with the filter. The gains are then: $k_{p,i} = L_f/\tau_i$ and $k_{i,i} = R_f/\tau_i$. Then for the inner voltage, $k_{p,v} = 1$ is chosen for an instantaneous response (relevant in a fault-ride-through mode where integrators must be frozen for an anti-windup purpose). $k_{i,v} = k_{i,i}/10$ is chosen to make the inner voltage loop dynamics 10 times slower than the inner current loop.

Another possibility is to use an innovative algorithm derived in [49] to optimize small-signal stability for a large number of cases. A result comparison between this approach and the classical method is done in this section.

The entire system has been modeled and simulated in Matlab Simulink. With the theoretical equations of the considered system, a complete Python model has also been implemented. Such theoretical and simulation models allow cross-validating both the model and the implementation. The considered equations are summarized in Appendix C.

The proposed gains are: $k_{p,v} = 0.52$, $k_{i,v} = 1.16$, $k_{p,i} = 0.73$, $k_{i,i} = 1.19$, which are significantly different from the gains derived by the classical method: $k_{p,v} = 1$, $k_{i,v} = 3$, $k_{p,i} = 0.4775$, $k_{i,i} = 30$.

Both inner loops design methods are compared with an example of voltage response on a step of voltage target. The parameters are chosen to be generic, i.e. with an intermediate grid strength ($SCR = 2.5$) and an intermediate resistive part ($R = \frac{X}{5}$). Filter RL part time constant is matched with the grid impedance. Simulation parameters are summarized in Table 3.3.

As can be seen in Fig. D.1, simulation fits to theoretical computation, which cross-validates both the Simulink and Python model implementations. Small differences may be attributed to implementation-specific elements and numerical artifacts (for example, the small measurements delays are not implemented the same way).

Inner loops designed with the algorithm method of reference [49] lead to a smoother but slower response to a voltage step. Oppositely, the classical tuning method leads to a sharper but faster response on this generic example. In both cases, a small overshoot is observed. Since the inner loops are accompanied by an outer loop anyway and because the RfG requirements ask for a fast response, the classical method is selected for the rest of this work.

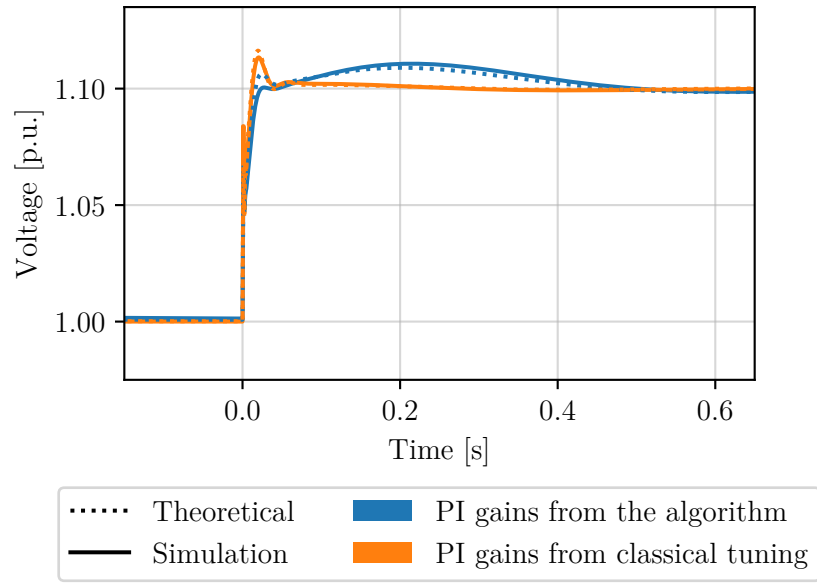


Figure D.1: Comparison of inner loops design methods on a generic example of a step of PCC voltage from 1 [p.u.] to 1.1 [p.u.]. Simulation fits to theoretical computation. Classical tuning method leads to a faster response and closer to a perfect step, compared to the algorithm method from [49].

E Details about modal analysis

The non-linear system can be written under the form: $\dot{\mathbf{X}} = \mathbf{f}(\mathbf{X})$ where $\mathbf{X}$ is the vector of state-space variables. The poles are found by computing the eigenvalues of the Jacobian matrix defined by $\mathbf{A} = \frac{d\mathbf{f}}{d\mathbf{X}}|_{\bar{\mathbf{X}}}$ where $\bar{\mathbf{X}}$ is the equilibrium steady-state operating point around which the system is linearized [16].

The whole system in dq Park's frame (whose equations has been written in appendix C), have 26 state-space variables:

$$\mathbf{X} = \left(\omega_{GFM}, \delta, I_{c,d}, I_{c,q}, V_{PCC,d}, V_{PCC,q}, I_d, I_q, V_{ref,int,d}, x_{v,d}, x_{v,q}, \right. \\ \left. \dot{i}_{ref,int,d}, \dot{i}_{ref,int,q}, V_{int,d}, V_{int,q}, V_{PCC,d,meas}, V_{PCC,q,meas}, \right. \\ \left. I_{c,d,meas}, I_{c,q,meas}, I_{d,meas}, I_{q,meas}, x_1, x_2, x_3, y_1, y_2 \right)^T \quad (\text{E.1})$$

Consequently, the system is represented by $\mathbf{f}: \mathbb{R}^{26} \rightarrow \mathbb{R}^{26}$ and the Jacobian matrix $\mathbf{A}$ has size 26×26 . Moreover, the system is *stiff*, because it uses both very fast dynamics (for quantity measurements) and relatively slow dynamics (e.g. for virtual inertia). Hence finding numerically the steady-state equilibrium point $\bar{\mathbf{X}}$ such that $\dot{\mathbf{X}} = \mathbf{f}(\bar{\mathbf{X}}) = 0$ is quite difficult. In practice, solving with `scipy.optimize.root()` gave hazardous results. Various methods have been tested, and some of them did not even converge. Method `broyden1` that *approximates* the Jacobian was empirically the best, but very often the residue $|\mathbf{f}(\bar{\mathbf{X}})|$ was still significantly higher than zero, which indicated an imperfect equilibrium point.

To enhance the accuracy of the modal analysis, another approach has been used to compute the eigenvalues. The equilibrium point and the Jacobian matrix have been found *exactly* by keeping the state-space variables symbolic, thanks to the *SimPy* package. The constant parameters have still been used numerically. By doing this way, the solving was less dependent on the difference in order of magnitude of time between the ODEs. Implementation has been realized thanks to generative IA, in accordance with the applicable rules and the declaration at the end of this work. This technique has been compared to the previous one, and gave the same results when the residue was already zero, which validates the implementation. Moreover, the occurrence of imperfect equilibrium points drastically decreased. Eigenvalues in imperfect case were closer to the expectations (logical evolution on parametric pole maps), confirming the robustness of the solution.

F Comparisons with the alternative Q - V outer loop

F.1 Alternative model: feedforward with filter on $Q^* - Q$ only

A stiffer response to a voltage target change may be achieved by applying the low-pass filter only on the reactive part linked to the droop control. When neglecting the droop part, voltage response would thus entirely rely on the inner loop dynamics. While it would be probably be inadvisable due to the risks of overvoltage seen in Fig. 3.5, it might however be interesting when used with LADRC. However this possibility has not been adopted since it has been observed that a slight low-pass filter on the voltage target is useful to reject high frequency oscillations with LADRC. The entire comparison with the model used in this work can be found in this section.

In this case, the *Model 2: feedforward with filter on $Q^* - Q$ only* outer Q - V loop equation is written:

$$V_{ref,d} = V_{PCC,d}^* + \frac{1}{\tau_f s + 1} D_q(Q^* - Q) \quad (\text{F.1})$$

Assuming the inner loops ideal (i.e. V_{PCC} is perfectly reached immediately), and by denoting $K_{grid} = \frac{X_g}{R_g^2 + X_g^2}$, the small signal closed-loop transfer function is:

$$\frac{dV_{PCC,d}}{dV_{ref,d}}(s) = \frac{\tau_f s + 1}{\tau_f s + D_q K_{grid} + 1} \quad (\text{F.2})$$

$$\approx 1 \quad (\text{F.3})$$

The action on the voltage is direct (in fact when D_q is small, it relies entirely on inner loops response, here neglected).

F.2 How to choose the suitable model between both Q - V outer loops ?

Comparison of both models is made on both theoretical (transfer functions neglecting inner loops) and simulation (complete system in Matlab Simulink) models, based on an intermediate case whose parameters are shown in Table 3.3. The example is chosen to be generic, i.e. with an intermediate grid strength ($SCR = 2.5$) and an intermediate resistive part ($R = \frac{X}{5}$). Filter RL part time constant is matched with the grid impedance. For both Q - V outer loops, a time constant $\tau_v = 0.02$ [s] has been considered, in accordance to the standard requirements (Section 3.1).

Responses of both models on a step of target voltage are shown in Fig. F.1. The model 2 (feedforward with filter on $Q^* - Q$ only) response corresponds, as expected, to the inner loops response previously shown in Fig. 3.5. The model 1 has dynamics slower than the inner loops, hence those latter have few impact on the response and can legitimately be considered as quasi-instantaneous.

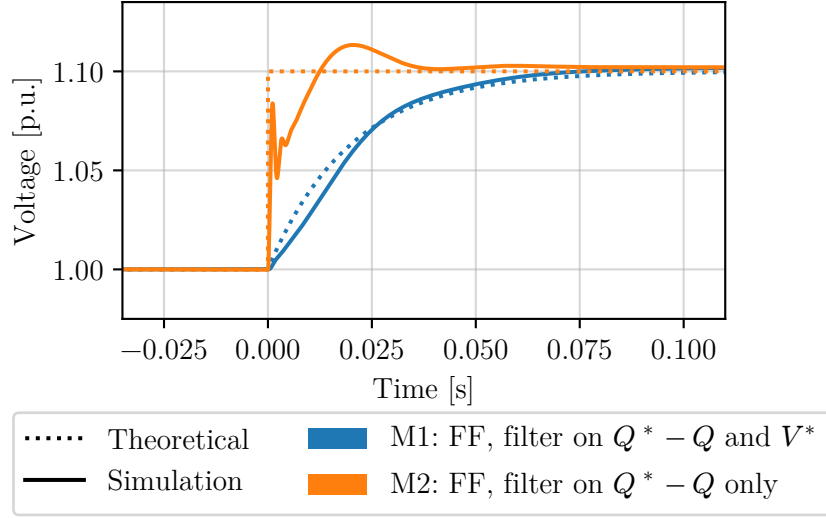


Figure F.1: Comparison of both Q - V outer loop models response on a step of voltage target from 1 [p.u.] to 1.1 [p.u.]. Model 1 (feedforward with filter on $Q^* - Q$ and V^*) is few impacted by inner loops dynamics. Model 2 (feedforward with filter on $Q^* - Q$ only) response is not ideal and corresponds to the inner loops dynamics.

In conclusion to this section, several possibilities exist to design the GFM Q - V outer loop. Two models have been derived.

The model 2 (feedforward with filter on $Q^* - Q$ only) has the fastest response, but it relies entirely on the inner loops dynamics, which includes a high dependency on grid characteristics and may lead to a voltage overshoot that may be problematic. Model 1 (feedforward with filter on $Q^* - Q$ and V^*) leads to an intermediately fast first-order response.

The results must however be nuanced, because standards requirements (Section 3.1) state that in practice, the TSO must ask for a rate-limited ramp for the voltage response to a change of target. Hence response on a voltage target step is not the only relevant information, and it can easily be imagined that the two remaining models will give about the same response on such a slow ramp. Hence the choice between models 1 and 2 must be made regarding other factors, for example the behavior with LADRC.

F.3 Q -LADRC vs V -LADRC, time domain comparison

When V -LADRC on model 2 is considered, gain b cannot be identified in Eq F.3 due to the ideal inner-loops assumption. Hence because the inner current loop can be considered fast and because a first-order internal model is expected, the inverse of the voltage inner-loop time constant is considered: $b_{V,4} = \frac{1}{10 \cdot \tau_i} = 100$. When V -LADRC on model 1 is considered, gain b can be identified in (3.3): $b_{V,3} = \frac{1}{\tau_f}$. However, since $\tau_f \ll \tau_{v,inner}$, the filter dynamics can be considered quasi-instantaneous compared to the voltage inner loop speed. Hence $b_{V,3} = b_{V,4} = 100$ is also considered. When Q -LADRC is considered, the gain b must instead be identified in the transfer function related to the Q

response. For models 1 and 2, it can be calculated²:

$$\frac{\partial Q}{\partial Q^*}(s) = \frac{\frac{K_{grid}D_q}{1 + K_{grid}D_q}}{\frac{\tau_f}{1 + K_{grid}D_q}s + 1} \quad (\text{F.4})$$

Where $K_{grid} = \frac{X_g}{R_g^2 + X_g^2} \approx \frac{1}{X_g}$.

Hence it can be identified: $b_Q = \frac{K_{grid}D_q}{\tau_f} = \frac{X_g}{R_g^2 + X_g^2} \frac{D_q}{\tau_f} \approx \frac{D_q}{X_g\tau_f}$.

In Fig. F.2 are compared the responses of PCC voltage to a step of voltage target from 1 [p.u.] to 1.1 [p.u.], with Q-LADRC or V-LADRC, and applied to Q - V outer loop model 1 (*FF, filter on $Q^* - Q$ and V^**) or model 2 (*FF, filter on $Q^* - Q$ only*). Since in steady-state $V_{PCC} > V_g$, the converter will produce reactive power Q . Thus because of the droop control, the new operating point is expected lower than 1.1 [p.u.].

Simulation results fit to theoretical computations, which cross-validates both the Simulink and Python model implementations. Small differences may be attributed to implementation-specific elements and numerical artifacts. The different responses are close to the desired response, though they are slower. Increasing Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$ may help reducing this error. Responses with Q-LADRC are identical either with model 1 (*FF, filter on $Q^* - Q$ and V^**) or model 2 (*FF, filter on $Q^* - Q$ only*), which was expected because V^* remains constant, so filtering have few effect. Q-LADRC responses seems generally more oscillating than V-LADRC responses. But V-LADRC responses shows more oscillations at the beginning of the step. These oscillations are more severe on model 2 than on model 1, due to the absence of the filter.

²Eq. (F.4) does not depend on the filter impedance Z_f because the considered reactive power Q is the one flowing through the grid equivalent impedance at the PCC level.

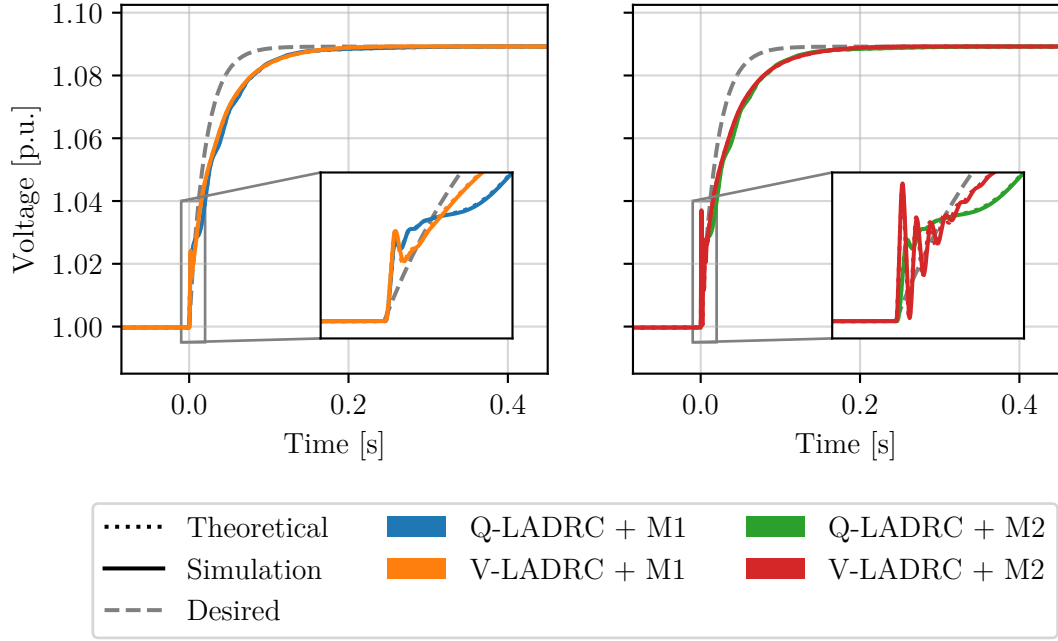


Figure F.2: Comparison of PCC voltage response to a step of voltage target from 1 [p.u.] to 1.1 [p.u.], with Q-LADRC or V-LADRC, applied to Q - V outer loop model 1 (FF , filter on $Q^* - Q$ and V^*) or model 2 (FF , filter on $Q^* - Q$ only). Q-LADRC responses are farther from the desired response than V-LADRC responses. V-LADRC responses shows a little jump at the beginning, with extra oscillations without filter on the V^* (model 2).

Comparing responses on a step of voltage target was interesting to observe the dynamics of the systems. However, it is not the most relevant situation in practice because as mentioned earlier, the TSO should ask for a slow rate-limited ramp as target. Hence it is also interesting to compare the behavior of the various systems when facing a grid disturbance.

In Fig. F.3 are compared the responses of PCC voltage to a grid voltage drop, here modeled by a step of infinite grid voltage V_g from the nominal 1 [p.u.] to 0.66 [p.u.]. Since in steady-state $V_{PCC} > V_g$, the converter will produce reactive power Q . Thus because of the droop control, the new operating point is expected lower than 1 [p.u.].

The previous comments regarding the systems dynamics for the case of a step of target also apply in this situation. However, it can be seen that the voltage converges much slower to the new operating point with Q-LADRC than with V-LADRC.

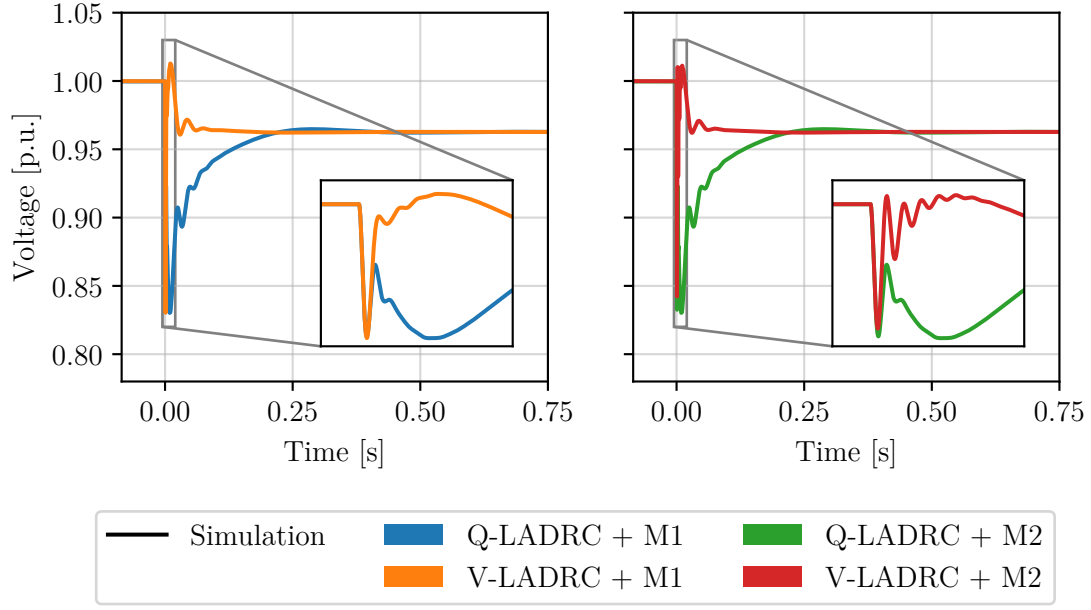


Figure F.3: Comparison of PCC voltage response to a grid voltage drop (V_g step from 1 [p.u.] to 0.66 [p.u.]), with Q-LADRC or V-LADRC, applied to Q - V outer loop model 1 (FF , filter on $Q^* - Q$ and V^*) or model 2 (FF , filter on $Q^* - Q$ only). Voltage drops instantaneously then recovers quickly. V-LADRC responses stabilize faster to the new operational voltage point. Extra oscillations are shown with V-LADRC without filter on V^* (model 2).

F.4 Q-LADRC vs V-LADRC, small-signal stability

Another way to observe the dynamics of the systems is to analyze their stability, which is also an important criterion that may help with the decision to use Q-LADRC or V-LADRC with model 1 (FF , filter on $Q^* - Q$ and V^*) or model 2 (FF , filter on $Q^* - Q$ only).

In Fig. F.4 are represented the pole maps for varying the Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$. The results confirm the observations in time domain: Q-LADRC systems have weakly attenuated low-frequency oscillations, while V-LADRC systems have high-frequency oscillations. When the observer bandwidth $\omega_{0,V}$ increases, these high-frequency oscillations are less and less attenuated, until the system becomes unstable. High-frequency oscillations with V-LADRC are stronger with the model 2 outer loop (FF , filter on $Q^* - Q$ only) than with the model 1 outer loop (FF , filter on $Q^* - Q$ and V^*) with the same observer bandwidth $\omega_{0,V}$.

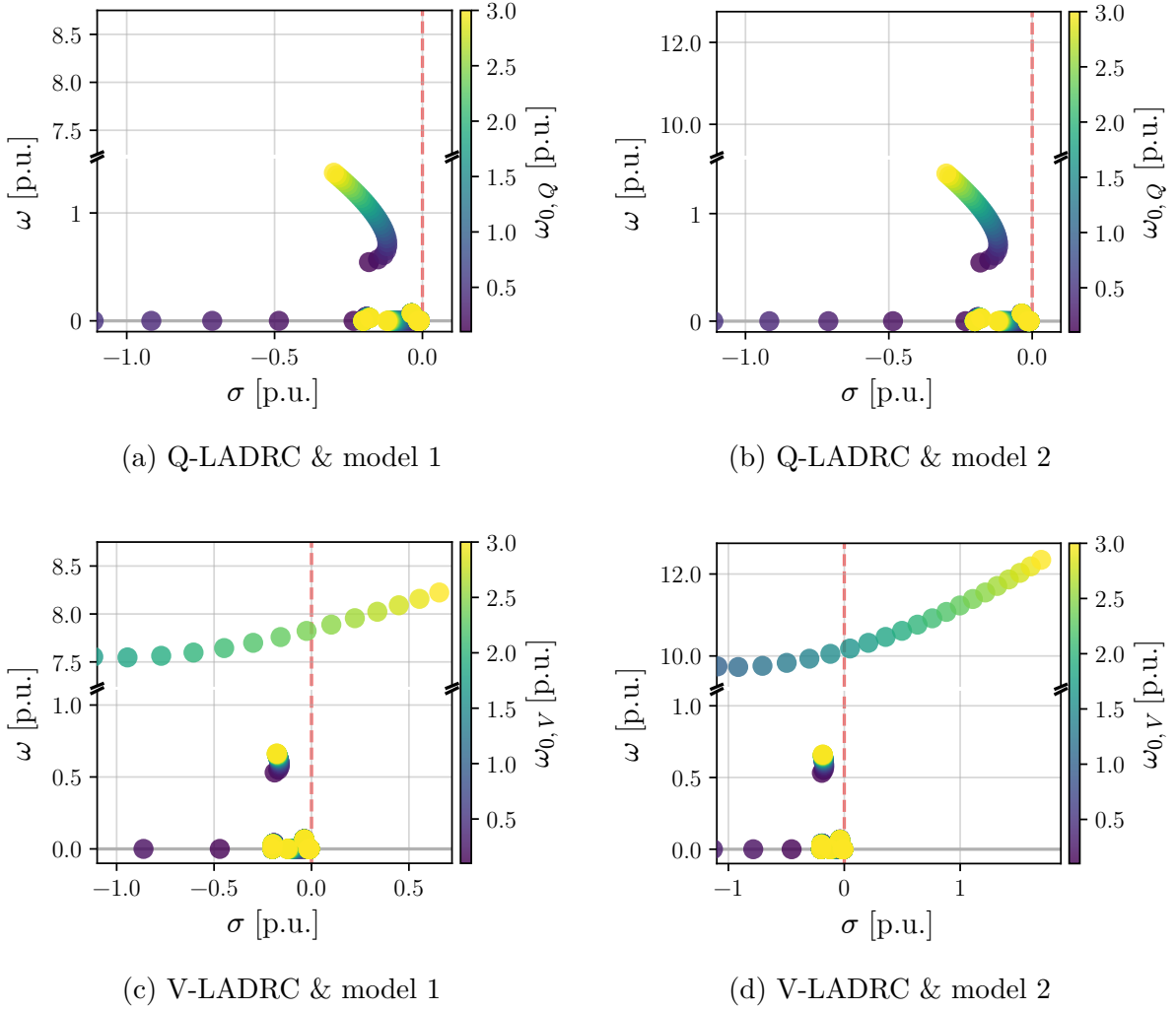


Figure F.4: Pole map with Q- or V-LADRC on models 1 (*FF, filter on $Q^* - Q$ and V^**) or 2 (*FF, filter on $Q^* - Q$ only*) of Q-V outer loop. Parametric small-signal stability analysis for varying the Q- or V-LADRC observer bandwidth $\omega_{0,Q}$ or $\omega_{0,V}$. Using V-LADRC may lead to high frequency oscillations and instability when $\omega_{0,V}$ is too high.

In Fig. F.5 are represented the pole maps for varying the low-pass filter time constant τ_f of the outer loops model 1 (*FF, filter on $Q^* - Q$ and V^**) or model 2 (*FF, filter on $Q^* - Q$ only*). For the time-domain example, $\tau_f = 0.001$ [s] was considered short compared to the voltage inner loop time constant ($\tau_{v,inner} = 0.01$ [s]), hence LADRC have been parametrized by considering that the estimated state was linked to the first order voltage inner loop. When this approximation is not true anymore (i.e. when $\tau_f \not\ll \tau_{v,inner}$), the LADRC must be parametrized by considering that the estimated state is mostly linked to the integral part of the first-order filter. Hence for this parametric analysis, a global $\tau = \tau_f + \tau_{v,inner}$ has been considered when computing the K_P and b_0 gains of the LADRC.

With Q-LADRC on models 1 or 2, the low-frequency oscillation is less and less attenuated when increasing the filter time constant τ_f , until the system becomes unstable when τ_f is too long. With V-LADRC on model 1 (*FF, filter on $Q^* - Q$ and V^**), this effect also exists but is less pronounced. With V-LADRC on model 2 (*FF, filter on $Q^* - Q$ only*), this oscillation is not affected by τ_f . However, the poles at $\omega = 0$ vary more with

τ_f than in the other cases, which still indicates that the time domain response may vary significantly with τ_f .

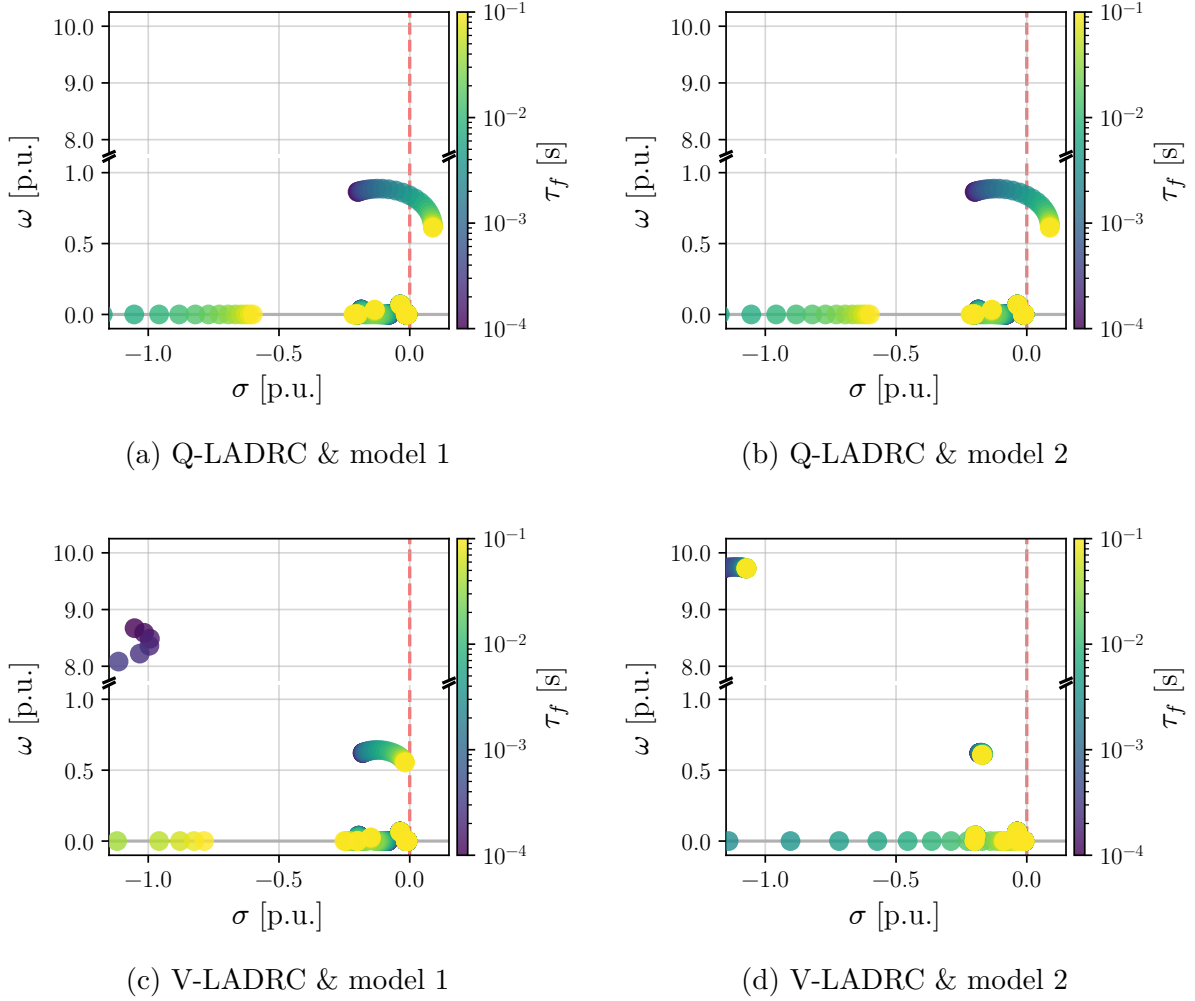


Figure F.5: Pole map with Q- or V-LADRC on models 1 (*FF, filter on $Q^* - Q$ and V^**) or 2 (*FF, filter on $Q^* - Q$ only*) of Q - V outer loop. Parametric small-signal stability analysis for varying the outer loop filter time constant τ_f . Except by using V-LADRC with model 2, weakly damped oscillations or instability may occur with Q-LADRC or V-LADRC when the filter dynamics is too slow.

In Fig. F.6 are represented the pole maps for varying the external droop coefficient σ_b . As expected, the ability of the system with Q-LADRC to regulate the voltage strongly depends on σ_b . This coefficient should be *small* such that the voltage remains near the target whatever the reactive power Q (Grid-Forming objective). However as can be seen, when σ_b is decreasing, a high-frequency oscillation is less and less attenuated, until the system becomes unstable when σ_b is too small. Referring to the block schematic (Fig. 3.8), the feedback on the voltage is proportional to $1/\sigma_b$. Thus when this amplification is too extreme, the control becomes unstable. This problem does not occur with V-LADRC: the regulation of the voltage does not rely on σ_b , because the external droop is only there to deviate slightly from the target following the reactive power Q . Referring to the block

schematic (Fig. 3.9), the feedback on Q is proportional to σ_b . Thus when this attenuation is very low, no undesirable effect is expected regarding voltage regulation. When V-LADRC is applied to model 2 (FF , *filter on $Q^* - Q$ only*), a high-frequency oscillation appears due to the absence of filtering on V^* , but this oscillation is quickly attenuated.

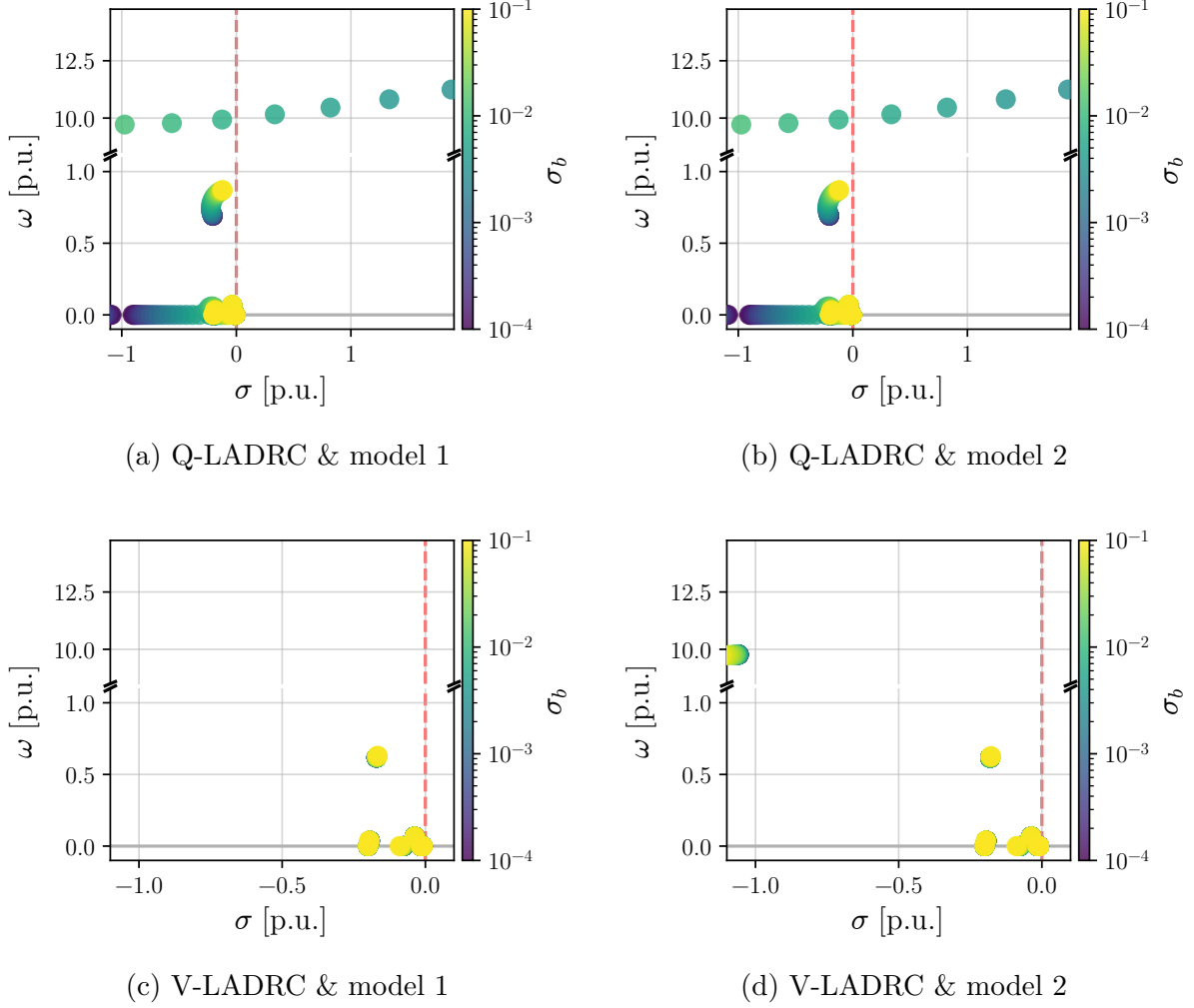


Figure F.6: Pole map with Q- or V-LADRC on models 1 (FF , *filter on $Q^* - Q$ and V^**) or 2 (FF , *filter on $Q^* - Q$ only*) of Q - V outer loop. Parametric small-signal stability analysis for varying the external Q - V droop coefficient σ_b . Using Q-LADRC may lead to high frequency oscillations and instability when σ_b is too low (meaning too strong voltage feedback on Q^*).

F.5 Q-LADRC vs V-LADRC: conclusions

In conclusion, both Q-LADRC and V-LADRC based systems, applied to Q - V outer loops models 1 and 2, have advantages and disadvantages.

Q-LADRC systems small-signal stability is less sensitive to high observer bandwidths $\omega_{0,Q}$, which may be useful to get precisely the desired response to a change of target. However, the response to a grid voltage drop is much slower than with V-LADRC.

V-LADRC systems small-signal stability is less sensitive to the filter time constant τ_f and the external droop coefficient σ_b . However, it becomes quickly unstable when increasing the observer bandwidth $\omega_{0,V}$, which reduces the possibilities to precisely replace the existing system dynamics by fast desired dynamics.

Models 1 and 2 have similar behaviors. Nevertheless, adding a slight low-pass filter on V^* (model 1) allows better attenuating the high-frequency oscillations.

Since the response to a grid disturbance is in practice more relevant than the response to a step of target, and because the precision of the response is not very important as long as it is fast, which is the case with the moderate observer bandwidth $\omega_{0,V}$, the V-LADRC applied to the Q - V outer loop model 1 (*FF, filter on $Q^* - Q$ and V^**) is selected for the rest of this work.

G Mathematical developments of the linearized P - V model

From the electrical system represented in Fig. 3.3, the voltage phasor V_{PCC} can be expressed:

$$\bar{V}_{PCC} = \frac{\omega C_f \left((R_f + jX_f) \bar{V}_g + (R_g + jX_g) \bar{V}_c \right)}{\omega C_f (R_f + R_g + jX_f + jX_g) + jR_f R_g - R_f X_g - R_g X_f - jX_f X_g} \quad (\text{G.1})$$

The objective of the whole system is to transmit power, and the objective of the filter is to attenuate high frequency oscillations coming from the power electronics. Hence serial elements R_f , X_f , R_g , X_g should be quite small. Thus the previous expression can be approximated neglecting the second-order terms at the denominator, compared to the first-order terms multiplied by ωC_f . The expression simplifies:

$$\bar{V}_{PCC} \approx \frac{(R_f + jX_f) \bar{V}_g + (R_g + jX_g) \bar{V}_c}{R_f + R_g + jX_f + jX_g} \quad (\text{G.2})$$

This is equivalent to neglecting the shunt capacitor, as represented in Fig. G.1. This approximation is widely used in the literature to simplify considerably the analytical expressions [24][30][50][63][64].

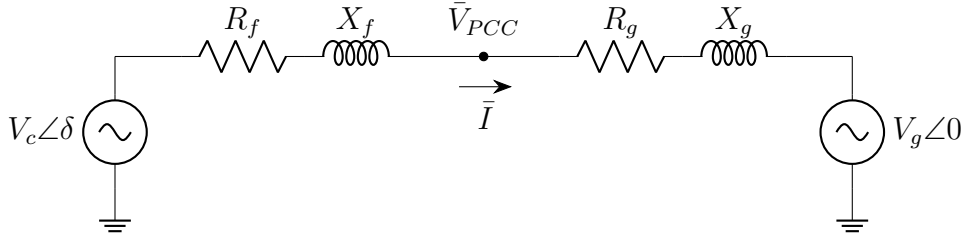


Figure G.1: Electrical system without shunt capacitor

Eq. (G.2) can indeed be written as a simple voltage divider:

$$\bar{V}_{PCC} = \frac{\bar{Z}_g}{\bar{Z}_f + \bar{Z}_g} \bar{V}_c + \frac{\bar{Z}_f}{\bar{Z}_f + \bar{Z}_g} \bar{V}_g \quad (\text{G.3})$$

The amplitude of $\bar{V}_{PCC}$ can be calculated:

$$V_{PCC} = \frac{\sqrt{V_c^2 (R_g^2 + X_g^2) + V_g^2 (R_f^2 + X_f^2) + 2V_c V_g ((R_f R_g + X_f X_g) \cos \delta + (X_f R_g - R_f X_g) \sin \delta)}}{\sqrt{(R_f + R_g)^2 + (X_f + X_g)^2}} \quad (\text{G.4})$$

However this expression is heavy and non-linear. Instead, (G.3) is linearized by approximating for $\delta \approx 0$ (hence $\bar{V}_c = V_c(\cos \delta + j \sin \delta)$ can be linearized in $\bar{V}_c \approx V_c(1 + j\delta)$).

When further approximating for $V_c \approx 1$, $V_g \approx 1$ and by using $\Delta V = V_c - V_g \approx 0$ (just like for the (P, Q) system), the expression reduces to:

$$\bar{V}_{PCC} = V_c + \frac{-\bar{Z}_f \Delta V + j\bar{Z}_g V_c \delta}{\bar{Z}_f + \bar{Z}_g} \quad (\text{G.5})$$

Taking the amplitude of (G.5) would bring back square roots in V_{PCC} . However because δ and ΔV are small, $V_c \gg \frac{-\bar{Z}_f \Delta V + j \bar{Z}_g V_c \delta}{\bar{Z}_f + \bar{Z}_g}$. Hence because V_c is real, the amplitude can be approximated by:

$$V_{PCC} \approx V_c + \Re \left(\frac{-\bar{Z}_f \Delta V + j \bar{Z}_g V_c \delta}{\bar{Z}_f + \bar{Z}_g} \right) \quad (\text{G.6})$$

$$= V_c - \Delta V \left(\frac{R_f(R_f + R_g) + X_f(X_f + X_g)}{(R_f + R_g)^2 + (X_f + X_g)^2} \right) + V_c \delta \left(\frac{R_g X_f - X_g R_f}{(R_f + R_g)^2 + (X_f + X_g)^2} \right) \quad (\text{G.7})$$

As can be seen in (G.7), linearized expression of V_{PCC} is not a linear combination of δ and ΔV as it was for P and Q . As could be expected, the PCC voltage does not only depend on ΔV (and δ), but also on the value itself of V_c (or V_g). Moreover, the last term is a non-linear cross-coupling due to the multiplication by $V_c \delta$.

Assuming the grid stable ($dV_g = 0$ then $d\Delta V = dV_c$):

$$dV_{PCC} = dV_c - \frac{R_f(R_f + R_g) + X_f(X_f + X_g)}{(R_f + R_g)^2 + (X_f + X_g)^2} dV_c + \frac{R_g X_f - X_g R_f}{(R_f + R_g)^2 + (X_f + X_g)^2} (\delta dV_c + V_c d\delta) \quad (\text{G.8})$$

Because $V_c \approx 1$ and $\delta \approx 0$, then $\delta dV_c \approx 0$ and $V_c d\delta \approx d\delta$. Finally the small-signal PCC voltage response is written:

$$dV_{PCC} = \frac{R_g X_f - X_g R_f}{(R_f + R_g)^2 + (X_f + X_g)^2} d\delta + \frac{R_g(R_f + R_g) + X_g(X_f + X_g)}{(R_f + R_g)^2 + (X_f + X_g)^2} dV_c \quad (\text{G.9})$$

H Complete system (without current limiter) implemented in Matlab Simulink

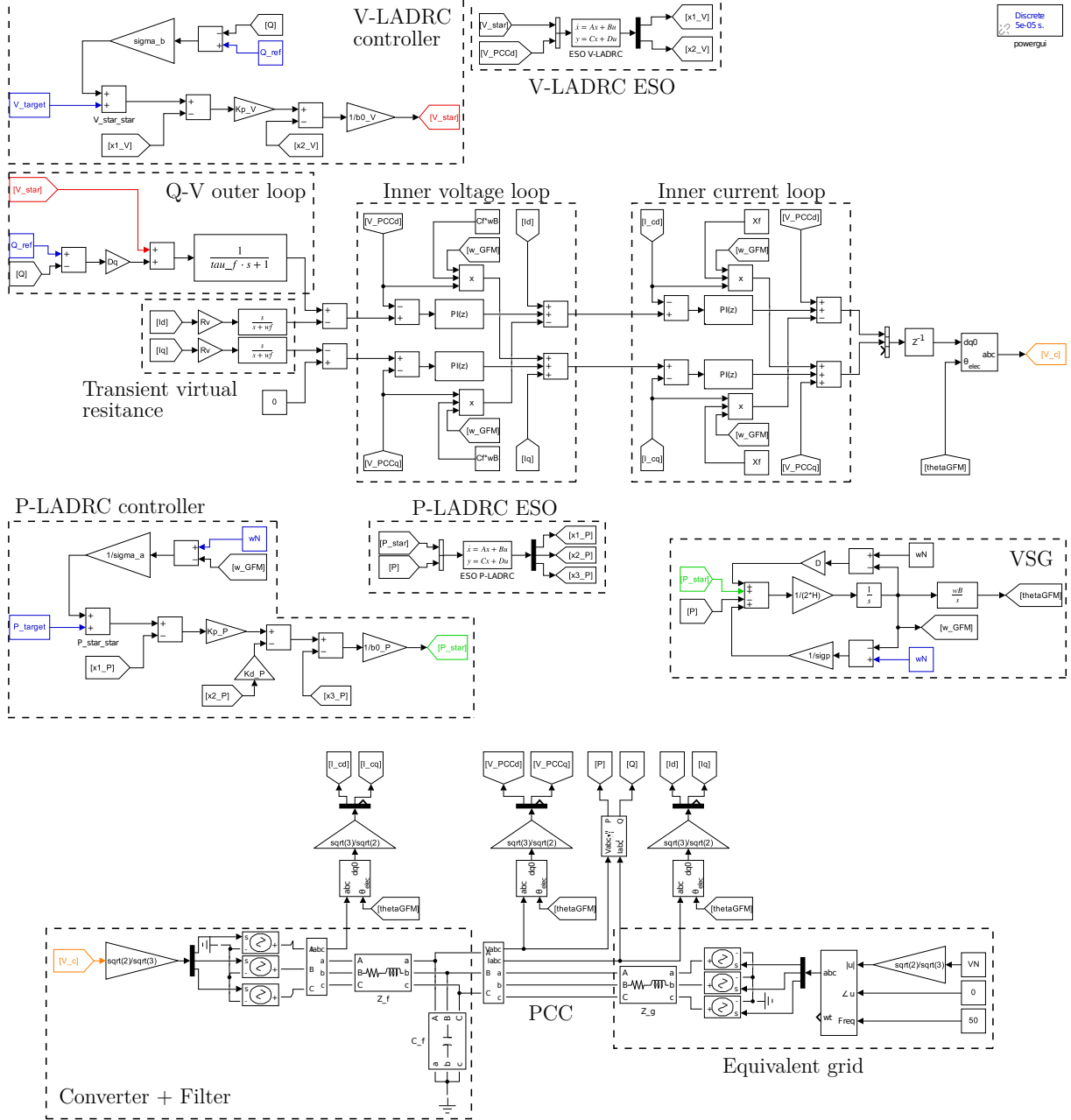


Figure H.1: Complete system (without current limiter) implemented in Matlab Simulink, adapted from [16]. Description from the top to the bottom. V-LADRC ESO and controller. Q - V outer loop *Model 1: feedforward with filter on $Q^* - Q$ and V^** . Transient virtual resistance, inner voltage loop, inner current loop. P-LADRC ESO and controller. Virtual Synchronous Generator (VSG). Power flow electrical system: converter on the left, filter, Point of Common Coupling (PCC), equivalent grid impedance, equivalent grid voltage (right). Blocks highlighted in blue are external inputs. In red and green, the links between LADRC outputs and base system inputs. In orange the output of the controller, input of the GFM converter.

I Complete system with current limiter implemented in Matlab Simulink

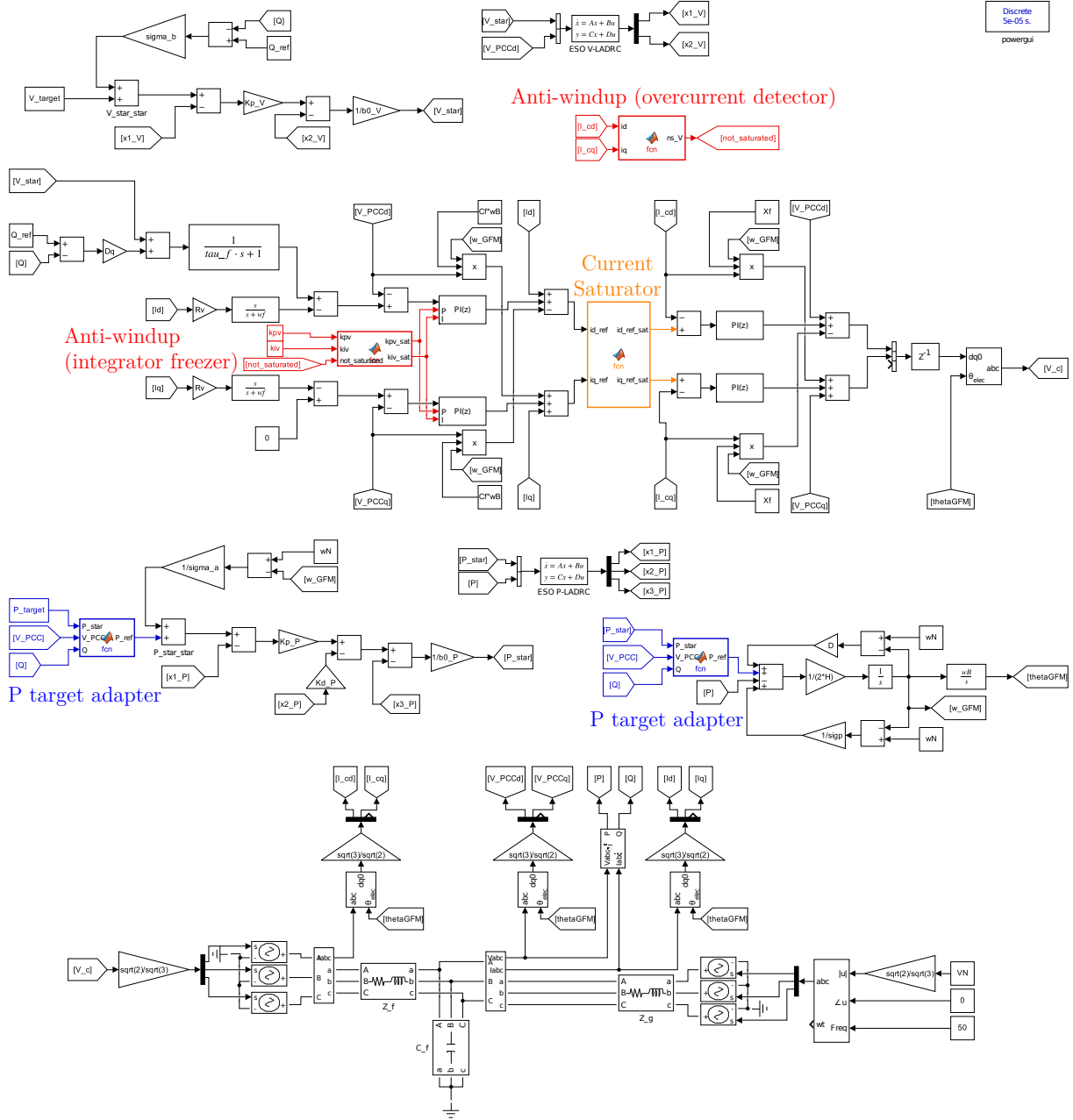


Figure I.1: Complete system with current limiter, implemented in Matlab Simulink. Base system is identical to the one shown in Fig. H.1. Highlighted blocks concern the current limiter. In red, the anti-windup system to freeze voltage loop integrators. In orange, the proportional current saturator. In blue, the active power target adapter.

J More material about faults 1 and 2

Fault 1: three-phase ground fault at the PCC, detail of the components of the FRT system (without LADRC)

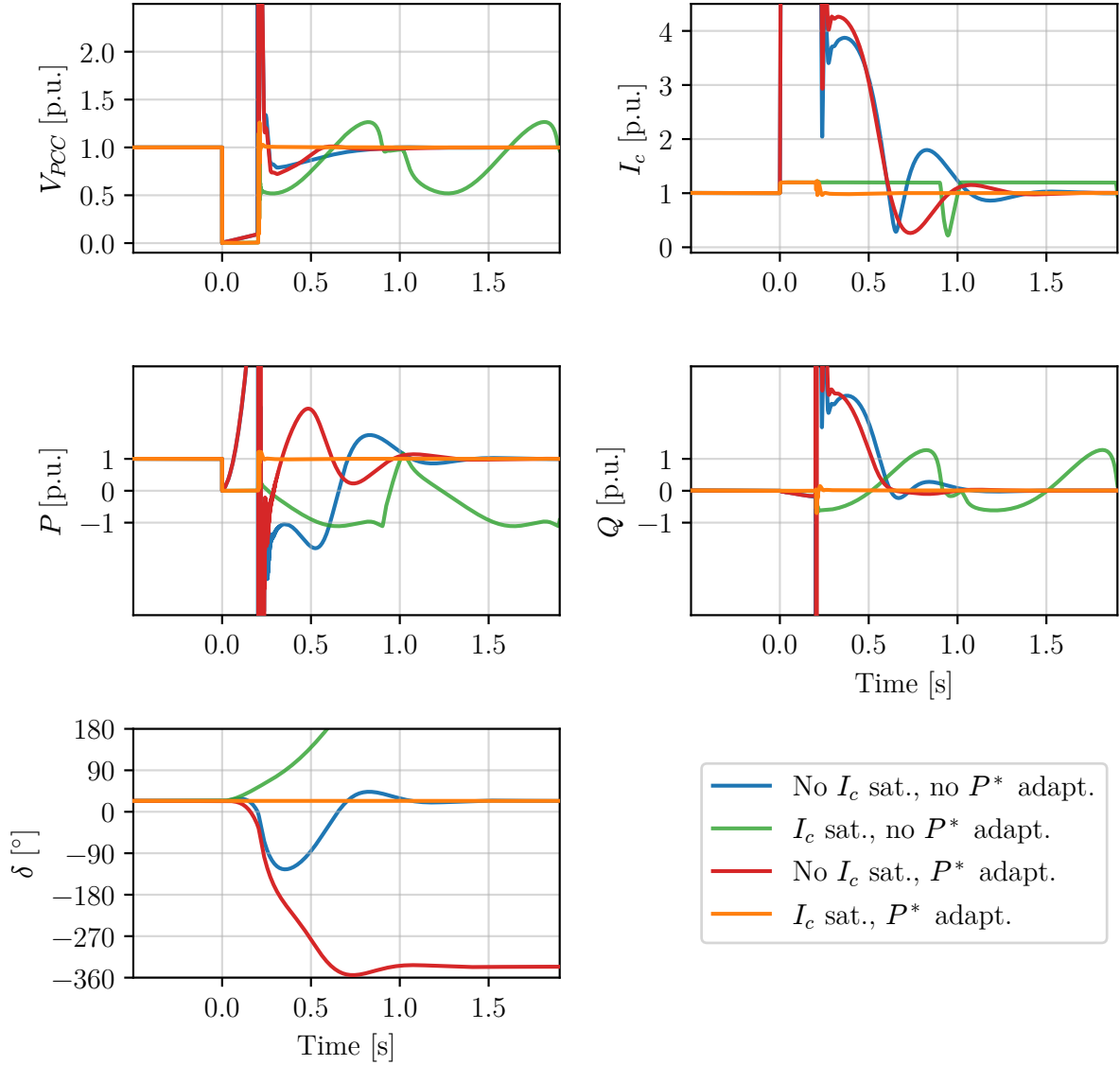


Figure J.1: Main electrical quantities reaction to a 3-ph fault at the PCC, with and without the FRT system (without LADRC). Detail of the importance of the current limiter components. Saturating the current without adapting the power set-point prevents the controller from finding an equilibrium point. Adapting the power set-point without saturating the current does not allow quickly limiting the overcurrent.

Fault 2: $\pm 45^\circ$ phase shift at the PCC

To reproduce in simulation such a phase angle shift at the PCC by only acting on the grid side, the phase angle at the PCC must be computed. Referring to the simplified electrical circuit of Fig. G.1 and by considering $R_f \ll X_f$ and $R_g \ll X_g$, the phase angle is given by (J.1).

$$\theta_{PCC} = \arctan \left(\frac{X_f V_g \sin \theta_g + X_g V_c \sin \theta_c}{X_f V_g \cos \theta_g + X_g V_c \cos \theta_c} \right) \quad (\text{J.1})$$

The phase angle at the PCC can be influenced, on the grid side, by varying V_g , X_g , and/or θ_g . To keep it simple, let us consider infinite grid voltage and equivalent reactance constant, and vary θ_{PCC} only by varying θ_g . Following the parameters, any θ_{PCC} phase angle cannot be reached. If $X_f V_g > X_g V_c$, the image set of (J.1) is $Im(\theta_{PCC}) =]-\frac{\pi}{2}, \frac{\pi}{2}[$. However $V_g \approx V_c \approx 1$ [p.u.], and in case of fault, it is likely that $X_f < X_g$. Then in the other case, $Im(\theta_{PCC}) = [\theta_c - \arcsin(\frac{X_f V_g}{X_g V_c}), \theta_c + \arcsin(\frac{X_f V_g}{X_g V_c})]$.

With the parameters used previously in this work (Tab. 3.3, $X_f = 0.15$ [p.u.], $X_g = 0.4$ [p.u.]), the maximum angle variation around θ_c possible by changing θ_g only is then $\pm \arcsin(\frac{0.15}{0.4}) = 22.02^\circ$. It can be concluded that the $\pm 45^\circ$ variation must only be realistic in other cases, notably with stronger grids (with lower X_g).

For this reason, the $\pm 45^\circ$ phase shift at PCC is simulated by applying a $\pm 90^\circ$ phase shift on θ_g with $X_g = X_f = 0.15$ [p.u.] (instead of $X_g = 0.4$ [p.u.]). The proper functioning of the system is shown in Fig. J.2. Individual results of the current limiter blocks are found in Fig. J.6.

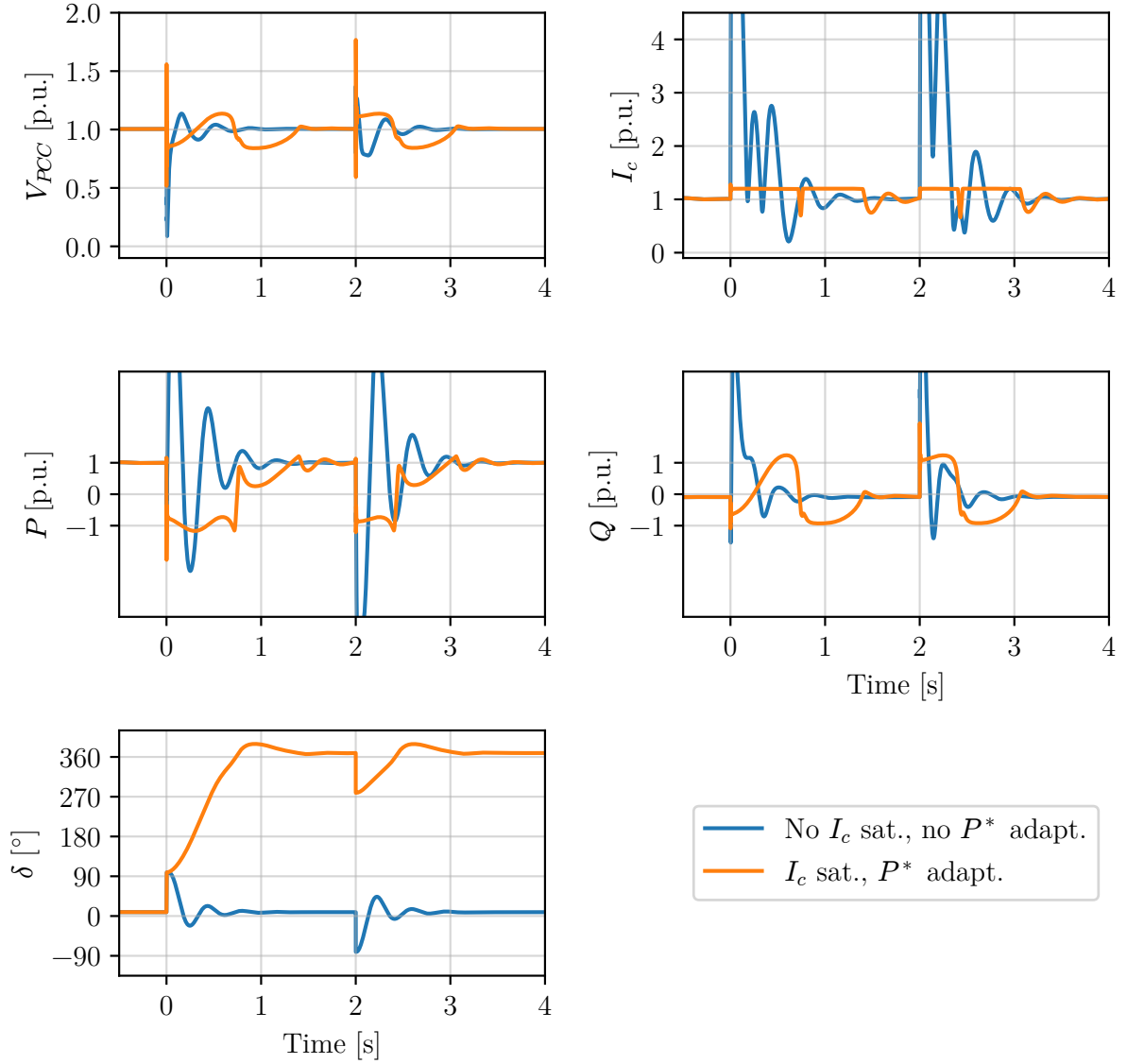


Figure J.2: Main electrical quantities reaction to $\pm 45^\circ$ phase shifts ($t = 0$ [s] and $t = 2$ [s]) at the PCC, with and without the FRT system (without LADRC). By saturating the current and adapting active power target P^* , overcurrent is limited until the voltage and powers recover. Converter phase angle adapts slowly.

P-LADRC and V-LADRC with high observer bandwidths ($\omega_{0,P} = 3$ [p.u.] and $\omega_{0,V} = 1$ [p.u.]) are successively applied to the system. Results are shown in Fig. J.3. The conclusions are about the same as for the three-phase fault. With V-LADRC enabled, the current remains clipped, while voltage also stabilizes to an excessive value, and P stabilizes at 0 [p.u.] (all the converter current is dedicated to the reactive power Q). With P-LADRC alone, the system recovers similarly as the base system without LADRC.

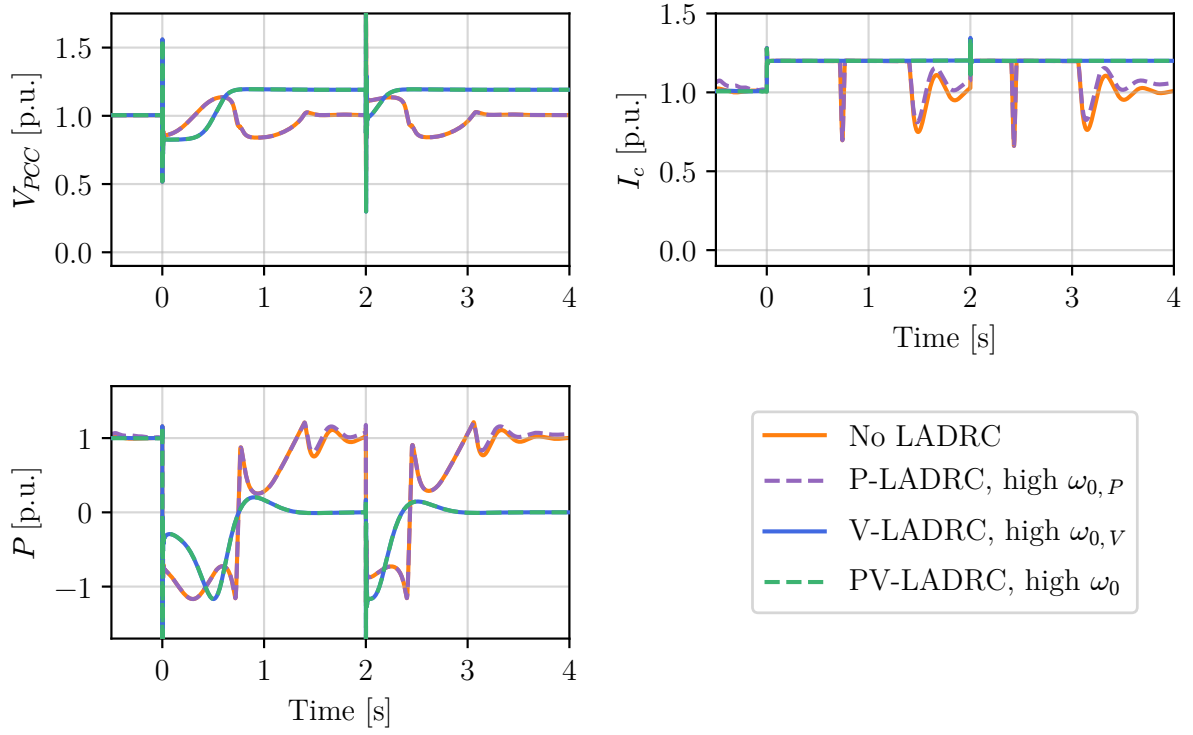


Figure J.3: Main electrical quantities reaction to $\pm 45^\circ$ phase shifts ($t = 0$ [s] and $t = 2$ [s]) at the PCC, with or without LADRCs, with high observer bandwidths ω_0 . When V-LADRC is used, the system keeps saturated and does not recover by itself.

Finally, P-LADRC and V-LADRC here also applied with low observer bandwidths ($\omega_{0,P} = \omega_{0,V} = 0$ [p.u.]), and results are shown in Fig. J.4. As expected, systems with low observer bandwidths LADRCs give the same Fault Ride Through Capability as the base system without LADRC.

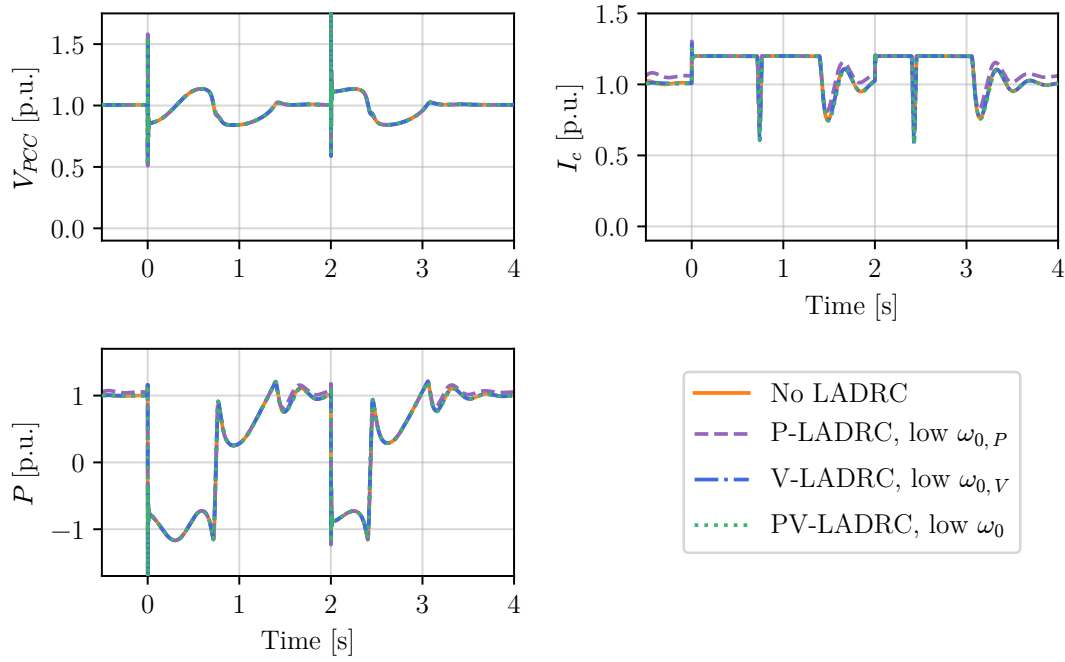


Figure J.4: Main electrical quantities reaction to $\pm 45^\circ$ phase shifts ($t = 0$ [s] and $t = 2$ [s]) at the PCC, with or without LADRCs, with low observer bandwidths $\omega_0 = 0$. Using P-LADRC and/or V-LADRC gives the same recovery as the case without LADRC.

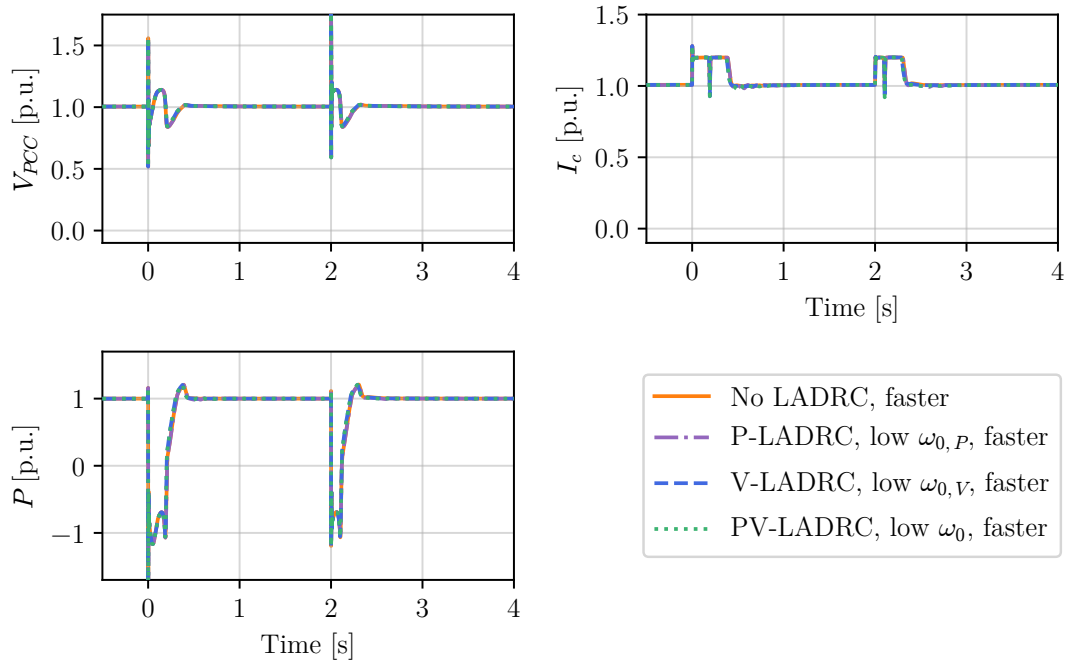


Figure J.5: Main electrical quantities reaction to $\pm 45^\circ$ phase shifts ($t = 0$ [s] and $t = 2$ [s]) at the PCC, with or without LADRCs, with low observer bandwidths $\omega_0 = 0$. The inertia constant H has been divided by 100, and the damping coefficient D have been divided by 10 when $P < 1$. The recovery is much faster than in Fig. J.4.

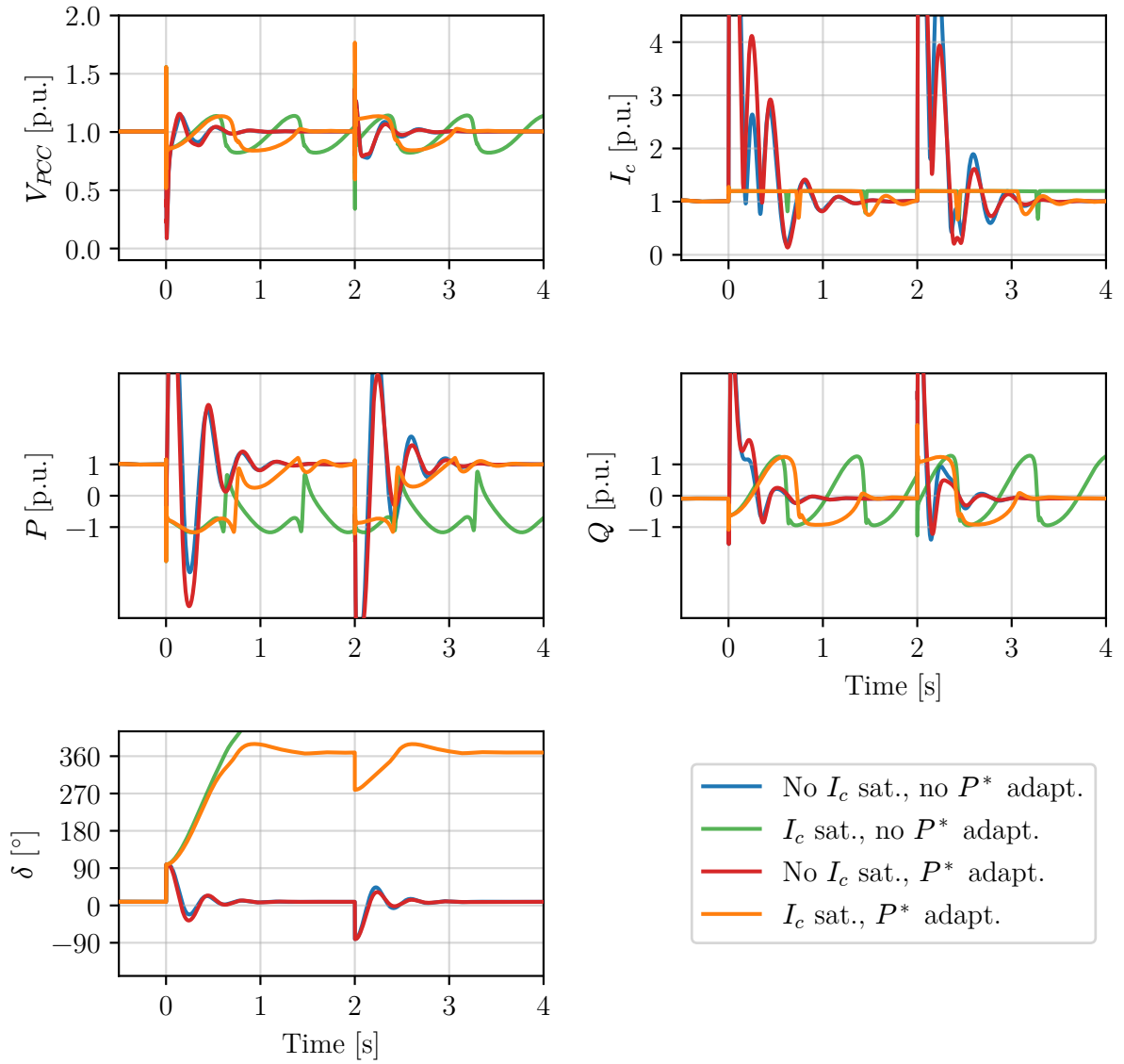


Figure J.6: Main electrical quantities reaction to $\pm 45^\circ$ phase shifts ($t = 0$ [s] and $t = 2$ [s]) at the PCC, with and without the FRT system (without LADRC). Detail of the importance of the current limiter components. Saturating the current without adapting the power set-point prevents the controller from finding an equilibrium point. Adapting the power set-point without saturating the current does not allow quickly limiting the overcurrent.

K Parallel operation, control of the same electrical node

Equivalent circuit of the two converters sharing the same Point of Common Coupling (PCC) is shown in Fig. K.1.

The idea is the following. To avoid instabilities between grid forming converters trying to impose their voltages, it may be a good solution to use a single grid forming converter to form the voltage, and grid following converters to complement the needs of power while adapting their control to avoid conflictual interactions.

As discussed in Sections 2.2 and 3.6, P-LADRC with high observer bandwidth $\omega_{0,P}$ brings a Grid-Following behavior. Thus combinations of parallel converters with and without LADRC are studied.

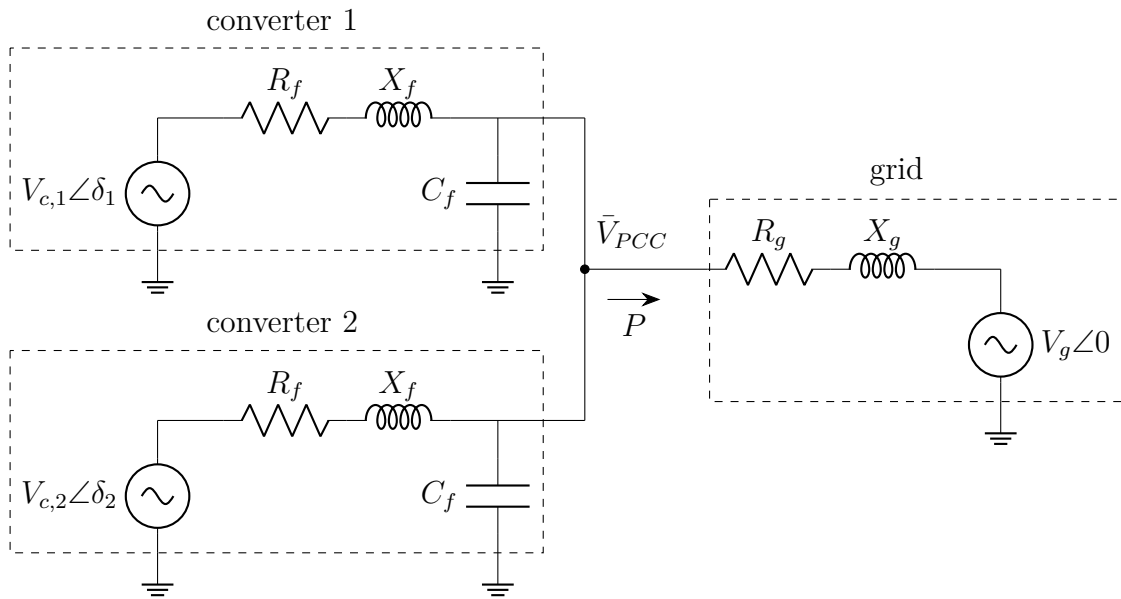


Figure K.1: Equivalent circuit for the two converters sharing the same controlled node (common PCC)

As the goal here is to simulate more realistic situations, the inertial grid model is used (Fig. 4.2 and Table 4.1).

In this case (Fig. K.1), the load is far in the grid. An active power reference is chosen to be $P_{ref,grid} = 1$ [p.u.]. The converters are chosen to be the same, with parameters being the same as in Section 3.6. Both power targets are set to be $P^{**} = 0.5$ [p.u.], such that the system is expected to be balanced at the nominal frequency of 50 [Hz].

All combinations of LADRC application (on the P and V loops, with high and low observer bandwidths, and on converters C1 and C2) have been tested. Results of voltage and power of some of them are represented in Figure K.2. In all cases, the system is unstable. Only the current limiter system prevents the system from diverging into extreme values. Notably, the idea of using P-LADRC with high observer bandwidth on converter C2 to better adapt to the pure grid forming converter C1 does not work.

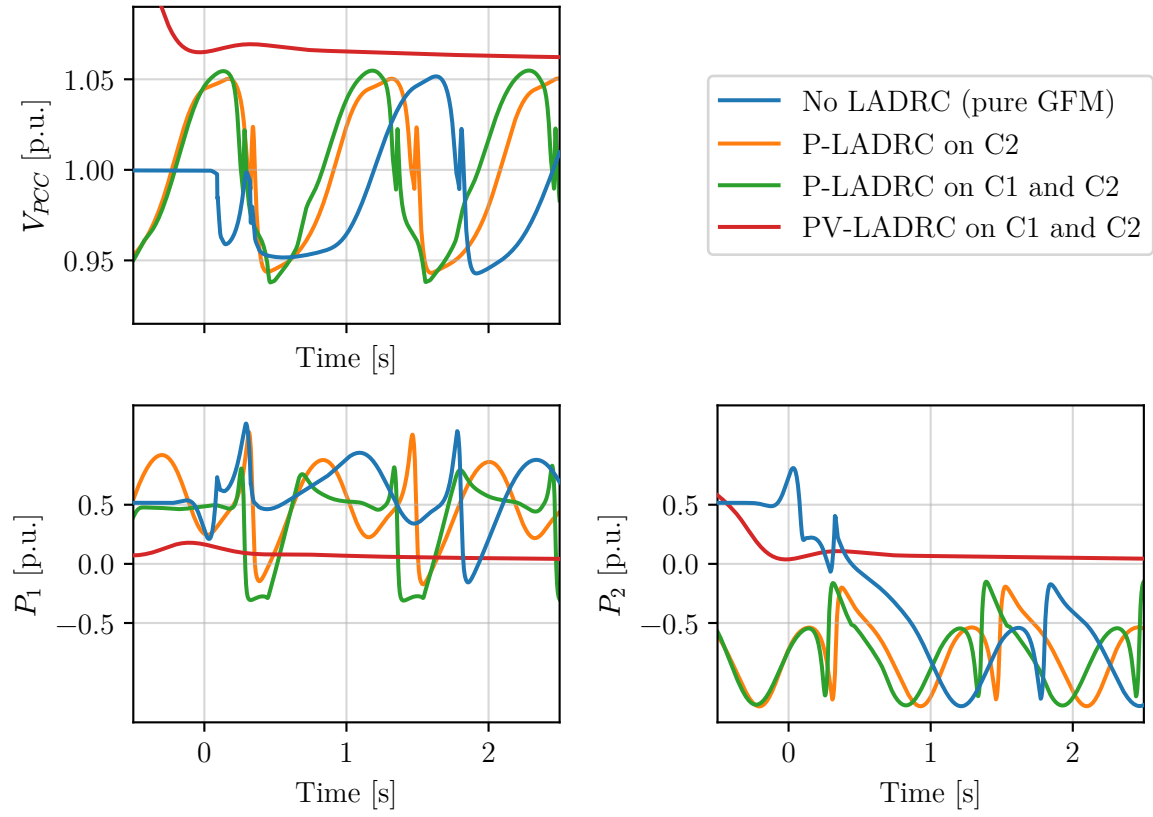


Figure K.2: Parallel operation with both controllers on the same electrical node. The system is unstable, neither with nor without LADRCs. Current limiter system leads to cyclic behaviors or saturation to unexpected values.

Declaration

The author of this work declares that the results presented are the fruit of his own research, and that all sources used were cited in good faith.

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- Symbolic enhanced implementation for the modal analysis, validated as explained in Appendix E. (Gemini)

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Raphaël Cavenaile, May 31, 2026

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